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Imagined Spatial Transformations of One's Hands and Feet

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These experiments examine two related phenomena: (a) the judgment of whether a human body part belongs to the left or right half of the body and (b) the imagined spatial transformation of part of one's body. In three of the experiments, participants made left–right judgments of a hand or foot. They apparently made this judgment by imagining *their own* hand or foot passing to the orientation of the stimulus for comparison. Time for (a) left–right judgments and (b) corresponding imagined spatial transformations depended on the extent of the orientation difference between the stimulus and the task or "canonical" orientation of the subject's hand (or foot). More important, time for (a) and (b) depended strongly, and in the same way, on the *direction* of this orientation difference. RT increased with *implicit awkwardness of stimulus orientation* (i.e., extent of anatomical and physiological constraints on movement to that stimulus orientation). Familiarity with the hand (and foot) in some nonawkward orientations reduced RT (or increased the rate of imagined spatial transformation). However, the effect of implicit awkwardness was more often apparently due to differences in *extent* of imagined paths for awkward and nonawkward orientations. Paths of *efficient* length were apparently imagined to *nonawkward* orientations, and rather *inefficient* paths were imagined to *awkward* orientations. These imagined paths seemed to simulate the paths used for physically moving the hand or foot between their task orientation and the orientation of the stimulus. These results and others suggest that kinematic and temporal properties of imagined spatial transformations are more object-specific in nature than could be previously assumed.

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When similar objects are at the same alignment, people can often readily discriminate differences in the composition and spatial arrangement of the objects' features. However, as the objects differ in orientation, the effort needed to discriminate between them increases. Exhaustively searching for and comparing, corresponding features of objects that are at different orientations can be difficult (e.g., Parsons, 1986a). People very often find it more efficient to imagine or physically produce the reorientation of one object to an orientation like that of the other (e.g., Hinton & Parsons, 1987, Shepard & Metzler, 1971). This latter fact has been exploited to study both the internal representation of shape (e.g., Cooper & Podgorny, 1976; Corballis, Zbrodoff, Shetzer, & Butler, 1978; Hinton & Parsons, 1981; Hock & Tromley, 1978) and imagined spatial transformations (Just & Carpenter, 1985; Metzler & Shepard, 1974; Parsons, 1983a, 1983b, 1987a, 1987b, 1987c, 1987d, 1987e, in press). The results reported here reveal some fundamental properties of (a) the internal representation of human body parts and (b) imagined spatial transformations. To judge which side of the human body a body part belongs to, people spontaneously imagine their own body part at the orientation of the to-be-judged stimulus. In the process, they seem to mentally simulate kinematic properties of the physical action of their body moving from their orientation during the experimental task to the orientation of the stimulus. People apparently avoid imagining physically awkward or impossible actions of their body.

Properties of Imagined Spatial Transformations

Time to imagine an object's reorientation often increases with the angle of orientation difference (e.g., Metzler, 1973; Cooper & Shepard, 1973; Parsons, 1983a, 1987d, in press). For the stimulus that has been examined in detail (i.e., one's own body as a whole, Parsons, 1987b), the rate of imagined reorientation for different planes or axes can vary by a factor of about 3. The rate can vary by a factor of about 2.5 for different directions within a plane of orientation difference (i.e., for clockwise and counterclockwise rotations about an axis, Parsons, 1987b). For some stimuli (e.g., those used by Shepard & Metzler, 1971), the rate may not vary with the plane or direction of reorientation. (However, recent results of Parsons (1987e) on the discrimination of the Shepard & Metzler objects suggest that imagined rotation rates may vary by a factor of at least 2 for different axes.) Finally, the rate of imagined reorientation is apparently influenced by properties of the imagined object. Rates can vary by more than an order of magnitude depending on the object's complexity or familiarity (compare results in Cooper, 1975; Kaushall & Parsons, 1981; Parsons, 1987b; Shepard & Hurwich, 1984; Shepard & Metzler, 1971). (For reasons to doubt the conclusion that the rate of spatial transformation depends on object complexity of familiarity, see Cooper & Podgorny, 1976; Cooper & Shepard, 1973.)

Overall, these and related results (e.g., Cooper, 1976; Pinker, 1980) are taken to imply that imagined spatial transformations produce an approximately continuous series of intermediate internal representations of a shape, that corresponds to its intermediate physical orientations. Such results are also thought to imply that objects are probably internally represented in three dimensions, rather than in two dimensions of projected three-dimensional information (as in a literally "pictorial" representation).

Limits of previous imagined spatial transformation studies. Most previous research used letters, numbers, or abstract two-dimensional and three-dimensional shapes. Only two studies had attempted to use natural or biological objects as stimuli in this paradigm (Ashton, McFarland, Walsh, & White, 1978; Cooper & Shepard, 1975), but the authors concluded that there was little difference between results with the stimulus representing the hand and results with letters, numbers, or unfamiliar and abstract stimuli. However, more recent findings indicate that quite basic information can be learned about imagined spatial transformations by using such natural stimuli in this paradigm (e.g., Parsons, 1983a; Sekiyama, 1982).

Further, in most of this previous research, two planes (or axes) of rotation were most efficient to correct for the difference in orientation between the standard and comparison objects. Most studies used orientation differences (*ODs*) in one or two planes (picture or depth), and trials were often blocked by the plane of OD. Such experimental designs fail to reflect an important aspect of human spatial transformations. Perceptual, imaginal, or motor systems are capable of interpolating, recognizing, representing, or effecting the *efficient* displacement of an object from one orientation to *any* other, with apparently *little* deliberation. An unresolved issue is the nature of the procedures and economies that allow us to select from among the indefinitely many paths an object can traverse. To understand this issue, researchers have begun to study imagined spatial transformations of objects, by developing conditions under which imagined paths can be compared to those produced by models based on different kinds of geometrical procedure (Just & Carpenter, 1985; Parsons, 1983a, 1983b, 1987d, 1987a, 1987b, 1987e).

Experimental paradigm for left–right judgments. With these issues in mind, I conducted a series of pilot studies of the left–right judgment of parts of the body. In one of these pilot experiments (which was exactly like Experiment 1), subjects viewed the palm or back of a left or right hand (Fig. 1), and pressed a left-hand button for a left hand and a right-hand button for a right hand. This design simplifies an experiment (with a different purpose) by Cooper and Shepard (1975). In four of six conditions, their subjects prepared to discriminate left from right hands at different picture plane orientations by imagining the back or palm of a left or right hand at one of six orientations. (In the two remaining conditions, subjects were given only advance orientation information about the stimulus or no advance information at all.) The stimulus was always at the expected orientation, but was equally likely to be a back or palm of a left or right hand. RT varied linearly with picture plane orientation of stimuli, and the authors proposed that subjects did this task,

> by moving a "phantom" of one of their hands into the portrayed position [of the stimulus] and by then comparing its imagined appearance against the appearance of the externally presented hand. (Cooper & Shepard, 1975, p. 48)

The experiments reported here examined more closely the imagined spatial transformations in the Cooper & Shepard task—specifically, the spatial or kinematic properties of such transformations. Here the number and variety of orientation differences between the internally represented standard and externally presented comparison objects are relatively unconstrained by experimental design. This permits examination of subjects' abilities and preferences for selecting planes or axes for imagined reorientations. These studies provide evidence discriminating among *classes* of spatial transformation procedures that differ with respect to the efficiency of their reorientation paths.

Geometrical basis of an object's reorientation. There are infinitely many paths for passing an object from one orientation to another, and a path can be produced by more than one spatial transformation procedure (cf. Parsons, 1987a). To illustrate some of the properties of this geometrical problem, I discuss three basic approaches (although there are many possible procedures—see Appendix B). Procedures (2) and (3) are examples of the class of procedures that overall produce paths of relatively efficient length; Procedure (1) is an example of the class of overall relatively inefficient procedures. Examples of the path of each procedure described below are shown in Fig. 2:

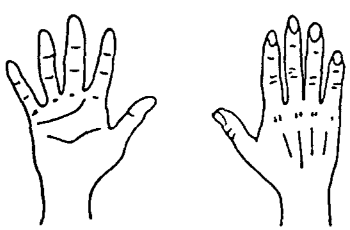


FIG. 1. Two of four stimuli in Experiment 1: the right back and palm of hand at OD of 0°.

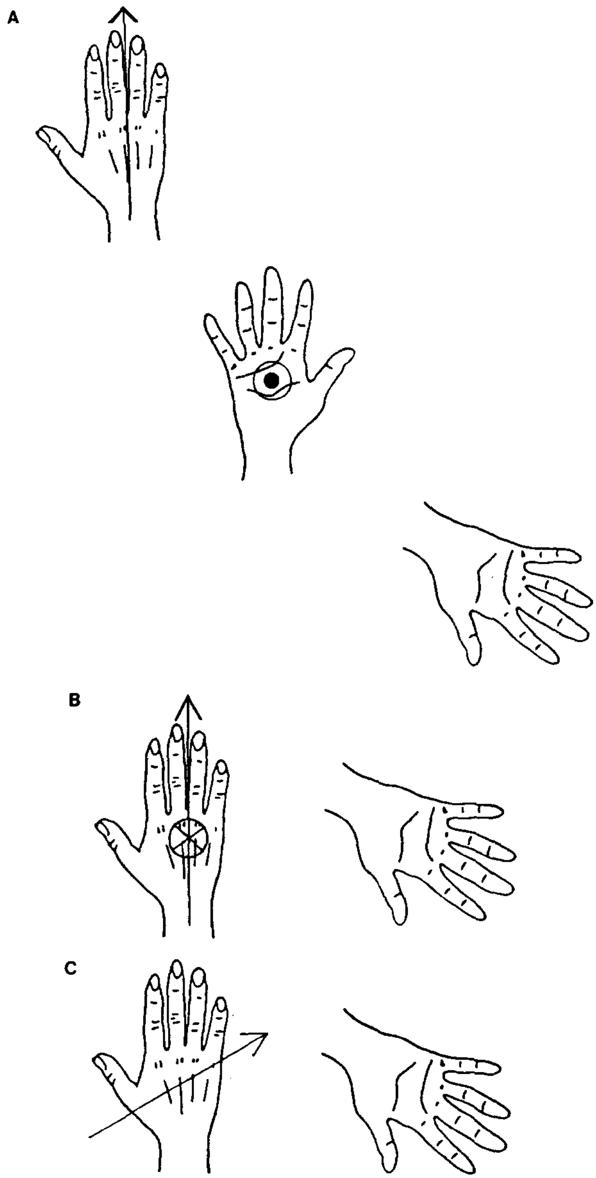


FIG. 2. Examples of three procedures for reorienting an object (see text and Appendix B). (a) Rotations-by-dimensions path uses a sequence of two rotations: 120° about its front–back axis, then 180° about the hand's long axis, then 120° about its front–back axis. For α (the angle of the long axis of the hand from upright) of 0, 30, 60, 90, 120, 150, 180°, this path requires 180, 210, 240, 270, 300, 330, 360° total of rotation. (b) Spin-precession path uses a simultaneous rotation about the hand's long axis and about the environmentally fixed axis shown. The effective axis changes instantaneously throughout reorientation, while the hand's long axis stays in the plane of this page. For α of 0, 30, 60, 90, 120, 150, 180°, this path requires 180, 182, 190, 201, 216, 234, 254° of rotation about this instantaneously changing axis. (c) Shortest path uses 180° rotation about the axis shown. The hand's long axis swings out of the plane of this page. For α of 0, 30, 60, 90, 120, 150, 180°, this path always requires 180° of rotation.

1. Rotations by dimensions: a sequence of rotations about a different axis (e.g., a principal axis of the object or the observer's visual frame of reference) for each dimension by which they differ in orientation (e.g., front–back, left–right, top–bottom).
2. Spin precession: rotation about an instantaneously changing axis produced by simultaneous rotations about two orthogonal axes (e.g., a principal axis of the object and a fixed axis of the observer's visual reference frame).
3. Shortest path: rotation about an axis (unique for each OD) to simultaneously correct for all differences in orientation while absolutely minimizing the degrees of rotation.

Different spatial transformations have different strengths and weaknesses (cf. Parsons, 1987a). For example, the shortest path for the orientation difference in Fig. 2 is not obvious. This may be because the axis of rotation is not coincident with one of the principal axes of the object (the hand). The paths for rotations-by-dimensions and spin-precession procedures may in general be more obvious, though they will usually be longer by varying amounts.

Here, the focus is on a procedure's (total) angle of rotation, because this has a monotonic, curvilinear relation to reaction time, our usual experimental measure. Each of these three procedures (or some variant) uses the same angle of rotation and path when the orientation difference is due to rotation about a principal axis of the object or the observer's visual frame of reference. Nearly all previous work used this kind of orientation differences, and so could not discriminate among different reorientation procedures. (The exceptions are (a) the studies of hands by Cooper & Shepard (1975) and the variants of that study reported by Ashton et al. (1978). However, this issue did not arise in their analyses; for this reason my research began with a simple variant of their study. Also see the recent work by Just & Carpenter, 1985.) In the series of experiments reported in this article, an attempt is made to assess whether people imagine spatial transformations such that the total extent of rotation is relatively efficient (like shortest path and spin precession) or inefficient (like rotations by dimensions).

EXPERIMENTS 1–3: LEFT–RIGHT JUDGMENTS OF HANDS AND FEET

Using the paradigm described earlier, a pilot study of the left–right judgment of a hand confirmed Cooper and Shepard's results but observed consistent and sizable effects they did not report. Subjects' RT-orientation functions and introspections suggested that the tendency to use efficient spatial transformations was influenced by the spatial relation between the orientation portrayed by a stimulus and an implicitly attached arm aligned with the subject's forearm. RTs to the palm at orientations lateral to this implicit forearm were longer by varying amounts than to corresponding medial (or contralateral) orientations. Because of the limited range of motion of joints of the body, these lateral orientations are very often more awkward and require greater motion to adopt.

Experiment 1 demonstrates this effect of implicit awkwardness on RT for these left–right judgments. To clarify and extend this finding, the number and variety of views of the hand are increased in Experiment 2. Then, in Experiment 3, subjects make left–right judgments of variously oriented feet—body parts with different limits on motion than hands. Subjects in Experiments 1–3 are *not* instructed in any way about how to make their judgments or whether to imagine their hands or feet. In Experiment A (in Appendix A), subjects rate the awkwardness of placing their hand or foot in the orientations portrayed by stimuli in Experiments 1–5.

Experiment 1: Left–Right Judgment of the Back and Palm of the Hand in the Picture Plane

Method

Subjects. Eleven right-handed University of California at San Diego (UCSD) students, who had not been in any similar experiments, participated for credit in a psychology course.

Stimuli. Drawings of the palm and back of left and right hands were presented in 12 orientations: upright (Fig. 1), upside down, and 30, 60, 90, 120, and 150° from upright in clockwise and counterclockwise directions. Left and right hands were mirror images of one another but were otherwise identical. Stimuli were displayed in a Gerbrands tachistoscope and subtended about 4° of visual angle.

Design. Subjects performed eight blocks (of 48 trials each) in two sessions. Each block contained each stimulus in each orientation in a different random order. The first two blocks were practice. Trials on which subjects made errors were *repeated* later in a block until a correct response was made.

Procedure. Subjects sat before a tachistoscope with their index fingers on a two-key microswitch, and pressed the left button for a left hand stimulus and the right button for a right hand. They were to respond as rapidly and accurately as possible, and to refrain from making large head and hand movements. (Large head movements were prevented by the edges of the viewing apparatus which fit around the sides of the head.) A trial started with the presentation of a black fixation point on a white background for 2 s. A stimulus was then presented until a response was made. An electronic timer recorded RT (within 1 ms) and accuracy of responses.

Results

Analyses uses RTs of correct responses only. Error rate was less than 2% on average, and was correlated with RT (r = .82, $F(1,46) = 91.90$, $p < .0001$, for means in Figs. 3–4 and errors). RT was affected by stimulus type, and extent and direction of OD (Figs. 3 and 4). An analysis of variance (ANOVA) was conducted using stimulus type, handedness of stimulus (or response), and OD. Longer RTs were observed (a) to palms than

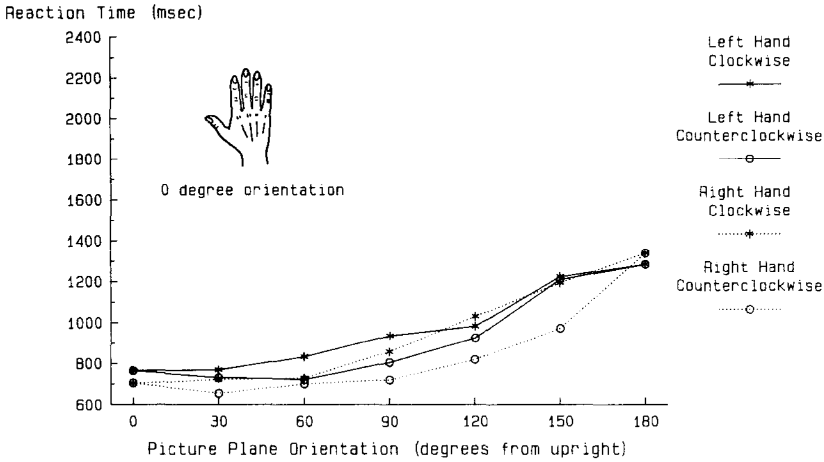


FIG. 3. Mean RT as a function of the clockwise and counterclockwise picture plane orientation of the backs in picture plane stimulus (Fig. 1).

to backs ($F(1,10) = 22.75$, $p < .001$), (b) to (or with) left than right hands ($F(1,10) = 20.78$, $p < .01$), and (c) for greater ODs ($F(11,110) = 22.47$, $p < .001$). The effect of OD on RT was different for left and right hands ($F(11,110) = 14.65$, $p < .001$) and different for palms and backs ($F(11,110) = 8.63$, $p < .001$). There was an interaction among stimulus type, handedness of stimulus, and OD ($F(11,110) = 4.38$, $p > .01$).

Effect of medial and lateral stimulus orientation. The relation of handedness of a stimulus (or response) to the clockwise direction of its OD

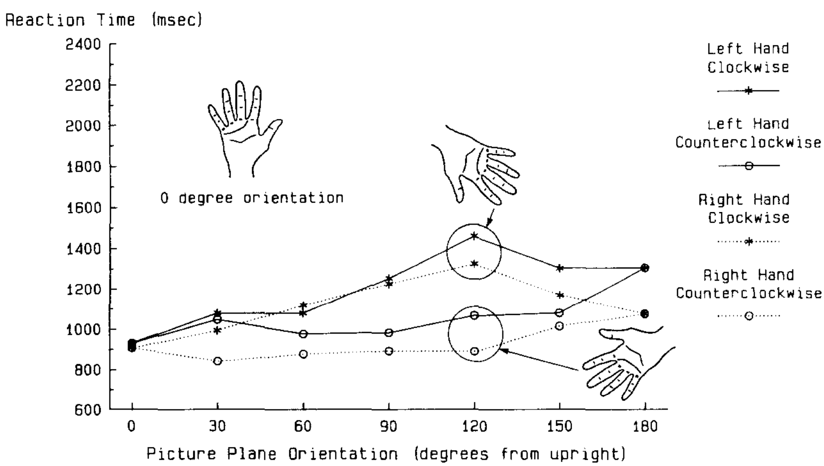


FIG. 4. Mean RT as a function of the clockwise and counterclockwise picture plane orientation of the palms in picture plane stimulus (Fig. 1).

modified the effect of OD on RT. This effect was similar for the back and palm of each hand: counterclockwise ODs produced longer RTs for left-hand backs and palms; and the clockwise ODs produced longer RTs for right-hand backs and palms. All the functions for backs had a similar shape. Palm functions showed either (1) a steep slope with a peak at an OD of 120° and a declivity of equal slope to 180° (cf. left palm counterclockwise and right palm clockwise functions) or (b) a very slight slope to 180° (cf. left palm clockwise and right palm counterclockwise functions).

Because the left hand at counterclockwise ODs and the right hand at clockwise ODs portray the hand lateral to an implicitly attached forearm aligned with the subject's forearm, they are *lateral* orientations. Left hands at clockwise ODs and right hands at counterclockwise ODs are *medial* orientations. Figure 5 shows RTs at lateral and medial orientations.

Separate ANOVAs using medial and lateral stimulus orientation, left and right hand, and five ODs (30, 60, 90, 120, 150°) showed the following effects. For backs, RTs were longer to (or with) left than right hands ($F(1,10) = 29.98$, $p < .01$) and to lateral than medial orientations $F(1,10) = 10.04$, $p < .01$). RTs increased with increasing OD ($F(4,40) = 34.40$, $p < .001$). Further, there was an interaction of medial and lateral orientation, stimulus or response handedness, and OD ($F(4,40) = 4.14$, $p < .01$). This interaction is due to a difference in RT advantage for medial ODs between left and right hands (134 as compared with 71 ms), and is concentrated at ODs of 120 and 150°. (This was replicated in Experiment 4 but not Experiment 2.)

For palms, RTs were longer for lateral than for medial orientations

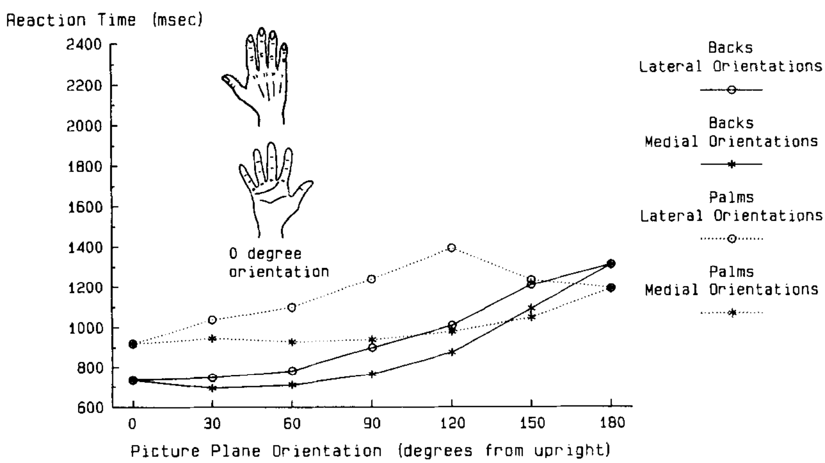


FIG. 5. RT-OD functions for left and right palms and backs stimuli at lateral and medial orientations (see text).

($F(1,10) = 47.98$, $p < .001$) and longer for left than for right-hand stimuli (or responses) ($F(1,10) = 9.79$, $p < .01$). RTs were different at different ODs ($F(4,40) = 4.47$, $p < .01$). The effect of OD on RT was different for lateral and medial orientations ($F(1,10) = 5.40$, $p < .001$).

Introspective reports. All subjects reported imagining moving their hand from its orientation during the task to the orientation of the stimulus to compare imagined and external (stimulus) hands. Only for backs near 0° did they report finding it unnecessary to imagine a spatial transformation. They noted difficulties imagining their hand in some orientations of the stimulus that were physically awkward to adopt.

Discussion

Model of performance. These and Cooper and Shepard's results suggest that the preferred strategy in this task is to imagine moving *one's hand* to the orientation of the stimulus. Subjects compare these two shapes at the *orientation of the stimulus.* They apparently do not imagine rotating the stimulus to a "standard" orientation. The latter method is used by people discriminating correct from mirror-reversed letters and numbers. The imagined spatial transformations used here apparently *originate* from the orientation of the subject's hand during the task—back of the hand facing the body's upper front, with fingers pointing up or forward. For the subject, this orientation is similar to that portrayed by the back of hand stimulus at 0°, or at near which subjects produced their shortest RTs and reported knowing stimulus handedness "immediately" (without imagining spatial transformations). (Analogously, when making a left–right judgment of an outstretched arm of a misoriented body, if the stimulus is upright with its back toward observer, the observer finds discriminating left from right body parts (e.g., an arm) obvious, Parsons, 1987b). It may be more efficient to imagine a spatial transformation of an internal representation than to imagine the rotation of the stimulus for comparison with the external stimulus. Imagining the rotation of the external stimulus requires one to maintain and compare *two* internal representations.

Subjects apparently used a *confirmation* strategy, imagining their left hand in the orientation of left-hand stimuli and their right hand in the orientation of right-hand stimuli. This is also suggested by the Cooper and Shepard results. In one condition, their subjects were given the information that the upcoming stimulus would probably be (e.g.) a *left* palm (in the picture plane) with the fingers pointing downward. If a *right* palm at that orientation were actually presented, subjects did not simply infer from the mismatch of shapes that it was the other hand. Instead, subjects produced a RT-orientation function that indicates they imagined a rotation of their "upright" right hand into the orientation of the stimulus.

Subjects did not first imagine their *dominant* (right) hand in the orientation of a stimulus, and then if a mismatch occurred, infer that it was the other hand. (That is, when the stimulus was an upside-down left palm, they did not first imagine an upside-down right palm, and then infer from the mismatch that stimulus was a left hand.) If they had, left and right stimuli would have produced identically shaped RT-OD functions separated only by the time to infer a mismatch. This possibility is ruled out by similar functions for left and right stimuli at lateral orientations, that are different from similar functions for left and right stimuli at medial orientations (e.g., Figs. 3–4), as predicted by a confirmation strategy. (In addition, Ashton et al., 1978, replicated the Cooper and Shepard, 1975, experiment with groups of left- and right-handed subjects, but found no interactions involving the factors of handedness of the subject and handedness of the stimulus.) The results here also rule out another possibility. Subjects could have *randomly* selected a left or right hand and initially imagined it at the stimulus orientation. Then, if this hand did not match the stimulus, they could have inferred that the stimulus was the opposite hand. This strategy predicts *no* difference (on average) between RTs for the left and right hand stimuli.

RT is strongly affected by the direction of the OD of the stimulus. The effect of OD on RT was strongly dependent on the relation of stimulus handedness to the direction of its OD (i.e., clockwise vs counterclockwise from upright in the picture plane). RTs to stimuli portraying the palm at orientations lateral to an implicitly attached arm (aligned with subject's arm) were longer by varying amounts than at corresponding medial orientations. The RT-OD function for the palms at lateral orientations was markedly different in shape from that at medial orientations.

This difference in performance for lateral and medial orientations seems to reflect mechanical properties of the hand's motion—specifically, its *limited ranges of motion.* It is much more difficult to put the hand at orientations of the palm stimulus lateral to the forearm than at orientations medial to the forearm. Accordingly, longer RT-OD functions were produced for the palm's lateral orientations. This is *not* caused by actual movement and inspection of the hand, because subjects did not move or see their hands during a trial.

The marked difference between functions for palms at lateral and medial orientations may result from *imagined paths of different extents,* where the path accommodates mechanical properties of the hand's motion. The flat function for palms at medial ODs may result from (a) use of shortest paths, which (other things being equal) produces uniform RT over ODs, or (b) use of spin-precession paths which produces a gradually increasing function (cf. Table 1). However, the flat function is quite unlike the function predicted by use of rotations-by-dimensions paths. Alternatively, it may be that either *the rate or initiation time* of imagined spatial transformations are slower through awkward than through nonawkward orientations. Shape and intercept of the function at lateral orientations are consistent with use of rotations-by-dimensions paths but not shortest or spin-precession paths (see General Discussion).

The smaller difference in medial and lateral functions for the back of hand is likely not due to differences in extent of imagined path, but to people's greater familiarity with the back of the hand at medial orientations. This is suggested by the greater range of uniformly rapid RTs near 0° for the slightly more awkward lateral orientations. Relatively slightly sloped functions for stimuli near some salient orientation (e.g., upright) are observed for discrimination of mirror-reversed and normal letters and digits (Cooper & Shepard, 1973; Hinton & Parsons, 1981) and abstract three-dimensional objects (Kaushall & Parsons, 1981). The differences in orientation in these other studies were in a single principal plane of the object, as is apparently true for the orientation difference between the back-in-picture-plane stimulus and the hand's task-specific or canonical orientation. A similar but more extensive range of RTs near upright is observed for left–right judgments of an outstretched arm of a misoriented human body (Parsons, 1983a, 1983b, 1987b).

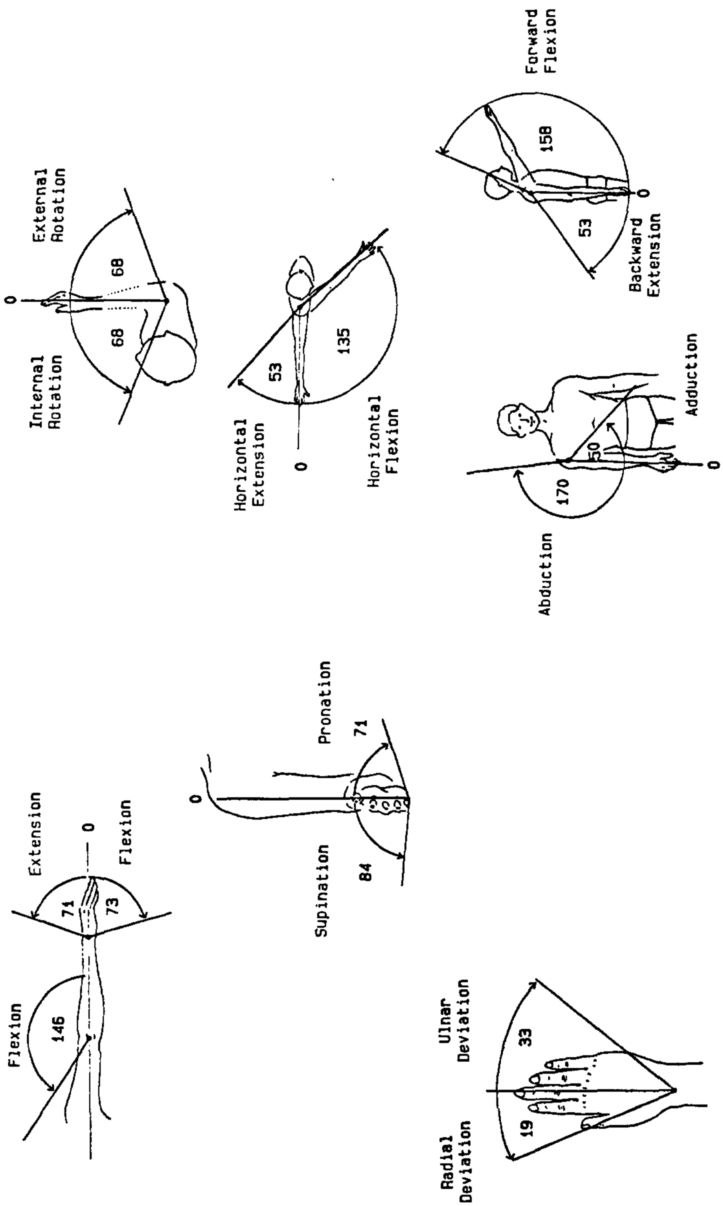
These tentative interpretations gain credibility in light of the results reported later (and in Parsons, 1983a, 1987b). More complete discussion of these and the following results is deferred until the General Discussion.

Experiment 2: Left–right Judgment of the Hand at Many Orientations

Experiment 2 uses a large set of views of the hand to map onto a more representative set of orientations, characteristics of the shape discrimination and imagined spatial transformation in left–right body-part judgments. It focuses on how these processes are affected by the implicit awkwardness of stimulus orientation. Subjects make left–right judgments of hands viewed from six cardinal perspectives: from the back, palm, fingers, wrist, and thumb and little finger sides (Figs. 7–11). Left and right versions of these are presented at 12 picture plane orientations.

Measures of the "awkwardness" of a stimulus orientation. To examine how these underlying processes are affected by the implicit awkwardness of stimulus orientation, two approaches were used to relate (a) stimulus orientation to (b) extent of physiological and anatomical constraints on movement to that orientation. One approach used people's *ratings* of the awkwardness of putting their hand at stimulus orientations (cf. Appendix A). A second approach relied on average normal *ranges of joints* used in the most efficient path from the task (or canonical) orientation to that of the stimulus. (The ranges of motion used in this paper are shown in Fig. 6.)

Relation of stimulus orientation to awkwardness is evaluated on two


External Rotation
68
0
68
Internal Rotation
Horizontal Extension
53
0
135
Horizontal Flexion
Forward Flexion
158
0
53
Backward Extension
Abduction
170
50
Adduction
0
Flexion
146
Extension
71
0
73
Flexion
0
Supination
84
Pronation
71
Radial Deviation
19
Ulnar Deviation
33

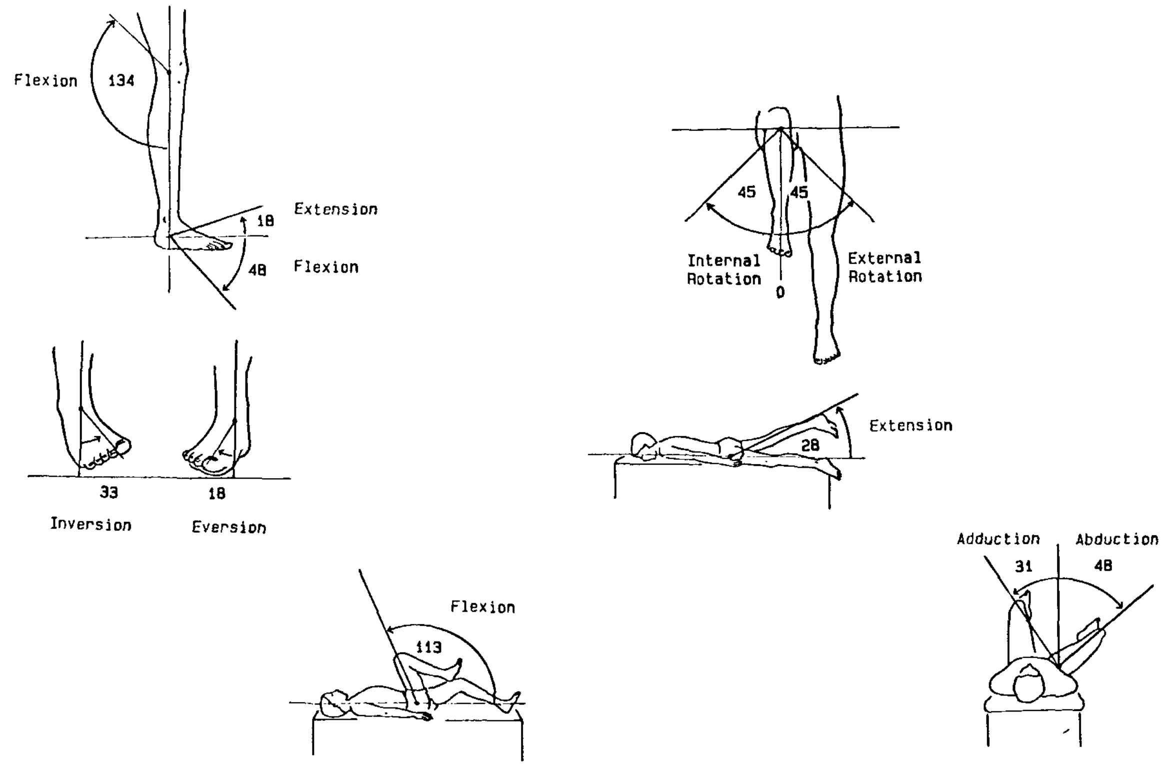


FIG. 6. Illustrations of the anatomical terms for motions of the joints of the limbs. Also shown are the average ranges of normal motion for those joints. The ranges are averages of four studies: The Committee on Joint Motion of the American Academy of Orthopaedic Surgeons (1965); Committee on Medical Rating of Physical Impairment, Journal of American Medical Association (1958); Committee of the California Medical Association and Industrial Accident Commission of the State of California (1960); and the Mayo Clinic (Clark, 1920).

dimensions: lateral and medial orientations, and orientations at ODs of 0 and 180°. Within-stimulus measures of implicit awkwardness are as follows. For each medial orientation of a stimulus, there is always a lateral orientation of corresponding angle from task (or canonical) orientation, ignoring joint limits. For palms in picture plane, 0 and 180° orientations are equidistant from the canonical or task orientation (i.e., back of the hand in the picture plane at 0°). However, for backs in picture plane, sides from thumb, and sides from little finger, the 0° orientation is closer (has a smaller angle) to the task or canonical orientation than is the 180° orientation. The converse is true for palms from fingers. Comparison of awkwardness *across* stimuli is assessed by overall correlations of awkwardness ratings with RTs in Experiments 2–5. (For a description of the relationship between ranges of motion and awkwardness ratings, see the following Method and Results sections.)

Reorientation by various spatial transformation procedures. In Table 1 are degrees of rotation for rotations-by-dimensions, spin-precession, and shortest paths from (a) the task (or canonical) orientation of hand (back in picture plane at 0°) to (b) each stimulus orientation. These values, with assumptions about rates of spatial transformation, aid interpretation of RT-OD functions. (See Appendix B for descriptions of these procedures.)

Descriptions of ranges of motion of body parts. Figure 6 illustrates the anatomical terms for body part orientation and position. It also shows the average normal ranges of motion of the joints of the limbs.

Method

Subjects. Eight right-handed UCSD students, who had not been in any similar experiments, participated for credit in a psychology course or for $4 an hour.

Stimuli, design, and procedure. All aspects of stimuli, design, and procedure are identical to Experiment 1, except the stimuli (Figs. 7–11) vary in size from 2.5 to 4° of visual angle, and subjects performed three blocks of 144 trials each (the first was practice).

Ranges of motion and awkwardness ratings. The ranges of motion and subjects' awkwardness ratings are generally positively related. They show similar values on the lateral–medial and 0–180° dimensions for palms in picture plane and sides from thumb. For sides from little finger, palms from finger, and backs in picture plane, awkwardness ratings indicate a difference in awkwardness between lateral and medial orientations—though ranges of motion do not. For palms from wrist, both measures indicate greater awkwardness for lateral than medial orientations, but ranges of motion indicate slightly more awkwardness to 180 than 0° orientations and ratings indicate a slight difference in the opposite direction. Both measures show a difference in orientations at 0 and 180° for palms from fingers and backs in picture plane; however, for sides from little finger, the ranges of motion showed a slight awkwardness difference in 0 and 180° ODs, whereas ratings showed no difference.

Results

Analyses use RT of correct responses only. Error rate was less than 4% overall, between 2 and 5% for individuals, and was correlated with RT (*r*

TABLE 1
Degrees of Rotation (Ignoring Joint Limits) between Task (or Canonical) Orientation (Backs in Picture Plane at 0° OD) and Stimulus Orientation of Hand for Three Spatial Transformation Procedures

	Picture plane OD:						
	0	30	60	90	120	150	180
				Rotations by dimensions			
Backs in picture plane	0	30	60	90	120	150	180
Palms in picture plane	180	210	240	270	300	330	360
Palms from wrist	90	120	150	180	210	240	270
Sides from thumb	90	120	150	180	210	240	270
Sides from little finger	90	120	150	180	210	240	270
Palms from fingers	270	240	210	180	150	120	90
				Spin precession paths			
Backs in picture plane	0	30	60	90	120	150	180
Palms in picture plane	180	182	190	201	216	234	254
Palms from wrist	90	95	108	127	150	180	201
Sides from thumb	90	95	108	127	150	180	201
Sides from little finger	90	95	108	127	150	180	201
Palms from fingers	201	180	150	127	108	95	90
				Shortest path			
Backs in picture plane	0	30	60	90	120	150	180
Palms in picture plane	180	180	180	180	180	180	180
Palms from wrist	90	94	105	120	139	159	180
Sides from thumb	90	94	105	120	139	159	180
Sides from little finger	90	94	105	120	139	159	180
Palms from fingers	180	159	139	120	105	94	90

$= .83$, $F(1,70) = 157.76$, $p < .0001$, for means in Figs. 7–11 and errors). For each stimulus, RT-OD functions for right-hand clockwise ODs and left-hand counterclockwise ODs had similar shape and intercept; these functions differed from RT-OD functions for right-hand counterclockwise ODs and left-hand clockwise ODs that had similar shape and intercept (as in Figs. 3 and 4). These trends were confirmed by ANOVAs, but for brevity, only ANOVAs using lateral and medial orientation, handedness, and five ODs are described.

Backs and palms in picture plane. RT-OD functions for palms and backs in picture plane replicated those in Experiment 1 (Fig. 7). Thus, RT was greater for implicitly awkward stimulus orientations. RTs were strongly correlated with awkwardness ratings in Experiment A (for backs, $r = .90$, $F(1,10) = 41.62$, $p < .0001$; for palms, $r = .90$, $F(1,10) = 41.62$, $p < .0001$). The palms function at medial orientations was consistent with use of shortest or spin-precession paths, but not with use of rotations-by-dimensions paths; shape and intercept of function at lateral orientations was consistent with use of rotation-by-dimension paths (see General Discussion) but not shortest or spin-precession paths.

RTs for backs were longer for greater OD ($F(4,28) = 8.73$, $p < .001$), longer for left than right hands ($F(1,7) = 11.43$, $p < .05$), and longer for lateral as opposed to medial orientations ($F(1,7) = 10.67$, $p < .01$). For palms in picture plane, RTs were longer for lateral than medial orientations ($F(1,7) = 26.65$, $p < .001$), different at different ODs (though marginally reliable ($F(1,7) = 2.48$, $p < .07$), and effect of OD on RT was different at lateral and medial orientations ($F(4,28) = 4.69$, $p < .01$).

Palms from wrist. To put the hand at these stimulus orientations involves flexion, supination and pronation, and internal and external rotation of the arm. Total joint motion of the forearm is 155°: 84 and 71° for supination and pronation (Fig. 6). Placing the hand at lateral orientations requires the shoulder's external rotation (which has a range of 90° from the orientation of a supinated hand). The shoulder's internal rotation (with a range of 70°) can turn the hand beyond the end of the natural range of pronation. Ranges of motion indicate that the 180° orientation is slightly more awkward than the 0° orientation, though awkwardness ratings indicate that the 0° orientation may be slightly more awkward.

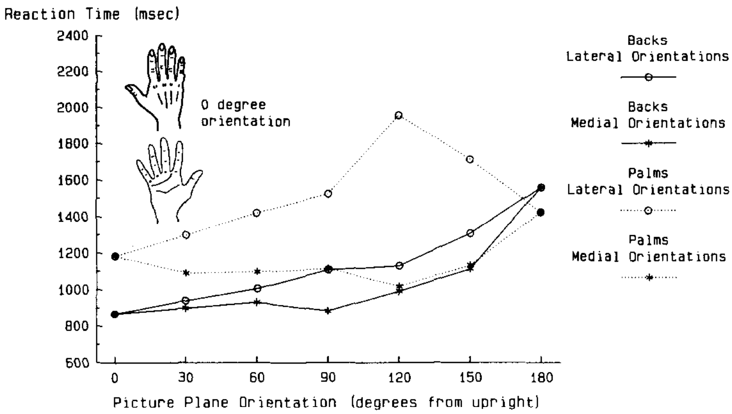
RT patterns had a suggestive correspondence to these ranges of motion (Fig. 8). For orientations within the range of pronation and supination, RT was uniformly rapid; outside this range, where action at the shoulder is necessary, RT increased approximately linearly to 90° OD, then decreased linearly at the same rate. RTs were strongly correlated with awkwardness ratings ($r = .89$, $F(1,10) = 38.85$, $p < .0001$).

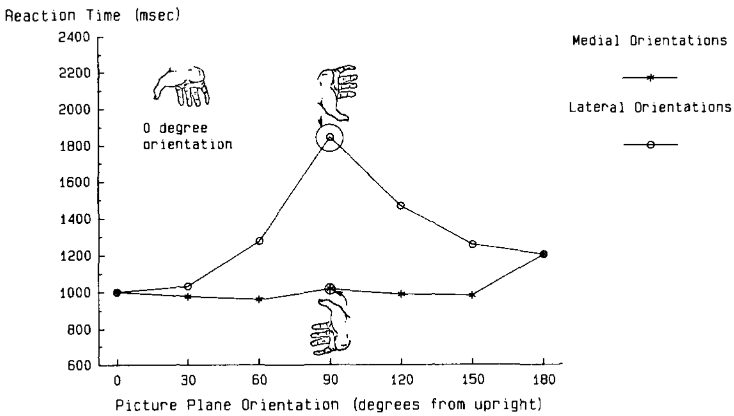
RT was 392 ms shorter at medial than at lateral orientations (varying from 66 to 830 ms for different ODs). Absolute values of increasing and decreasing slopes of the lateral function were not different (two-tailed t test, $p > .05$); nor were they different from slopes for backs in picture plane at ODs over 90° (two-tailed t test, $p > .05$). The medial (nonawkward) function resembles that predicted by shortest or spin-precession paths, and the lateral function suggests use of rotation-by-dimension paths (see General Discussion). RT at "palms up" orientation (OD of 180°) was 115 ms longer than at "palms down" orientation (OD of 0°). This result was consistent with a greater difference in orientation (ignoring joint limits) and slightly greater awkwardness (indicated by joint limits) at 180 than at 0° orientations. RTs were longer for lateral than for medial orientations ($F(1,7) = 25.40, p < .001$), different at different ODs ($F(4,28) = 5.89, p < .001$), and effect of OD on RT was different for medial and lateral orientations ($F(4,28) = 4.18, p < .01$).

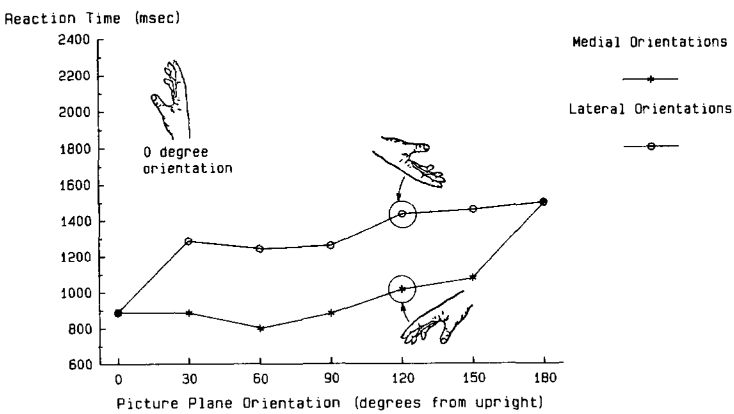
Sides from thumb. The hand's motion to medial orientations involves supination and flexion, which have ranges for shortest (or at least very efficient) paths like those used for palms in picture plane at medial orientations. Lateral orientations are rather awkward, because of limited adduction and external rotation of the arm. Awkwardness ratings show this same pattern. The hand can be placed at lateral 150 and 180° ODs (where fingers point downward) as follows. The elbow can be flexed and the arm internally rotated, so that the hand's thumb edge faces backward and the arm is fully extended and pointed downward. There is greater awkwardness (by ratings) and extent of motion (ignoring joint limits) for the orientation where fingers point upward or forward than where fingers point downward or toward observer.

The RT-OD function corresponded to the greater awkwardness of motion to lateral orientations (Fig. 9). RT at lateral ODs was 423 ms longer than at medial ODs. This function is consistent with (a) use of shortest or spin-precession path for 0° and medial orientations (where such paths are permitted by anatomical and physiological structures). It is also consistent with (b) greater awkwardness and greater difference in task (or canonical) orientation and 180° OD orientation. Specifically, (a) and (b) are consistent with the medial function's low intercept (with respect to backs of hand), and the 401-ms advantage for 0° over 180° orientation. RTs were very well correlated with awkwardness ratings ($r = .87, F(1,10) = 30.46, p < .001$). The function for lateral (awkward) orientations was apparently not produced by shortest, spin-precession, or rotations-by-dimensions paths. Nor is the path of natural motion to such orientations produced by these procedures. RT was longer to lateral than to medial orientations ($F(1,7) = 18.40, p < .01$) and increased with increasing OD ($F(4,28) = 3.42, p < .05$).

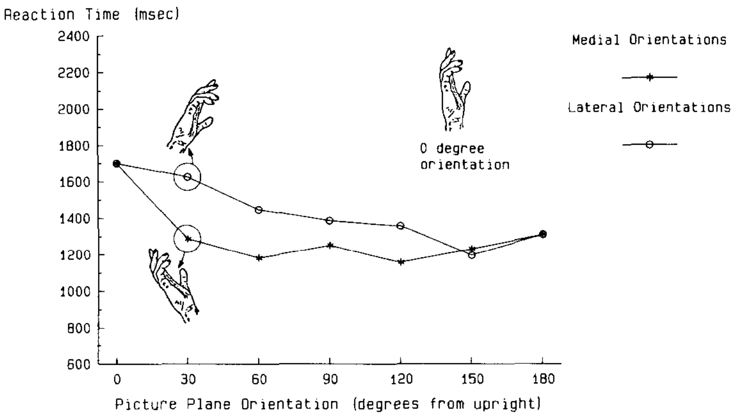
Sides from little finger. For orientations away from that in which fingers point up or forward (0° OD), ranges of motion show little differ-

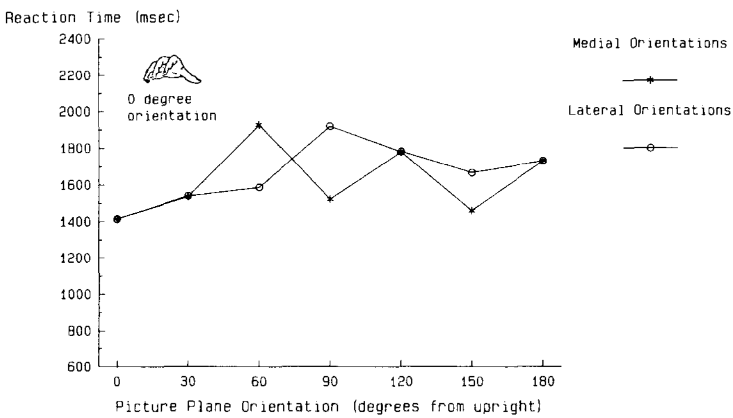






FIGS. 7–11. Discrimination RT-OD functions for the left and right version of each hand stimulus at lateral and medial orientations. Also shown is the standard or 0° orientation of each stimulus. Medial orientations are produced by turning *right*-hand (standard) versions of all but palms from fingers and palms from wrist counterclockwise by less than 180°, and corresponding lateral positions are produced by comparable clockwise turns. The opposite is true for palms from fingers and palms from wrist.





FIGS. 7–11—*Continued.*

ence in awkwardness at medial and lateral orientations. Near this "fingers up" orientation, there is slightly more awkwardness for lateral orientations (according to joint ranges). This is confirmed by awkwardness ratings. Movement to the "fingers up" orientation (0° OD) requires more degrees of rotation (because of joint limits) and is more awkward than that to the "fingers-down" orientation (180° OD).

RT was positively related to awkwardness of these hand and arm movements. It was longest near the fingers-up orientation, and (collapsing across lateral and medial orientations) it decreased to where fingers pointed down or toward observer (Fig. 10). Use of shortest, spin-precession, and rotations-by-dimensions paths predicts the opposite slope. There was a moderate RT advantage for medial orientations (177 ms). These RTs were moderately correlated with awkwardness ratings ($r = .58$, $F(1,10) = 5.10$, $p < .05$, and without RT at 0°, $r = .75$, $F(1,9) = 11.47$, $p < .01$). To accommodate joint limits, subjects may have imagined motions like those about the shortest path axis, but rotated the long way about. If so, they would produce a function peaking at 0° OD (a 27° rotation) and decreasing down to 180° OD (a 180° rotation). This explanation is consistent with the observed function's slope and intercept (relative to backs in picture plane). RT was different at different ODs ($F(4,28) = 3.24$, $p < .05$), and effect of OD on RT was different for lateral and medial orientations ($F(4,28) = 2.64$, $p < .05$).

Palms from fingers. More than one motion can efficiently put the hand at these lateral and medial orientations. Because the different motions involve different joint limits, awkwardness of an orientation cannot be related to RT without knowing the imagined path (which was not possible here). Subjects rate medial orientations as more awkward than lateral ones. Ranges of motion and awkwardness ratings show less awkwardness for "palms-down" than "palms-up" orientations (0 and 180° ODs, respectively). The hand is more readily put at the "palms-down" orientation (by supination and flexion of the wrist) than at the "palms-up" orientation (which requires motion to the limits of extension and pronation of the wrist and internal rotation of the arm).

RTs (Fig. 11) corresponded to these ranges of motion. The more awkward "palms-up" orientation had a greater mean RT (by 316 ms) than the "palms-down" orientation, though, ignoring joint limits, it was half as far from the task (or canonical) orientation. RT was 55 ms longer at medial than lateral ODs (though not reliably so), corresponding to the more awkward ratings for medial orientations. The overall decrease in RT across ODs was opposite that predicted by use of shortest, spin-precession, and rotation-by-dimension paths. The effect of OD on RT was different at lateral and medial orientations ($F(4,28) = 3.63$, $p < .05$). The tangle of observed function corroborates subjects' claim that they used different strategies for different ODs of this stimulus. RTs are not correlated with awkwardness ratings.

Introspective reports. For five stimuli, introspections were like those in Experiment 1. For palms from fingers, subjects reported using three strategies (each of which may show the influence of implicit awkwardness). This was apparently because the hand points toward observer and because various fairly efficient motions can put the hand at stimulus orientations. Subjects reported sometimes imagining (a) paths like efficient physical movement, (b) grasping the stimulus as in a hand shake, and (c) rotating their body 180° about its head–toe axis, with their hand in the appropriate orientation.

Discussion

RT patterns correspond to implicit awkwardness of stimulus hand's orientation. This pattern of RTs corresponds in general to how difficult the stimulus orientation is to physically adopt (as indicated by joint limits on the hand's motion and subjects' awkwardness ratings). For within-stimulus comparisons, this is true for (a) medial and lateral orientations for all stimuli and (b) 0 and 180° orientations for palms in picture plane and sides from little finger. However, for four other stimuli, both (a) difference in task (or canonical) and stimulus orientation (ignoring joint limits) and (b) awkwardness are greater for 180° than for 0° orientations. So it is not known whether implicit awkwardness causes this greater RT for 180° orientations. (The latter is true for backs in picture plane, sides from thumb, palms from wrist, and palms from fingers.)

The correlation of RTs for left–right judgment with awkwardness ratings ranges from .90 to .87 for four stimuli, .58 for a fifth, and is negligible for a sixth. Across all stimuli, this correlation is .81 ($F(1,70) = 129.37$, $p < .0001$) and thus, like within-stimulus measures, shows the effect of implicit awkwardness. By contrast, the correlation of RTs with rotation angle from task (or canonical) orientation to that of the stimulus, *ignoring joint limits,* is .31 ($F(1,70) = 7.75$, $p < .01$). (This is consistent with the awkwardness hypothesis, because the hand has larger ranges of motion in some directions than in others.) Thus, a model including the factor of joint limits accounts for nearly *seven times* the variance in RT.

Some of the functions observed are consistent with the hypothesis that for awkward orientations people use rotations-by-dimensions paths or paths that traverse "the long way" around a shortest path axis. Other functions are consistent with the use of either shortest or spin-precession paths for nonawkward orientations. All of the paths inferred to be used here are like those used for equivalent physical motion (see General Discussion).

Experiment 3: Left–Right Judgment of Feet

This experiment seeks converging evidence that awkwardness of placing a body part at the orientation of a stimulus affects its left–right judgment and imagined spatial transformation (see Appendix C). It examines the left–right judgment and imagined spatial transformation of the foot, which has a different range of motion than the hand. Subjects make left–right judgments of feet viewed from six cardinal perspectives: from inside and outside, from soles and tops, and from heel and toes (Figs. 12–17). Left and right stimuli were presented at 12 picture plane orientations.

Measures of awkwardness of the foot's orientation. The ranges of motion for the foot (and leg) are *smaller* and have a *different* relation to its principal planes than those of the hand (and arm) (Fig. 6). The wrist has ranges of flexion and extension of 73 and 71°, the ankle of 48 and 18°. The forearm has ranges of supination and pronation of 84 and 71°; foot, ankle, and lower leg provide only limited inward or outward rotation of the foot —inversion and eversion have ranges of 33 and 18°. The relation of elbow and knee (both hinge joints) to the body are different. The elbow flexes forward 146° in the workspace about the long axis of upper arm, from 80° toward the midline (internal rotation), to 60° away from sagittal plane (external rotation). The knee flexes backward 134° in the workspace about the long axis of upper leg, from about 45° toward the midline (with the hip in flexion and externally rotated), to about 45° away from midline (hip in flexion and internally rotated). Finally, ranges of motion for flexion, extension, abduction, and adduction are all greater at the shoulder than hip (Fig. 6).

Because of this small range of motion for the foot (and leg), greater differences (ignoring joint limits) between task (or canonical) orientation and that of stimulus are usually associated with greater awkwardness. That is, many moderate and all large motions away from task (or canonical) orientation are awkward. Thus, effects of implicit awkwardness on RT are less readily detected with feet than with hands; for hands, distinct differences between these two factors provide clear comparison cases. For the feet, awkwardness ratings are moderately correlated with the difference (ignoring joint limits) between task (or canonical) and stimulus orientations ($r = .45$, $F(1,70) = 17.66$, $p < .0001$; for hands this correlation is negligible ($r = .16$, $F(1,70) = 1.85$, $p > .05$). (See the following Method and Results sections for a description of the relationship between the ranges of motion and awkwardness ratings.)

Total angles of rotation of various spatial transformation procedures. Table 2 shows degrees of rotation for rotations-by-dimensions, spin-precession, and shortest paths from (a) task (or canonical) orientation of feet (like that of tops in picture plane at 0°) to (b) each stimulus orientation.

Method

Subjects. Nine right-handed UCSD students, who had not been in similar experiments, participated for credit in a psychology course or for $4 an hour.

Stimuli, design, and procedure. All aspects of stimuli, design, and procedure were identical to those of Experiments 1 and 2 except that stimuli (Figs. 12–17) subtended 2.5 to 3.5° of visual angle; subjects pressed a left-hand button for a left foot, and a right-hand button for a right foot.

Ranges of motion and awkwardness ratings. Ranges of motion and awkwardness ratings correspond for some stimuli and some orientations but not for others. Ranges of motion and awkwardness ratings both show differences between orientations portrayed by stimuli at ODs of 0 and 180° for tops and soles in picture plane, and soles from heel. Awkwardness ratings show a difference between orientations portrayed by inside and outside views, and tops from toes at ODs of 0 and 180°, though ranges of motion do not. Only for the inside view do both measures show awkwardness differences for lateral and medial orientations. For top in picture plane and outside view, ranges of motion indicate an awkwardness difference between medial and lateral orientations but ratings do not. Neither measure shows a difference in awkwardness for lateral and medial orientations of soles in picture plane, soles from heel, and tops from toes. For each medial orientation of each stimulus except inside and outside views, there is always a lateral orientation of corresponding angle from the task or canonical orientation (ignoring joint limits). For inside view, the path from task (or canonical) orientation to that of the stimulus is longer to lateral than medial orientations; the reverse is true for outside view (cf. Table 2). The 0 and 180° orientations correspond for inside and outside views, and soles in picture plane; but for tops in picture plane and soles from heel, 0° orientation has smaller angle to task (or canonical) orientation; the converse is true for tops from toes. Comparisons of awkwardness across stimuli are assessed by overall correlations of RTs and awkwardness ratings.

Results

Analyses use RTs of correct responses only. Error rate was 5% on average, and was correlated with RT (r = .86, $F(1,70)$ = 191.48, $p <$ .0001, for means in Figs. 14–19 and errors). ANOVAs of RT were conducted using medial and lateral orientation, left and right hand, and five ODs.

Tops in picture plane. Joint limits on the foot's motion to lateral orientations of this stimulus are slightly more constraining than to medial ones. Motion to the 180° orientation is more extensive and awkward than to the 0° orientation (which, according to introspections and RTs, is like that of the task or canonical orientation). These patterns are confirmed by awkwardness ratings.

Shape and slope of function (Fig. 12) for medial and lateral orientations were similar, but RT was 70 ms longer to lateral orientations (though not reliably so). The latter RT difference was concentrated at 120 and 150° ODs. This is consistent with slightly more constrained motion to lateral orientations. Shortest RT of all for foot stimuli was observed at the 0° orientation, corroborating subjects' introspections that no imagined spatial transformation was necessary at this orientation, and that the orientation is like that from which their imagined spatial transformations originated. RT increased gradually to 180° OD, consistent with use of any of three spatial transformation procedures discussed here. RTs and awkwardness ratings were strongly correlated (r = .92, $F(1,10)$ = 52.97, $p <$ .0001). RT increased with greater OD ($F(4,32)$ = 16.74, $p < .001$). In Experiment 5, and in an identical pilot study (N = 8) with three of the six stimuli used here, there was a reliable RT advantage for medial ODs.

TABLE 2
Degrees of Rotation (Ignoring Joint Limits) between Task (or Canonical) Orientation (Tops in Picture Plane at 0° OD) and Stimulus Orientation of Foot for Three Spatial Transformation Procedures

	Picture plane OD						
	0	30	60	90	120	150	180
Rotations by dimensions							
Tops in picture plane	0	30	60	90	120	150	180
Soles in picture plane	180	210	240	270	300	330	360
Soles from heel	90	120	150	180	210	240	270
Tops from toes	270	240	210	180	150	120	90

	Picture plane OD											
	0	30	60	90	120	150	180	−150	−120	−90	−60	−30
Inside view of foot	180	150	120	90	120	150	180	210	240	270	240	210
		[------------	------------	medial	------------	------------]		[------------	------------	lateral	------------	------------]
Outside view of foot	180	210	240	270	240	210	180	150	120	90	120	150
		[------------	------------	lateral	------------	------------]		[------------	------------	medial	------------	------------]

Spin precession paths							
Tops in picture plane	0	30	60	90	120	150	180
Soles in picture plane	180	182	190	201	216	234	254

Soles from heel	90	95	108	127	150	180	201
Tops from toes	201	180	150	127	108	95	90

	Picture plane OD											
	0	30	60	90	120	150	180	−150	−120	−90	−60	−30
Inside view	127	108	95	90	95	108	127	150	180	201	180	150
of foot		[..........		medial		..........]		[..........		lateral		..........]
Outside view	127	150	180	201	180	150	127	108	95	90	95	108
of foot		[..........		lateral		..........]		[..........		medial		..........]

Shortest path

Tops in picture plane	0	30	60	90	120	150	180
Soles in picture plane	180	180	180	180	180	180	180
Soles from heel	90	94	105	120	139	159	180
Tops from toes	180	159	139	120	105	94	90

	Picture plane OD											
	0	30	60	90	120	150	180	−150	−120	−90	−60	−30
Inside view	120	105	94	90	94	105	120	139	159	180	159	139
of foot		[..........		medial		..........]		[..........		lateral		..........]
Outside view	120	139	159	180	159	139	120	105	94	90	94	105
of foot		[..........		lateral		..........]		[..........		medial		..........]

Soles in picture plane. Joint limits and awkwardness ratings both indicate that it is more awkward to put the foot at the toes "upward" than toes "downward" orientation (0 and 180° ODs). There is slightly more awkwardness for medial than for lateral orientations of this stimulus, especially at 90–150° ODs; however, more than one motion and position can be used for various orientations.

The shape of RT-OD functions (Fig. 13) was not predicted by any of the spatial transformation procedures discussed here, but was consistent with greater awkwardness for orientations where toes point "upward" and for medial orientations. The functions had similar shape and slope, but RT was 265 ms greater for medial than lateral ODs (this effect was concentrated at 90 and 120° ODs). Awkwardness ratings showed corresponding differences in lateral, medial, and 0 and 180° orientations, and were well correlated with RTs ($r = .87$, $F(1,10) = 30.20$, $p < .001$). RTs were different at different ODs ($F(4,32) = 12.47$, $p < .001$) and longer to medial than to lateral orientations ($F(1,8) = 6.81$, $p < .05$).

Inside view. Joints used in efficient motion to these medial orientations allow relatively free movement. Placing the foot at lateral orientations requires more extensive motion (ignoring joint limits), and is more awkward, especially at 90–150° ODs. This is confirmed by awkwardness ratings which also show somewhat more awkwardness for 180 than 0° ODs (although ranges of foot's motion do not show greater awkwardness for the 180° OD). Paths passing the foot (ignoring joint limits) from task (or canonical) orientation to that of the stimulus are different for medial and lateral orientations (cf. Table 2). For medial orientations, all three procedures produce minimal path length at the 90° OD. From 90 to 180° ODs and 90 to 0° ODs, path length increases slightly for shortest and spin-precession procedures, and steeply for rotations by dimensions. For lateral orientations, all three procedures produce maximal path length at the 90° OD. From 90 to 180° ODs and from 90 to 0° ODs, path length decreases slightly for shortest path and spin-precession procedures, and decreases steeply for rotations by dimensions.

RTs (Fig. 14) reflected greater awkwardness of the foot's motion to lateral and 180° ODs. The functions complemented those for outside view and were well correlated with awkwardness ratings ($r = .76$, $F(1,10) = 13.92$, $p < .01$). The flat function at medial ODs was consistent with use of shortest or possibly spin-precession paths, but not rotations-by-dimensions paths. At lateral ODs, RTs increased linearly to 120° OD and decreased with the same slope to 180° OD. A peak RT at a lateral OD of 120° was not predicted by any of the three spatial transformation procedures, though it was consistent with awkwardness for orientations at 90–150° lateral ODs. RT was 144 ms longer for 180 than 0° orientations (consistent with ratings). RTs were at different ODs ($F(4,32) = 5.54$, $p <$

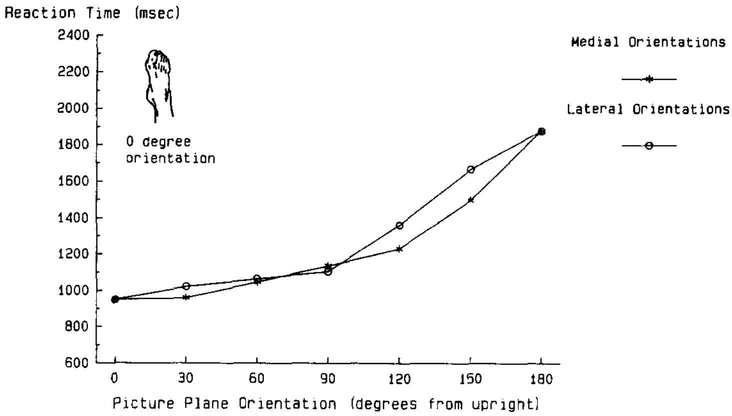
.01) and longer to lateral than to medial orientations ($F(1,8) = 27.81, p <$ .001). The effect of OD on RT was different for lateral and medial orientations ($F(4,32) = 3.90, p < .01$).

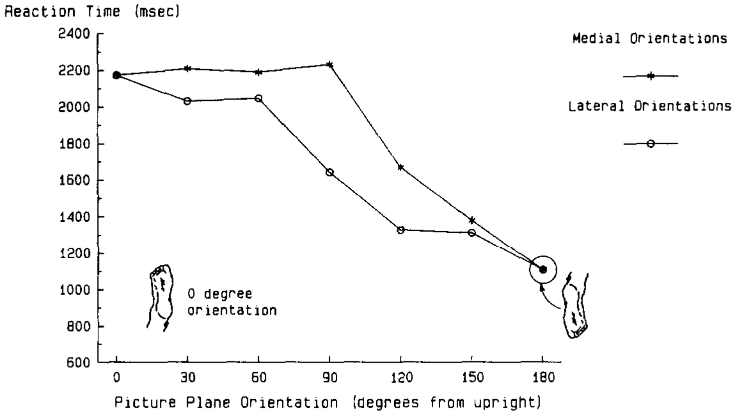
Outside view. As with motion to medial orientations of inside view, ranges of motions to *lateral* orientations of outside view allow relatively efficient paths. Placing the foot at medial orientations requires more extensive motion (ignoring joint limits), and is more awkward, especially at 90–150° ODs (because of limits in supination and pronation, and external rotation of the leg). These patterns in joint limits are similar to trends in awkwardness ratings, which also show somewhat more awkwardness for 180 than 0° OD (though range of motions do not). Paths passing the foot (ignoring joint limits) from task (or canonical) orientation to that of the stimulus are different for medial and lateral ODs. For lateral orientations, all three procedures minimize path length at 90° OD. In addition, from 90 to 180° ODs and 90 to 0° ODs, path length increases slightly for shortest and spin-precession procedures, and steeply for rotations by dimensions. For medial orientations, all three procedures maximize path length at 90° OD. From 90 to 180° ODs, and from 90 to 0° ODs, path length decreases slightly for shortest path and spin-precession procedures, and steeply for rotations by dimensions (cf. Table 2).

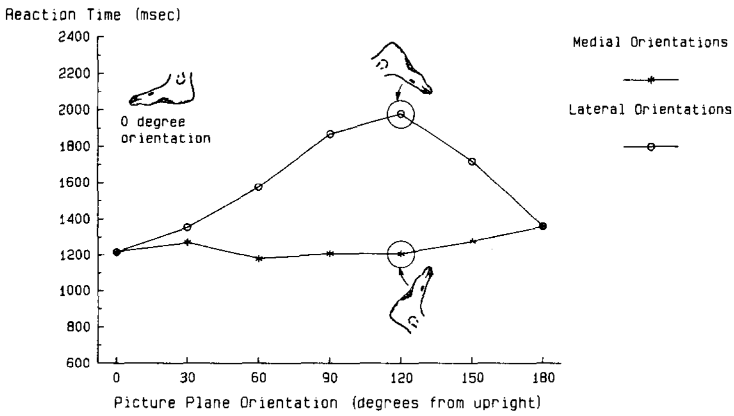
RTs correspond to greater awkwardness for the medial and 180° orientations (Fig. 15). RTs were moderately correlated with awkwardness ratings ($r = .57$, $F(1,10) = 4.79, p < .05$). The flat function at lateral ODs was consistent with use of shortest or possibly spin-precession paths, but not rotations-by-dimensions paths. RTs at medial ODs increased fairly linearly to 120°, then decreased at the same rate to 180°. A peak RT at medial ODs of 120° was not predicted by any of the three spatial transformation procedures, but was consistent with greater awkwardness for 90–150° medial ODs. RTs were different at different ODs ($F(4,32) = 4.13, p < .01$), longer to medial than lateral orientations ($F(1,8) = 15.26$, $p < .01$), and the effect of OD on RT was different for lateral and medial orientations (though marginally so, $F(4,32) = 2.55, p < .058$).

Soles from heel. Ranges of motion and awkwardness ratings show slightly greater awkwardness for lateral than for medial orientations, especially at lateral ODs of 120–150°. It is more awkward and more extensive (ignoring joint limits) to place the foot at orientations where the sole faces upward of forward than downward or backward (180 and 0° ODs, respectively).

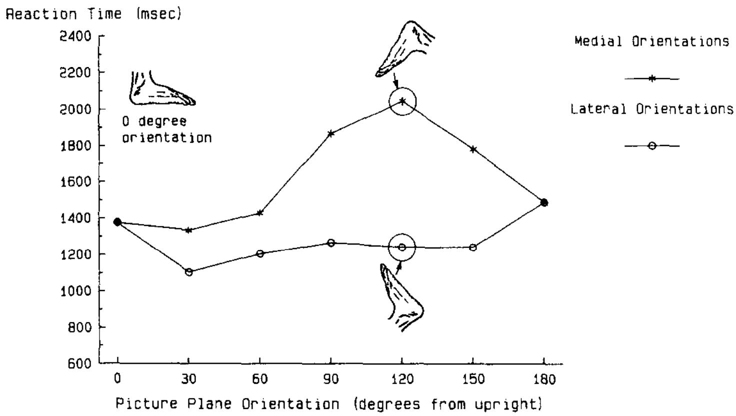
RT again reflected implicit awkwardness of stimulus orientation (Fig. 16). Means were very strongly correlated with awkwardness ratings ($r =$ .96, $F(1,10) = 124.49, p < .0001$). Shortest mean RTs were for the sole facing downward, and increased fairly linearly to 150°. The peak at lateral ODs of 150° (the longest RT of any foot stimulus) was consistent with

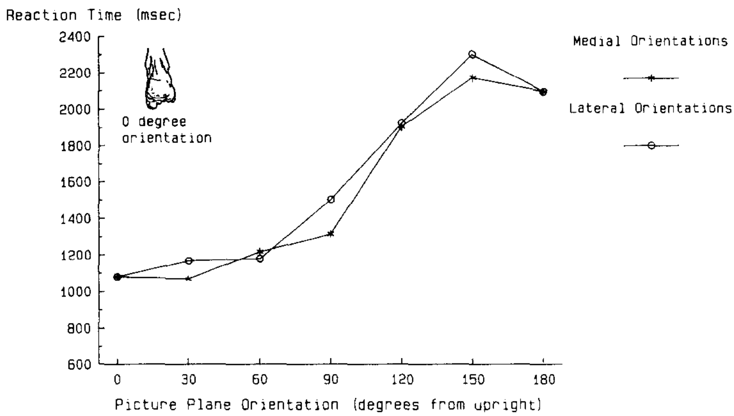


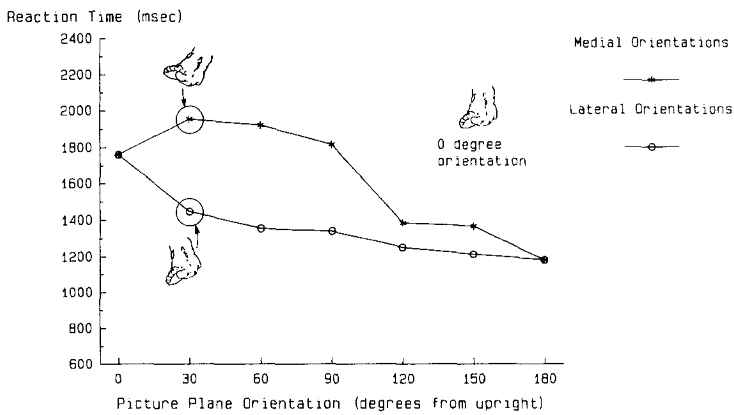




FIGS. 12–17. Discrimination RT-OD functions for left and right versions of each foot stimulus at lateral and medial orientations. Also shown is the standard or 0° orientation of each stimulus. Medial orientations are produced by turning *right*-foot (standard) versions of all but tops and soles in picture plane clockwise by less than 180°, and corresponding lateral positions are produced by comparable counterclockwise turns. The reverse is true for tops and soles in picture plane.







FIGS. 12–17—*Continued.*

joint limits but not with use of either shortest, spin-precession, or rotations-by-dimensions paths across all ODs. RT was slightly longer at lateral ODs (but not reliably so). RT was different at different ODs ($F(4,32) = 18.77, p < .001$).

Tops from toes. Ranges of motion indicate slightly more awkwardness for medial than lateral orientations. Motion to orientations near "sole down" (0° OD) is more extensive (ignoring joint limits) and awkward (by ranges of motion) than near "sole up" (180° OD). Awkwardness ratings indicate only that all orientations of this stimulus are very awkward.

RT was 367 ms longer at medial than at lateral ODs, with the difference concentrated near 0° orientation (Fig. 17). RT was shortest at 180° OD—when soles face upward (or forward), and increased gradually to the 0° OD, which was about 580 ms longer than at the 180° OD. Both of these observations are consistent with ranges of motion, and the latter is also consistent with the difference between task (or canonical) and stimulus orientations. RTs are not correlated with awkwardness ratings. (For this stimulus, toes point toward the observer. Thus, as when fingers point directly at the observer, it may invoke diverse strategies that are influenced by implicit awkwardness. The influences of awkwardness could vary across groups of subjects, if one sample of subjects relied on a different subset of these strategies than another. See palms from fingers in Experiment 2.) RTs were longer to medial than lateral orientations ($F(1,8) = 22.40, p < .001$) and to left rather than right feet, ($F(1,8) = 10.09, p < .05$), different at different ODs ($F(4,32) = 7.68, p < .001$), and effect of OD on RT was different for lateral and medial orientations ($F(4,32) = 4.12, p < .01$).

Introspective reports. Subjects reported imagining moving their foot from its orientation during trials to the orientation of the stimulus to compare imagined and stimulus feet. For stimuli near the orientation of tops in picture plane at 0°, subjects found it unnecessary to imagine a spatial transformation of their foot. They found some trials problematic because it was difficult to imagine their feet in orientations awkward to adopt.

Discussion

Model of performance. As with the left–right judgments of hands and of the outstretched arm of whole body (Parsons, 1983a, 1987b), these RTs and introspections suggest that people make left–right judgments of feet by imagining moving their foot to the stimulus orientation for comparison. As for the other left–right judgments, subjects' imagined spatial transformations of their foot apparently originated from its orientation during the task (which is similar to that of "top of the foot in picture plane" at 0°). RTs were fastest near this orientation, and longest for soles from heel at lateral OD of 150°.

RT patterns correspond to the awkwardness of stimulus foot's orientation. To summarize, most of the observed RT patterns correspond to how physically difficult the stimulus orientation is to adopt (as indicated by subjects' awkwardness ratings and/or joint limits on foot's motion). For within-stimulus comparisons of implicit awkwardness and RT, this is true for (a) medial and lateral orientations for all stimuli, and (b) 0 and 180° ODs for inside and outside views, and soles in picture plane. However, for three other stimuli, awkwardness and path lengths from task or canonical orientation (ignoring joint limits) to stimulus orientation are confounded for 0 and 180° ODs. So, in the latter cases, it is unclear whether implicit awkwardness causes RT difference in those cases. (This is true for tops in picture plane, sides from heel, and tops from toes.) For individual stimuli, the correlation of RTs and awkwardness ratings ranged from .92 to .76 for four stimuli, .57 for a fifth, and was negligible for a sixth. Over all stimuli, RTs are moderately correlated with awkwardness ratings ($r = .65$, $F(1,70) = 49.99$, $p < .0001$), and without tops from toes, this correlation is $r = .80$ ($F(1,58) = 100.68$, $p < .0001$).

These correlations within and across stimuli are positive indications of the effect of implicit awkwardness. These effects are *not* due to actual movement because subjects did not move or see their feet during a trial. Because of the foot's limited motion, awkwardness is rarely dissociated from the difference (ignoring joint limits) between task (or canonical) and stimulus orientations. The correlation of awkwardness ratings and this orientation difference (ignoring joint limits) is .45 (it is negligible for hands). So RTs and differences between task (or canonical) and stimulus orientations (ignoring joint limits) are moderately correlated ($r = .75$, $F(1,70) = 89.55$, $p < .0001$); this contrasts with that for hands ($r = .31$), which have a greater range of motion.

Comparison of the awkwardness effect of stimulus hands and feet on RTs. Despite these confounded factors for feet, results for hands and feet can be compared to show that differences in the relationship of joint limits to principal planes of the hand and foot are associated with corresponding differences in judgment RT. For example, consider (a) backs and palms in picture plane (Figs. 5 and 7) and (b) tops and soles in picture plane (Figs. 14 and 15). These pairs of stimuli apparently represent comparable differences between orientations of stimuli and the spatial origin of subjects' imagined spatial transformations. Backs of hands and tops of feet in picture plane at 0° seem close to or at the orientation where imagined spatial transformations originate. Palm and sole in picture plane depict surfaces opposite the backs and tops. To imagine their hand or foot moving from the task (or canonical) orientation to the orientation of the stimulus in these cases, subjects must contend with a reorientation problem apparently like that in Fig. 2.

However, despite the apparently comparable ODs, the associated RTs are quite different, as are the joint limits on motion. Awkwardness ratings for orientations of (a) backs and palms in picture plane with (b) tops and soles in picture plane (respectively) are not correlated, nor are their associated RTs (r = .13, $F(1,22)$ = 0.37, p > .05; and r = .23, $F(1,22)$ = 1.18, p > .05). This lack of correspondence seems related to the influence of joint limits on left–right judgments. Two features of RTs indicate the specificity of awkwardness effects: differences in (a) mean RTs for 0 and 180° ODs and (b) slopes of palms and soles functions. RTs for palms and backs of hands were shortest when fingers pointed up or away from observer. RTs for tops of feet were shortest when toes pointed up or away, but RTs for soles were shortest when toes pointed down or toward observer. This difference for palm and sole is consistent with different ranges of supination and pronation, and with backward knee flexion and forward elbow flexion. A second difference in that all four functions for tops of feet and backs of hands are very similarly shaped, while the two palms functions are very different in shape and the two soles functions are very similar in shape. The function for palms is flat at medial ODs, but is quadratic at lateral ODs, with a slope comparable to that of backs of hands. These observations are consistent with distinct and large differences in awkwardness of the hand's movement to lateral and medial orientations of palm stimuli. There is much less difference in shape of the two soles functions.

Awkwardness effects are independent of response mode. In addition, these data show that RTs of these left–right judgments are influenced by awkwardness of stimulus orientation, even if subjects respond with a body part other than that of stimulus. This corroborates findings for left–right judgments of part of a misoriented body that show that comparable RT-OD functions are produced with manual and vocal responses (Parsons, 1987b).

EXPERIMENTS 4 AND 5: IMAGINED SPATIAL TRANSFORMATIONS OF ONE'S HANDS AND FEET WITHOUT LEFT–RIGHT JUDGMENT OF STIMULUS

The model of performance used to interpret RT-OD functions in Experiments 1–3 has three main hypotheses. (1) Subjects seek full confirmation by imagining their left body part moving to orientation of left body-part stimuli, their right body part moving to orientation of right body-part stimuli. (2) The origin of imagined spatial transformations is an orientation at or close to that of the body part during Experiments 1–3. (3) The effect of implicit awkwardness of stimulus orientation on RT is primarily due to its effect on imagined spatial transformations, and not on comparison of shape involved in left–right discrimination.

Experiments 4 and 5 attempted to confirm this model by instructing subjects to "*mentally simulate*" *their own actions*. Subjects were instructed to imagine moving their left or right hand (or foot) from its task orientation and position to the orientation of the stimulus, and to say "Now" when the imagined spatial transformation is complete. Trials were blocked so that stimulus handedness was known in advance, and so no left–right judgment of the stimulus was required. Experiment 4 used the six views from Experiment 2 of the left and right hand at 12 picture plane orientations. Experiment 5 used the six views of the left and right foot from Experiment 3 at 12 picture plane orientations.

This "simulation" paradigm is reminiscent of that in which an object's rotation is imagined in a specific plane in response to a cue providing preparatory information about an upcoming trial (Cooper, 1975; Cooper & Shepard, 1975; Metzler, 1973; Parsons, 1987b). The observed linearly increasing slope of preparation time (as a function of orientation) is like the RT-OD function for discriminating mirror-imaged objects (Cooper, 1975). In a study like Experiments 4 and 5, RT-OD functions of left–right judgments of an outstretched arm of a misoriented body were very strongly correlated with the time to imagine the spatial transformation of one's body and arm from the task orientation to the orientation of the stimulus (Parsons, 1987b). However, differences in RT patterns across planes of orientation were slightly less extreme in the simulation than in discrimination paradigm.

Interpretation of the observed RT patterns. Of interest is whether subjects who are imagining their hand (or foot) moving between pairs of orientations like those in Experiment 2 (or 3), and who already know the handedness of the stimuli, produce RT-OD functions comparable to those of subjects making left–right judgments in Experiments 1–3. Comparison of the sets of RT-OD functions could reveal whether the origin of the uninstructed imagined spatial transformations in Experiments 1–3 is different from the origin subjects are instructed to use in Experiments 4 and 5. Differences in the origin of 30° (in any direction) could theoretically be detected, but in light of the underlying variability of responses, only a disparity of at least 60° can be validated.

For example, suppose the spatial origin was really at an orientation like that of palms from wrist at 0° (Fig. 8). This is a likely alternative spatial origin, and it has an intermediate disparity (90°) with the orientation of the hand in task. The pattern of differences (ignoring joint limits) between the orientation of stimuli and this alternative spatial origin would be *quite different* from that for the origin of back in picture plane at 0°. The correlation of degrees of rotation for (a) paths from palms from wrist at 0° to stimulus orientations and (b) paths from backs in parallel plane at 0° to stimulus orientations is .28 ($F(1,70) = 5.79$, $p < .02$).

One unfortunate possibility is that subjects ignore the instruction to mentally simulate motion to the stimulus orientation from their hand's (or foot's) orientation during the task and instead imagine spatial transformations from some other orientation. If so, the comparison of functions in Experiments 2 and 3 to those in Experiments 4 and 5 would not indicate relation of hand's and foot's task orientation and spatial origin of imagined spatial transformations. Apart from this possibility, if functions in Experiments 4 and 5 are comparable to those in Experiment 2 and 3, it is good evidence for the model of performance above and for the hypothesis that imagined spatial transformations of a part of one's body are strongly influenced by its normal range of motion.

Experiment 4: Imagined Spatial Transformation of One's Hand

Method

Subjects. Fifteen right-handed UCSD undergraduates, who had not been in similar experiments, participated for credit in a psychology course or for $4 an hour.

Stimuli, design, and procedure. All aspects of stimulus, design, and procedure are identical to those of Experiment 2 except these. Trials were grouped by handedness of stimulus: 36 trials with left-hand stimuli were alternated with 36 trials with right-hand stimuli. Within each set of 36 trials, the view and orientation of the stimulus were randomly ordered and equally likely to be any member of the stimulus set. Subjects were to imagine their left or right hand passing from its orientation and position during a trial (like that in Experiments 1 and 2) to the orientation of stimulus, and say "Now" as soon as the imagined motion was complete. They knew handedness of a stimulus before each trial. Their vocal response triggered a voice activated relay that stopped an electronic timer.

Results

All subjects reported having no difficulty understanding and following the instructions. They reported imagining moving their hand from the orientation of the hand during task to the orientation of stimulus on each trial. RT-OD functions (Figs. 18–22) were quite similar to those in Experiment 2 for left–right judgments of these stimuli, and to awkwardness ratings of stimuli. ANOVAs of RTs to each stimulus using left and right hand, medial and lateral orientation, and five ODs (30, 60, 90, 120, 150°) showed the effects in the following section. To summarize, for each stimulus there was a difference for medial and lateral orientations in overall RT and effect of OD on RT. RT was longer to left than to right hands for four stimuli.

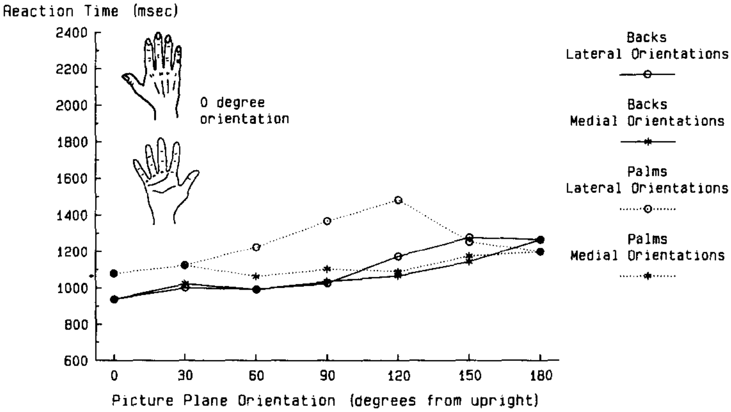
For backs in picture plane, RT was longer to greater OD ($F(4,56) = 10.62$, $p < .001$), to lateral rather than medial orientations ($F(1,14) = 6.02$, $p < .05$), to left as opposed to right hands ($F(1,14) = 8.84$, $p < .01$), and effect of OD on RT was different for lateral and medial orientations ($F(4,56) = 5.12$, $p < .01$). RT advantage for medial orientations was greater for right than for left hands ($F(1,14) = 14.66, p < .01$). For palms in picture plane, RT was longer to lateral than to medial ODs ($F(1,14) = 30.45, p < .001$), different at different ODs ($F(4,56) = 5.43, p < .001$), and effect of OD on RT was different for lateral and medial orientations ($F(4,56) = 10.73, p < .001$).

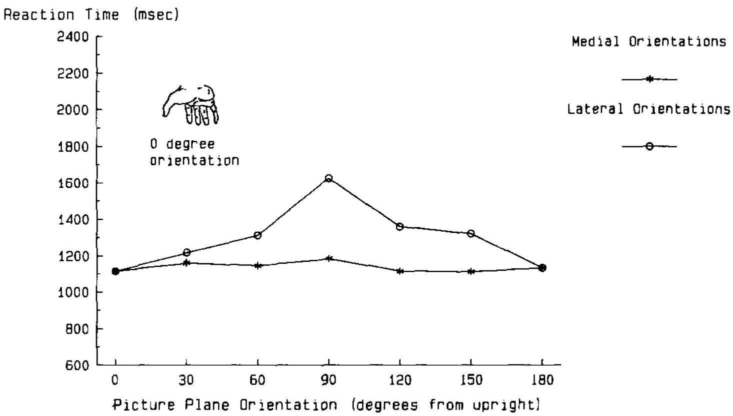
For palms from wrist, RT was longer at lateral than medial orientations ($F(1,14) = 38.29, p < .001$), to left than right hands ($F(1,14) = 10.33, p < .01$), different at different ODs ($F(4,56) = 12.80, p < .001$), and effect of OD on RT was different for lateral and medial orientations ($F(4,56) = 8.90, p < .001$). RT advantage for medial orientations was larger for left than for right-hands ($F(1,14) = 4.67, p < .05$), and effect of OD on RT was more extreme for left than right hand ($F(4,56) = 5.01, p < .01$).

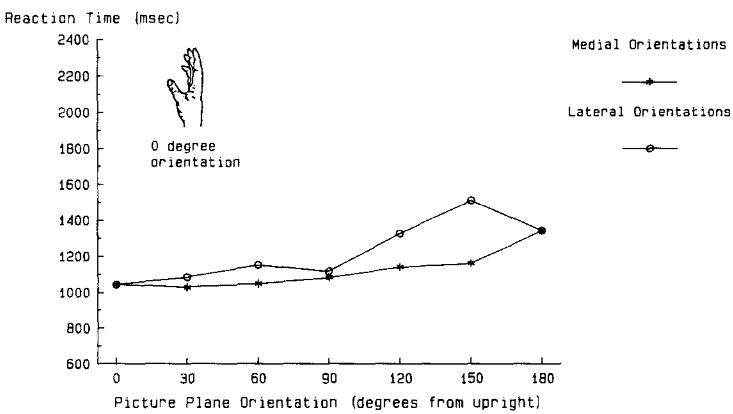
For sides from thumb, RT was longer at lateral rather than medial orientations ($F(1,14) = 24.80, p < .001$), different at different ODs ($F(4,56) = 23.40, p < .001$), and effect of OD on RT was different for lateral and medial orientations ($F(4,56) = 8.15, p < .001$). For sides from little finger, RT was longer at lateral rather than medial orientations ($F(1,14) = 14.03, p < .01$) and longer to left than to right hands ($F(1,14) = 11.59, p < .01$). For palms from fingers, RT was longer at medial than lateral orientations ($F(1,14) = 7.19, p < .05$), left than right hands ($F(1,14) = 6.03, p < .05$), and was different at different ODs ($F(4,56) = 4.68, p < .01$).

Imagined spatial transformation times and awkwardness ratings. There was a *very strong* correlation between these mean RTs and mean awkwardness ratings in Experiment A (Appendix A) at lateral, medial, and 0 and 180° orientations ($r = .93$, $F(1,70) = 445.17, p < .0001$). This correlation was between .93 and .88 (in every case, $p < .0001$) for each stimulus except sides from little finger ($r = .80, p < .01$).

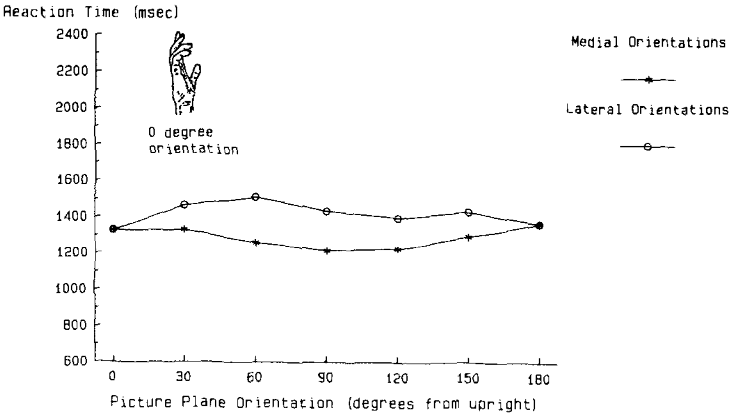
Imagined spatial transformation times and RTs of left–right judgments. RTs were *very well* correlated with RTs in Experiment 2 for left–right judgments of the same stimuli ($r = .85$, ($F(1,70) = 183.66, p < .0001$). For four stimuli, it was between .94 and .81 ($F(1,10)$, $p < .001$). For sides from little finger, it was .50 ($F(1,10) = 4.83, p < .05$), and excluding RT at 0°, it was .74 ($F(1,9) = 10.67, p < .01$). RTs to palms from fingers were not correlated with those in Experiment 2 ($r = .50, p < .10$), but were strongly correlated with awkwardness ratings and with RTs in a pilot of Experiment 2 ($N = 5$) with four of its six stimuli ($r = .85$, $F(1,10) = 26.46, p < .001$). Because the palms from fingers stimulus evokes diverse strategies, one sample of subjects could have relied on strategies different from the others (cf. Introspective Reports in Experiment 2). Though the functions here had very similar shape and same overall mean RT as those in Experiment 2, they showed less extreme effects of stimulus orientation.

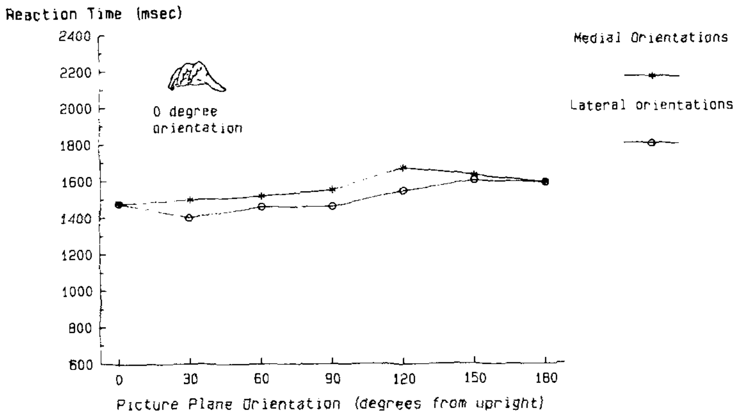






FIGS. 18–22. Simulation RT-OD functions for left and right versions of each hand stimulus at lateral and medial orientations.





FIGS. 18–22—*Continued.*

Discussion

RTs for mental simulation of moving one's hand correspond to RTs for left–right judgment of a hand. The time to imagine spatial transformations of one's hand to an orientation is well-correlated with how awkward that orientation is to physically adopt. Imagined spatial transformations of one's hand are apparently strongly affected by its normal range of motion. Further, the RT-OD functions for simulating the hand's motion from its task (or canonical) orientation to the orientation of the stimulus are very similar to those for left–right judgments of those stimuli (in Experiment 2). The latter finding is observed when (a) no left–right judgment of the stimulus is required, and (b) when subjects are instructed to imagine spatial transformations apparently like those in Experiment 2. Thus, the results are good support for the performance model used to interpret

RT-OD functions for left–right judgments of hands. These findings suggest that imagined spatial transformation of a part of one's body is strongly affected by its normal range of motion. Experiment 5 provides a comparable confirmation of these conclusions for the left–right judgment of feet and imagined spatial transformations of one's foot.

Experiment 5: Imagined Spatial Transformations of One's Foot

Method

Subjects. Thirteen right-handed UCSD undergraduates, who had not been in similar experiments, participated either for credit in a psychology course or for $4 an hour.

Stimuli, procedure, and design. Stimuli are identical to Experiment 3, and all aspects of the procedure and design were identical to Experiment 4 except that subjects were to imagine their left or right foot passing from its orientation and position during a trial to the orientation of the stimulus, and say "Now" as soon as an imagined spatial transformation was complete.

Results

All subjects reported having no difficulty following instructions to imagine moving their foot to the orientation of a stimulus from the orientation of their foot during task. RTs (Figs. 23–28) were very similar to those in Experiment 3 for left–right judgments of the same stimuli, and to awkwardness ratings of stimuli. ANOVAs of RT to each stimulus using left and right foot, medial and lateral orientation, and five ODs (30, 60, 90, 120, 150°) showed the following effects. For five of the stimuli, there was a difference in RT for medial and lateral orientations, and an effect of OD on RT; for all stimuli, RTs were different at different ODs; and for two stimuli, RTs were longer for left than right feet.

For tops in picture plane, RT was longer at lateral than medial orientations ($F(1,12) = 38.02$, $p < .001$), greater ODs ($F(4,48) = 23.55$, $p < .001$), and effect of OD on RT was different for medial and lateral orientations ($F(4,48) = 3.88$, $p < .01$). For soles in picture plane, the only reliable effect was that RT decreased with increasing OD ($F(4,48) = 12.52$, $p < .001$). Though there was a trend here for lateral and medial orientations that was similar to that in results in Experiment 3, it was not reliable ($p > .20$).

For inside view, RT was longer at lateral than medial orientations ($F(1,12) = 41.20$, $p < .001$), to left than right feet ($F(1,12) = 5.09$, $p < .05$), different at different ODs ($F(4,18) = 13.60$, $p < .001$), and effect of OD on RT was different for medial and lateral orientations ($F(4,48) = 9.72$, $p < .001$). For outside view, RT was longer for medial than lateral orientations ($F(1,12) = 48.84$, $p < .001$) and for left than right feet ($F(1,12) = 11.55$, $p < .01$). It was also different at different ODs ($F(4,48) = 26.71$, $p < .001$), and the effect of OD on RT was different for medial and lateral orientations ($F(4,48) = 5.33$, $p < .001$). RT advantage for lateral orientations was greater for right than left feet ($F(1,12) = 7.25$, $p < .05$).

For soles from heel, RT was longer at lateral than medial orientations ($F(1,12) = 14.82$, $p < .01$), different at different ODs ($F(4,48) = 35.35$, $p < .001$), and effect of OD on RT was different for medial and lateral orientations ($F(4,48) = 4.37$, $p < .01$). For tops from toes, RT was longer at medial than lateral orientations ($F(1,12) = 28.92$, $p < .001$), different at different ODs ($F(4,48) = 11.11$, $p < .001$), effect of OD on RT was different for medial and lateral orientations ($F(4,48) = 5.81$, $p < .001$), and RT advantage for lateral orientations was greater for right than left feet ($F(1,12) = 12.78$, $p < .01$).

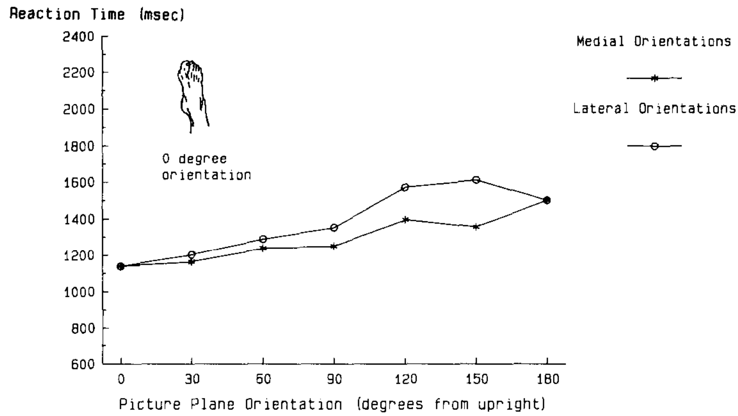
Imagined spatial transformation times and awkwardness ratings. RTs are well correlated with awkwardness ratings for stimuli at lateral, medial, 180, and 0° orientations ($r = .77$, $F(1,70) = 99.25$, $p < .0001$). Without tops from toes, this overall correlation was *quite strong* ($r = .85$, $F(1,58) = 154.74$, $p < .0001$). For five stimuli, the correlation was between .97 and .80 ($F(1,10)$, $p < .002$ at least); for tops from toes it was not reliable.

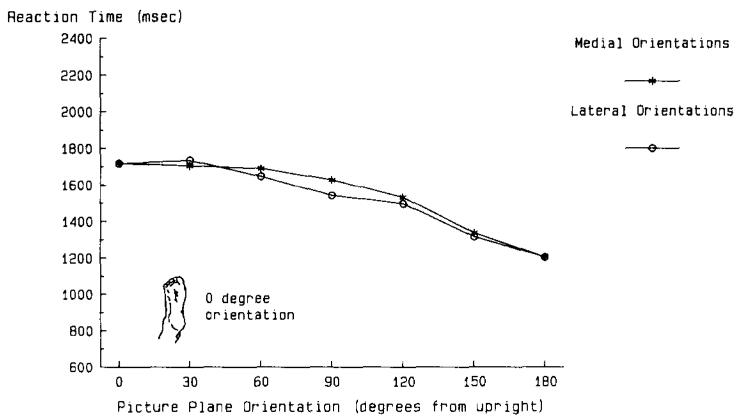
Imagined spatial transformation times and RTs of left–right judgments. There was a *very strong* correlation between these mean RTs and those in Experiment 3 for left–right judgments of the same stimuli ($r = .89$, $F(1,70) = 253.89$, $p < .0001$). Correlations for each stimulus ranged from .97 to .83 ($F(1,10)$, $p < .001$). As with Experiments 4 and 2, these functions had very similar shape and the same overall mean RT as those in Experiment 3, but with less extreme effects of stimulus orientation.

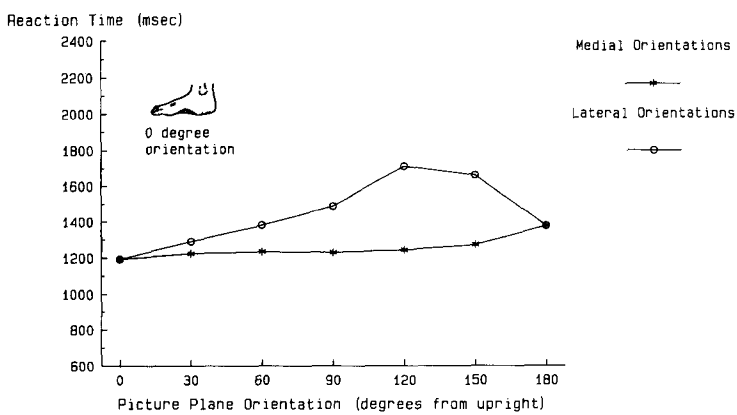
Discussion

RTs for mental simulation of moving one's foot correspond to RTs for left–right judgment of a foot. RT-OD functions for imagining one's foot moving from its task orientation to the orientation of the stimulus are very similar both to those for left–right judgments of the same stimuli (in Experiment 3), and to awkwardness ratings of stimuli. The similarity between RT-OD functions for feet in Experiments 3 and 5 corroborates that for hands in Experiments 2 and 4. There is also a similar difference (a) between overall mean *discrimination* RT for hands and feet in Experiments 2 and 3 (1292 and 1440) and (b) between overall mean *simulation* RT for hands and feet in Experiments 4 and 5 (1259 and 1440).

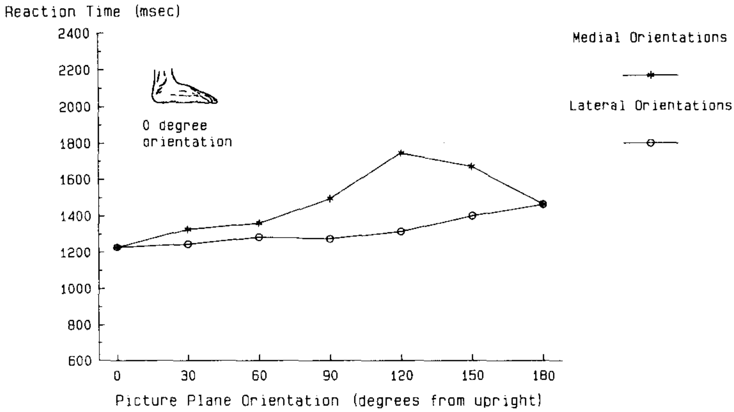
One difference between RTs in Experiments 2 and 3 and those in Experiments 4 and 5 is that effects of stimulus orientation are less extreme in the latter. Less extreme effects were also observed for analogous pairs of studies for left–right judgment of outstretched arm of a misoriented

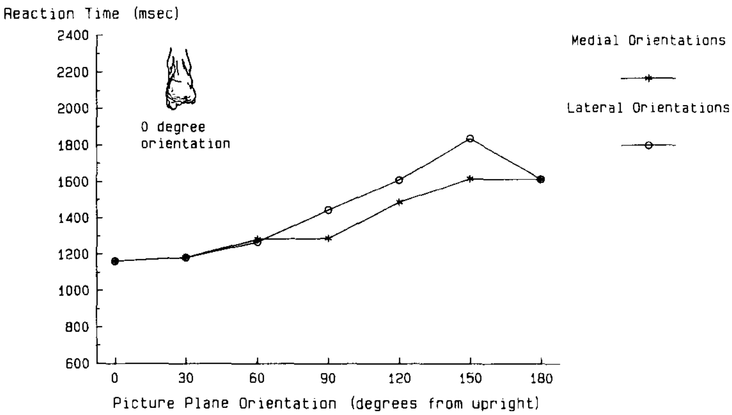


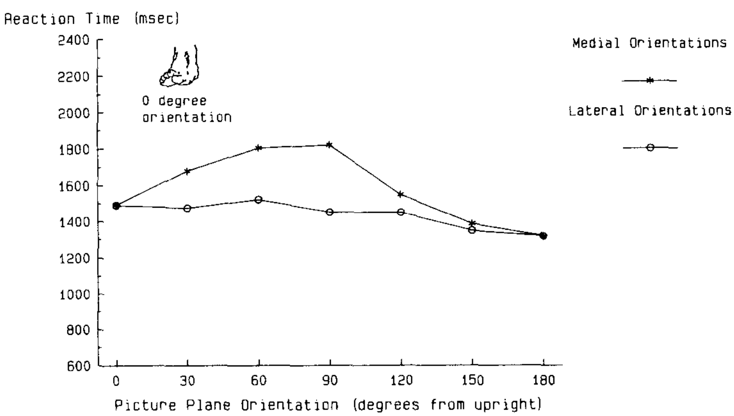




FIGS. 23–28. Simulation RT-OD functions for left and right versions of each foot stimulus at lateral and medial orientations.







FIGS. 23–28—*Continued.*

human body (Parsons, 1987b). Less extreme effects may result because less detailed internal representations of the hand (or foot) may be required for imagining movement than for making a left–right judgment. Less detailed internal representations may be less affected by the implicit awkwardness of a stimulus orientation. Awkwardness of stimulus orientation may also affect shape comparison required for left–right judgment. For example, subjects may imagine moving the "wrong" hand or foot to the stimulus orientation first if the orientation of the fingers in the stimulus is one that is more common, or less awkward, for the "wrong" hand. After a comparison of shapes shows that their initial guess was wrong, they may confirm the correctness of the other hand or foot by imagining it at the stimulus orientation. Further work is necessary to determine the exact nature of the imagined spatial transformations used in the discrimination and simulation tasks studied here.

These very similar RT-OD patterns for simulation and discrimination tasks suggest that the origins of imagined spatial transformations in Experiments 2 and 3 are within at least 60° of orientation of hand and foot in the task. This assumes that subjects followed instructions to imagine their hand or foot moving from the task orientation to the orientation of the stimulus, and that their imagined spatial transformations did not originate from some other orientation. Overall, this match in RT-OD functions supports the model of performance used to analyze RT-OD functions for left–right judgments of hands and feet.

GENERAL DISCUSSION

Results and Model of Performance

RTs and introspections here, in Parsons (1987b), and in part in Cooper and Shepard (1975), suggest that left–right judgments of a body part are made as follows. (1) Subjects imagine moving their own corresponding body part to the orientation of a stimulus to compare imagined and external body parts. (2) Their imagined spatial transformations originate from an orientation like that of the body part during the task here: the back of the hand up or toward observer, fingers forward or up; and the top of the foot up or toward observer, toes forward or up. (3) Subjects seek confirmation rather than disconfirmation in their judgments. They imagine their left body part in the orientation of left body part stimuli, their right body part in the orientation of right body part stimuli.

This model of performance is confirmed when people "mentally simulate" motion of their hand or foot from its orientation during the task to the orientation of the stimulus, without judging stimulus handedness. Time to complete simulations as a function of stimulus orientation is very similar to RT-OD functions for left–right judgments of the same stimuli (though with smaller effects of stimulus orientation). Analogous agreement (and slightly smaller stimulus orientation effects for simulation) is seen in RTs of (a) left–right judgments of an outstretched arm of a misoriented body and (b) imagined spatial transformation of one's body and arm from the orientation and position during the task to the orientation of the stimulus (Parsons, 1987b).

This model suggests that the most convenient internal representation of body part handedness for comparing with an external stimulus is that of *one's own* body part. These internal representations of body parts seem to include the connections to the rest of one's body. They also represent the body part at a single specific orientation (from which imagined spatial transformations originate). Further, the most convenient spatial transformation to imagine is apparently that of imagining one's body part at the orientation of the stimulus. People do not imagine the spatial transformation of the stimulus. Thus, people appear to spontaneously mentally simulate actions that could be taken to solve the discrimination problem by physical means.

Subjects may prefer imagining the spatial transformation of a known internal representation, because it may be more efficient than imagining the rotation of the stimulus, which requires maintaining and comparing *two* internal representations. Moreover, imagining one's own body part at the orientation of the stimulus may be the most convenient spatial transformation to imagine if spatial transformation processes used in the planning (or execution) of analogous physical movement are readily available. This possibility is consistent with some subjects' reports that kinesthetic impressions or sensations accompany imagined spatial transformations of body part stimuli (Cooper & Shepard, 1975; Parsons, 1983a; Sekiyama, 1982).

Spatial origin of imagined spatial transformations of one's body parts. Stronger confirmation of this performance model awaits findings that provide more precise and direct information about processes underlying these judgments. One problem is that precise indicators of the *spatial origin* of imagined spatial transformations are not available here, though the overall pattern of results consistently suggests a neighborhood of candidate origins.

In the task, subjects' hands and feet were in orientations (relative to the body) like those of stimuli portraying the back of the hand and top of the foot in the picture plane at a 0° OD.[1] Moreover, very similar RT-OD

[1] Subjects' hands rested on a response button panel inclined 35° from horizontal, with their upper body leaned forward to fit their head into the viewing apparatus, and with feet resting flat on the floor. Thus, hands and feet were in front of the body, with wrist and ankle in a resting state, forearms horizontal, and lower legs approximately vertical. The back of the hand and the frontal plane of chest were within about 30° of parallel, and back of hand in picture plane at 0° OD appeared to viewer in an orientation like that of their hands, as

functions were observed in Experiments 2 and 4 and Experiments 3 and 5. This finding suggests that the spatial origin of imagined spatial transformations in Experiments 2 and 3 (in a discrimination paradigm) is within at least 60° of these orientations, assuming subjects followed instructions to imagine moving their hand and foot from their task orientation.[2] (Work is in progress to determine whether or not the origin of imagined spatial transformations is independent of the current body orientation.)

Final position of imagined spatial transformations. There is also no precise measure of the final *position* (or destination) of imagined representations, at which comparison with a stimulus is made. For example, it is not known whether the location or destination varies across orientations. The hand or foot could be imagined in a particular orientation at different positions relative to the body (behind the back, down to the side, on the contralateral or ipsilateral side, above the head, etc.). One could chose the least awkward position to minimize imagining difficult orientations. Alternatively, one could chose the position most directly facing the upper front of body (to visualize the hand or foot with features apparent in the stimulus). Thus, imagined destination of the foot could be (a) aligned with a stimulus relative to the lower leg or to a global egocentric frame of reference, rather than (b) aligned to face the upper front of the body. This latter strategy may be a simulation of a spatial (or kinesthetic) rather than "visual" congruence. (Such congruence could be used to advantage for stimuli portraying the foot and side of the hand from little finger, for which a "visual" congruence may be difficult.)

Alternative models of performance. Despite these uncertainties, some alternative performance models and explanations can be considered. One alternative to this performance model is that people *imagine spatial transformations of stimuli to some standard orientation,* as when discriminating normal from mirror-reversed letters and numbers. It is not obvious why imagining rotation of a shape (an outline of a detached hand or foot) should be so strongly affected by its orientation relative to an implicitly attached forearm aligned with the subject's forearm. This alter-

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suggested by subjects' introspections (and shortest RTs). The top of the foot was oriented toward the upper front of the body, with the toes forward; top of foot in picture plane at 0° OD appeared to the viewer in an orientation like that of their feet, again as suggested by introspections and RTs.

[2] Some support for the idea that the origin of imagined spatial transformations is different from that assumed in this model may be found in (a) Experiment 2, when RT for sides from thumb stimuli at 90° OD are shorter than those for backs in picture plane at 0°, and (b) in Appendix A where soles from heel at 0 and 30° ODs are rated less awkward than tops of foot in picture plane.

native is more plausible if awkwardness of stimulus orientation, and familiarity for appearance at each orientation were correlated. If this were true however, imagined spatial transformation rates in visually unfamiliar (awkward) orientations would usually need to be 7.75 times slower than that in familiar (nonawkward) orientations (for differences in orientation, ignoring joint limits, greater than 90°). (This estimate assumes slopes of functions in Experiments 2 and 3 indicate rate of imagined spatial transformations.) Such a difference in rate for different planes of rotation would be surprising (see later discussion).

Another alternative is that subjects seek *disconfirmation* rather than confirmation. However, the data contradict all three obvious disconfirmation models.

(1) Subjects might first imagine their *dominant* (right) hand or foot at the orientation of a stimulus, and then if a mismatch occurs, infer that it was the other hand. (That is, when the stimulus was an upside-down left palm, they did not first imagine an upside-down right palm, and then infer from the mismatch that stimulus was a left hand.) This predicts that left and right stimuli would produce identically shaped RT-OD functions separated by the time to infer a mismatch. So it is ruled out by the fact that functions for left- and right-hand lateral orientations (which are similar) are different from the functions for left- and right-hand medial orientations (which are similar—see Figs. 3–4). (The results of Ashton et al., 1978, and Cooper & Shepard, 1975, also make this hypothesis doubtful.)

(2) A related alternative is that subjects *randomly* select a left or right hand and initially imagine it at the stimulus orientation. Then, if this hand does not match the stimulus, they infer that the stimulus was the opposite hand. However, this strategy predicts *no* difference (on average) between RTs for the left- and right-hand stimuli. This alternative strategy is also contradicted by different RT patterns for lateral and medial orientations.

(3) Another related alternative is that subjects use "*likely guesses*": they first imagine the hand or foot for which the orientation is not awkward, at the stimulus orientation. Suppose that on a particular trial the right palm in picture plane is presented at an OD of 90° clockwise (where the fingers point to the observer's right). This orientation is awkward for the right hand but not awkward for the left hand. Then subjects would initially imagine their left palm with fingers pointing to the right. Upon detecting the mismatch, they would infer that it was the other hand. A long RT would be produced for such awkward orientations because a constant additional period of time would be required to infer that the stimulus was the other hand. There are problems with this account however. First, it would not explain the many cases in which long RTs are observed for positions awkward for both hands or both feet (e.g., soles in picture plane at 0 and 180° ODs). Also, because the RT difference be-

tween awkward and nonawkward orientations is not constant but varies considerably, this tendency to imagine the wrong hand or foot at particular awkward orientations would need to be probabilistic. In addition, subjects report *infrequently* imagining the inappropriately handed body part at the orientation of the stimulus. A "likely guess' hypothesis predicts wrong "first guesses" would be systematically and frequently occurring events.

Weak and strong models of confirmation strategy. There is a strong and weak form of the hypothesis that subjects use a confirmation strategy. The *weak* form is that subjects *infrequently* imagine the reorientation of the wrong hand. When they do, they either may infer the stimulus is the other hand, or they may imagine the correct hand in the orientation of the stimulus for comparison. The *strong* form is that the hand imagined initially by subjects at the orientation of the stimulus is *always* correct. Thus, the incorrect hand is never compared with the stimulus.

The weak form of this hypothesis is more consistent with the subjects' introspections. In response to a questionnaire, they reported that they infrequently (about 14% of the time) imagined the rotation of the wrong hand, or compared the wrong hand to the stimulus (see Appendix C). Unfortunately, neither RTs nor errors discriminate between the strong and weak hypotheses. The strong form of the hypothesis suggests that there is early handedness information accurately guiding imagined spatial transformations, but not influencing decision processes. The weak hypothesis, supported by subjects' introspections, suggests that the early handedness information is not perfectly accurate, but very good. Only two other studies have produced evidence consistent with such conclusions. Corballis et al. (1978) found that time to identify a letter or number, when subjects were instructed to ignore whether it was in its mirror reversed or correct form, was uniformly rapid and independent of its picture plane orientation (about 600 ms). However, RT for a mirror reversed stimulus was 40 ms longer than that for a correct one. This result suggests that early in the perception of letters and numbers there is some effect of the handedness of a stimulus, but that this effect does not influence later decision processes (also see the related results of Teichner & Krebs, 1974, p. 93ff). Further research is necessary to understand these hypotheses, which may have important implications for theories of the perception and internal representation of object shape.

Effect of Implicit Awkwardness of Stimulus

Time to perform left–right judgments and imagined spatial transformations was strongly affected by physiological/anatomical constraints on motion to the orientation of the stimulus. Such findings for both left–right judgments and corresponding "mentally simulated" spatial transformations confirm the performance model above and suggest that the effect of implicit awkwardness on left–right judgments is primarily due to its effect on imagined spatial transformations.

Effect of implicit awkwardness on comparison of shapes of left and right body parts. Awkwardness of stimulus orientation may also affect the comparison of shape required for left–right judgment. For example, subjects may imagine moving the wrong hand (or foot) to the stimulus orientation first, because the orientation of the fingers (or toes) in the stimulus is one that is more common, or less awkward, for the wrong hand (or foot). Following this, their response could be inferred from the mismatch. Alternatively, following a mismatch and they could make a confirmation (rather than a simple inference) of the correctness of the other hand (or foot) by imagining it at the stimulus orientation. Such tendencies might explain the facts that (a) errors were correlated with RT and awkwardness, and (b) effects of stimulus orientation on discrimination RTs were more extreme than in simulation RTs.

Explanations of the effect of implicit awkwardness on imagined spatial transformations. There are three obvious, plausible explanations for the relation between time to imagine a spatial transformation of one's hand or foot to the orientation of a stimulus and awkwardness of equivalent physical motion. First, the *rate* of imagined spatial transformation may be slower through ranges of awkward orientations. Second, *time to initiate* (e.g., plan) imagined spatial transformations may be longer for awkward orientations. Third, the *path* of an imagined hand and foot may be selected from their normal range of motion, so that longer paths are imagined for awkward than nonawkward orientations.

Given the extensive range of effects, it seems unlikely that any of these *alone* could account for all differences between RT-OD functions at awkward and nonawkward orientations. For example, rate (or initiation time) of imagined spatial transformations would have to be very different in awkward and nonawkward orientations. Inference of the rate of imagined spatial transformations from the slopes of functions in Experiments 2 and 3 shows that the rates in awkward orientations would have to be 7.75 times slower than that in nonawkward ones. (This estimate is based on differences in task (or canonical) and stimulus orientations, ignoring joint limits, of greater than 90°.) Such a difference in imagined spatial transformation rates for different planes of rotation would be surprising. In studies of imagined rotation rates through different planes for abstract three-dimensional objects and all of one's body (Parsons, 1987b, 1987e), rates varied by a factor of about three. (Apparently no other studies show greater differences in rates in different planes.) If rate of imagined spatial transformation is assumed to be that in simulation Experiments 4 and 5, then rates would have to be usually four times as slow in awkward as in nonawkward orientations. Thus, these hypotheses seem doubtful but cannot yet be ruled out.

Several cases are presented below illustrating how major aspects of these results are consistent with two hypotheses: first, that RT differences at awkward and nonawkward orientations are due to imagined paths of different extent selected from *within* the normal range of the hand's and foot's motion. Second, the RT decreases and rate of imagined spatial transformation increases with familiarity of the hand (and possibly foot) at orientations within their normal ranges of motion.

Paths of Imagined Reorientation and Normal Ranges of Motion

When joint limits allow efficient paths to stimulus orientation. Five examples for which ranges of motion allow very efficient paths to stimulus orientations are palms in picture plane, palms from wrist, sides from thumb, and inside view of feet, all at medial orientations, and outside view of feet at lateral orientations. In each case, (a) orientation of the stimulus differs from the hand's or foot's task (or canonical) orientation by a rotation about more than one of the hand's or foot's principal axes. Further, in each case, consistent with very efficient (e.g., shortest or spin-precession) paths, (b) the RT-OD function has a flat or slight slope, and (c) the RT-OD function has the appropriate intercept relative to RTs for other stimuli (i.e., backs of hands or tops of feet).

Consider, for example, RT-OD functions of medial palms in picture plane (Figs. 5 and 7) and the motion used to rotate the hand from where the back faces up and fingers point up or forward, to where the palm faces up and fingers point contralaterally. The hand's long axis swings out of the plane initially containing the palm and back surfaces. This is not the path of (a) a sequence of rotations about principal axes of the object. Nor is it the path resulting from (b) "simultaneous" rotations about a principal axis of object and an axis fixed in the observer's visual reference frame (Fig. 2). From the task (or canonical) orientation to the palm at the medial OD of 90° the hand follows a path like that of a rotation about an axis through the wrist in the plane of the hand, oriented at 45° clockwise from fingers' goal orientation. This effective axis results from flexing the wrist (i.e., bending it "downward") at half the rate the forearm is supinated (turned). Assuming these stimuli are seen in a plane roughly aligned with the hand's task (or canonical) orientation, then rotation about this axis is the shortest path between the two orientations. If shortest paths—approximations of which are available for motion between comparable physical orientations—were imagined for all of the palm's medial orientations, then the reorientation is always a single 180° rotation. If so, other things being equal, a constant RT would be produced, as is observed.

In each of the other four examples where joint limits allow efficient paths to stimulus orientations, the slopes of functions are somewhat flatter than would be predicted by the use of shortest or spin-precession paths (assuming the same spatial transformation rate for all planes of motion). For the inside view of foot at medial ODs, and the outside view of foot at lateral ODs, use of shortest or spin-precession paths would predict a shallow monotonic decrease in functions to 90° (due to 90° OD orientation being 30° closer to the task or canonical orientation than 0 and 180° OD orientations). For the palms from wrist and sides from thumb, use of shortest or spin-precession paths predicts a gradual increase in RT from 30 to 150° ODs. (By the shortest path, the 150° OD is 65° closer to task or canonical orientation than the 30° orientation; by spin precession it is 85° closer.) It is possible that familiarity with the stimulus at these orientations could produce a faster rate of imagined spatial transformation (as it may with backs of hands and tops of feet, see Figs. 5, 7, 15, 18, 26, and the following discussion). Some orientations are near the hand's or foot's task (or canonical) orientations, where shortest RTs were observed.

When joint limits require inefficient paths to stimulus orientations. RT-OD functions (and introspections) suggest that when stimuli are at awkward orientations, people imagine paths of inefficient length (ignoring joint limits). Three examples of this are (1) palms in picture plane, (2) palms from wrist, and (3) sides from little finger, all at lateral ODs. (The anatomical terms for body part motion, orientation, and position are shown in Fig. 6.)

(1) To adopt lateral orientations of 30–120° ODs of palms in picture plane, the hand is supinated (so the palm is facing the body or up), put into radial deviation, and the arm (flexed at the elbow) is adducted and externally rotated at the shoulder. This path is like that of a 180° rotation about the hand's long axis to reverse back and palm, then a turn to point the fingers in the appropriate direction (Fig. 2A). RT-OD functions are consistent with use of such imagined paths. For example, (a) parallel slopes were observed for (i) the palms function at lateral ODs of less than 120° and (ii) the backs function at lateral and medial ODs greater than 60°. The similarity in slopes and the comparable difference in task (or canonical) and stimulus orientations suggest that similar paths were imagined in each case. (b) The intercept of the lateral palms function is 250 ms longer than that of the lateral backs function. This intercept difference may reflect time needed to imagine reversing back and palm. The intercept difference is comparable to that observed for comparable OD for left–right judgments of the outstretched arm of a body (Parsons, 1983a, 1987b). In those studies, similar intercept differences were observed when the body was viewed directly from the back or front and presented at picture plane ODs (and thus also spatially comparable to those of backs and palms in picture plane). In a study of the rate of imagined spatial transformation of the body in different planes, the rotation of one's body 180° about the vertical axis, to reverse front and back, required 900 ms. This duration of

RT was equal to the duration of RT for a 135° rotation about an axis running front to back through the center of the body. This difference in rates for different axes accounts for the intercept difference of RT-OD functions for imagined paths to orientations of back and front facing bodies (analogous to orientations of back and palm here). So an analogous rate difference could explain why the functions for palms at medial orientations intersect the functions for backs of hands at an OD of about 135 rather than 180°. (c) RTs decline for palms in picture plane for lateral 150–180° ODs, probably because of either of two possibilities. (i) Subjects imagined the hand in a path like that of flexing the wrist, and abducting and internally rotating the arm. This passes the hand in shortest paths similar to those for medial ODs near 180°. These paths are shorter than those described above for orientations near lateral ODs of 120°. (This amounts to imagining rotation to the 180° OD end of the functions in Figs. 5, 7, and 18 and then imagining rotation about the long axis of the hand, back up toward lateral ODs of 150 and 120°.) (ii) Another possibility is that subjects imagined rotating the palm (long way about) more than 180° through medial ODs of palm in picture plane. The latter strategy is suggested by fact that comparable slopes are produced for palm at lateral ODs of 30–120° ODs and backs in picture plane at lateral ODs.

(2) The function for palm from wrist stimuli at lateral ODs (Figs. 8 and 19) is symmetrically shaped and quadratic, with a peak at 90°. This function could be produced if, while imagining flexing the wrist, simultaneous rotations were imagined in one direction about the forearm's long axis (for awkward ODs from 0 to 90°) and "long way round" in the opposite direction through medial ODs (for 120 to 180° ODs). Such rotations use the range of efficient motion defined by joint limits (cf. palms from wrist in Results in Experiment 2). (Use of this procedure is equivalent to starting at the 0° end of functions in Figs. 8 and 19 and imagining rotation about the long axis (passing through the medial ODs) to 180° and then back up toward lateral ODs of 150 and 120°.) These paths for lateral orientations of palm from wrist are like those for backs in picture plane in that the absolute values of the slopes of the increasing and decreasing segments of each function are not different (beyond 60° ODs).

(3) The decreasing slope of RT-OD functions for sides from little finger from 0 to 180° OD is opposite that predicted by use of shortest, spin-precession, or rotations-by-dimensions paths. If subjects imagined shortest path motions but rotated the long way about the shortest path axis in order to accommodate joint limits, they would produce a function peaking at 0° OD (which would be a 270° rotation) and decreasing down to 180° OD (which would be a 180° rotation). This predicted function is

not inconsistent with the observed function's slope and intercept (relative to backs in picture plane).

Familiarity with a Hand at Orientations within its Normal Range of Motion

A second hypothesis to account for effects of implicit awkwardness of stimulus orientation on RT, is that familiarity with the hand at orientations within its normal ranges of motion decreases RT or increases rate of imagined spatial transformation. For example, for backs of hands in picture plane, RT functions at medial and lateral ODs are similarly shaped. Further, the difference between the stimulus orientation and apparent origin of imagined spatial transformations is in a single principal plane of the hand. Both functions resemble other RT-OD functions that have slight slope near upright. For example, they resemble RT-orientation functions for discriminating nonupright correct and mirror-reversed letters and numbers. Again, the orientation of stimuli are also different from the internally represented standard in a single principal plane of objects. Lateral and medial functions for backs of hands differ mainly in the extent of uniformly rapid RTs at small ODs. There is a flat function at lateral ODs to 60° for backs of hands, and at (less awkward) medial ODs to 90°. These flat functions suggest that subjects are familiar with the back of hand at a broader range of medial orientations, presumably where there is greater use of the hand. (This may also be true for tops of foot in picture plane, cf. Fig. 23.)

SUMMARY AND CONCLUSION

Results here and in Parsons (1987b) illustrate how in left–right judgments, very different RT-OD functions are observed for what may be similar relative differences in orientation of an externally presented comparison object and an internally represented standard. Corresponding simulation experiments show very similar results, suggesting that the rate, path length, and/or initiation time of imagined spatial transformations depend on the object imagined and the direction as well as angle of difference between initial and final orientations. Many of these effects (especially the large ones) seem best accounted for by the hypothesis that different functions (for comparable relative difference in orientation) result from *differences in lengths of the paths* in which objects are imagined to move. A minority of (often smaller) effects are more likely due to the effect of (extraexperimental) familiarity on the rate of imagined spatial transformation.

If these interpretations are correct, results from these objects suggest that the path used to imagine an object passing between two orientations, depends on the object's properties and the relative direction involved. It is not yet known whether a path can be influenced by properties of objects other than those effective here. These objects are distinguished by their association with habitual spatial transformations controlled by the body's motor system. The results here imply that the processes underlying the imagination are more closely related to *action* than previously thought, possibly complementing work showing a similarity of processes underlying imagination and perception of visual information (Finke, 1980; Shepard & Podgorny, 1978).

Variation in path of imagined spatial transformation. The evidence here suggests that people may use a number of different spatial transformation procedures. (1) In some cases, mechanical restrictions on body part movements seem to influence people to imagine reorientation paths like those of a sequence of rotations about an object's principal axes. Findings are mixed as to whether people prefer to use procedures that produce such inefficient paths in other situations requiring imagined reorientations (e.g., situations that involve other stimuli). Just and Carpenter (1985) found that subjects of high spatial ability appeared to use procedures producing paths of fairly efficient length in imagining the reorientation of cubes to compare symbols on the cube faces. However, their low spatial ability subjects seemed to imagine paths like those produced by a rotations-by-dimensions procedure. Results in studies involving imagined reorientation of one's whole body and abstract three-dimensional objects suggest that people do not use spatial transformation procedures producing paths of relatively inefficient length (Parsons, 1987b, 1987e).

(2) In other cases, if the paths are available and are used for the equivalent natural motion, people appear to imagine very efficient (possibly shortest) paths. The author's unpublished results suggest that people do not ordinarily know shortest paths between orientation of objects if the orientation difference is not in one of the object's principal planes. (When asked for an efficient path between such orientations, people often indicate a spin-precession path.) Further, subjects have difficulty learning shortest paths between pairs of orientations when the axis of rotation is not a principal axis of either the object or the subject's visual frame of reference (Parsons, 1987b). The wrist has a structure that naturally allows (at least approximately) shortest paths for some important regions of the hand's workspace. The results here suggest that these shortest paths may be mentally simulated by people. (The wrist has three degrees of freedom for motion to medial orientations: if the hand is turned simultaneously about each axis at rates proportional to the difference—for each degree of freedom—between initial and goal orientations, it rotates about the

shortest path axis; cf. General Discussion: When joints allow efficient path to stimulus orientation.)

(3) In some cases here, people seem to have used other spatial transformation procedures that allowed them to simulate the kinematics of motions of their body. These motions are not produced by the simple application of the spatial transformation procedures discussed here; analytic kinematic descriptions of them are relatively complicated and are apparently not yet available.

Influence of mechanical properties on imagined spatial transformations. It is not known how or why properties of the execution of motion of one's body or body parts influence their imagined spatial transformation. This influence may show nothing importantly intrinsic to processes underlying spatial transformational procedures. They may be "newsreels" inplementing or reflecting belief about how objects move, and may be completely different with other instructions (see, e.g., Pylyshyn, 1981). (That is, with different beliefs, other "newsreels" would be composed for producing spatial transformations.)

Alternatively, these results may illustrate how our mental representations internalize important and pervasive constraints of the ecology (cf. Shepard, 1984). It may be that these imagined spatial transformations rely on processes involved in the planning (or even execution) of movement. To be effective, the latter processes would need to accurately represent ranges of motion of body parts. (Indeed in various ways, the effectiveness of the motor control system depends on the form and accuracy of the internal model it has of itself: see, e.g., Atkeson, 1986).

Internal representation of the human body. Recently, some investigators have explored issues of the representation of the human body and its movement (e.g., Parsons & Shimojo, 1987; Pellionisz & Llinas, 1980, 1982; Robinson, 1982; Soechting, 1982; Soechting & Ross, 1984; Soechting, Lacquaniti, & Terzuolo, 1986). One such promising approach is that of Marr and Vaina (1982). They extended the Marr and Nishihara (1978) three-dimensional model representation of static shapes to allow for the description of actions and gestures. Their representation segments movements into stationary and motion phases, and describes the human body and its parts as hierarchically nested sets of cylindrical primitives. Spatial relations between moveable parts are encoded as allowable angles of rotation between pairs of connected shape primitives. Angles are described with respect to spherical and cylindrical coordinate systems centered on the subpart and part (respectively). An action is represented as the direction, amount, and rate of change in joint angles for each part and its subparts, with respect to the other parts and to the whole body. Further investigation and theoretical development is necessary to determine whether an internal representation of this kind underlies the mental simulation of the movement of one's body.

Generality of processes underlying imagined spatial transformations. Overall, these findings (and those in Parsons, 1983a, 1987b, 1987d, 1987e) suggest that imagining an object's spatial transformations is *not* always a process of applying very *general* procedures, as could be assumed from earlier work (cf. Shepard, 1975). People do not seem to use spatial transformations that produce the same "minimum angle" path (with a uniform rate) for every object at every (absolute) orientation difference.

Object-specific imagined spatial transformations. Object-specific spatial transformation procedures may use a rotation operator or process which is more or less primitive and is constrained by knowledge about available or typical paths for the spatial transformation of a particular object. Knowledge about available paths could be of a mechanical or a merely visual nature (i.e., an axis could be part of the object's shape, such as a door's hinges). Or, object-specific procedures could use a "simulator" process modeling concrete properties of an object's actual motion: (a) its internal mechanical workings (e.g., the wrist's anatomical/physiological structure, kinesthetic sensations, etc.) and (b) properties of its physical motion (such as velocity, acceleration, and the forces and torques producing movement).

Testing of these hypotheses, and further confirmation of interpretations described here, requires studies that provide more precise information about kinematics, initiation (planning) time, and rate of imagined spatial transformations.

APPENDIX A

Experiment A: Ratings of the Awkwardness of Adopting the Orientation of Hand and Feet Stimuli

This experiment assesses the extent to which stimuli in Experiments 1–5 portray the hand and foot at physically awkward orientations. Subjects view left and right versions of six hand and six feet stimuli (Figs. 7–17), presented at 12 picture plane orientations and rate the awkwardness of adopting the orientation of each. On trials with hands, subjects placed the appropriate hand into the orientation of the stimulus before rating its awkwardness on a scale from 1 to 5. To rate the awkwardness of orientations of feet, they placed the appropriate foot in the orientation of the stimulus while seated normally in a chair; when the orientation was impossible to adopt (while seated), they rated awkwardness by imagining placing their foot into the stimulus orientation. (Subjects remained seated while judging awkwardness of feet orientations, so that, during judgments, their physical position was like that of subjects in Experiments 1–5.) Trials with hands were performed first.

Method

Subjects. Seven right-handed UCSD undergraduates who had not been in any related experiments, participated for credit in a psychology course.

Stimuli. Drawings of right hands and feet are in Figs. 12–17. Other aspects of the construction and display of stimuli were identical to those of Experiments 1–5.

Design. Subjects performed two blocks of 144 trials each, the first with hands and the second with feet. Other aspects of the design were identical to those of Experiments 2–3.

Procedure. Subjects sat in a chair before a tachistoscope. They said "left" or "right" to indicate whether a stimulus was a left or right hand (or foot), and then rated the awkwardness of its orientation on a scale of whole numbers from 1 (*easy*) to 5 (*difficult*). With hands, subjects put the appropriate hand at the orientation of stimulus and then rated its awkwardness. Subjects put the appropriate foot at the orientation of a stimulus only when it was possible while sitting normally in a chair. When this was not possible, they were to imagine "as realistically as possible" putting the appropriate foot into the orientation of the stimulus.

Results

Tables 3 and 4 show the mean awkwardness ratings for each stimulus at 0 and 180°, and at lateral and medial ODs of 30 to 150°. ANOVAs of ratings for each stimulus were conducted using OD (30, 60, 90, 120, 150°) and lateral and medial stimulus orientation. Correlations were computed between these ratings and relevant RTs in Experiments 2–5.

Hands. For each stimulus, ratings depended on OD and lateral and medial orientation: backs in picture plane ($F(4,24) = 30.82, p < .001$, and $F(1,6) = 6.69, p < .05$); palms in picture plane ($F(4,24) = 5.57, p < .01$, and $F(1,6) = 24.14, p < .01$); palms from fingers ($F(4,24) = 4.90, p < .01$, and $F(1,6) = 25.5, p < .01$); palms from wrist ($F(4,24) = 23.87, p < .01$, and ($F(1,6) = 3.92, p < .01$); sides from thumb ($F(4,24) = 21.18, p < .001$, and $F(1,6) = 29.03, p < .01$); and sides from little finger ($F(4,24) = 2.115, p > .05$, and $F(1,6) = 10.91, p > .01$).

Also, the effect of OD on the ratings was different for lateral and medial orientations for palms in picture plane ($F(4,24) = 5.10, p > .01$), palms from wrist ($F(4,24) = 7.08, p < .001$), sides from thumb ($F(4,24) = 5.63, p < .01$), and sides from little finger ($F(4,24) = 3.43, p < .05$).

Correlation of ratings with RTs of left–right judgments in Experiment 2 for the same stimuli is .81 ($F(1,70) = 129.37, p < .0001$). This correlation was between .90 and .87 (in every case, $p < .001$) for all but sides from little finger and palms from finger, for which the correlations are .58 (.75 without RT at 0°) and .04.

Ratings were strongly correlated with mean RTs in Experiment 4, in which subjects imagined spatial transformation of their hands into orientations of the same stimuli, without having to make left–right judgments

TABLE 3
Mean Awkwardness Ratings of Hands in Experiment A ($N = 7$)
(Scale: 1 (Easy) to 5 (Awkward))

	Picture plane OD						
	0	30	60	90	120	150	180
	Backs in picture plane						
Medial:	1.429	1.357	1.429	1.571	1.286	2.643	3.214
Lateral:		1.429	1.714	2.071	2.214	3.500	
	Palms in picture plane						
Medial:	1.357	1.429	1.143	1.286	1.429	1.929	2.143
Lateral:		1.714	2.500	3.429	3.214	3.000	
	Palms from wrist						
Medial:	2.000	2.240	1.786	1.786	1.786	1.929	1.714
Lateral:		2.000	3.000	3.714	3.786	2.857	
	Sides from thumb						
Medial:	1.786	1.429	1.571	1.786	1.929	2.143	2.643
Lateral:		1.857	2.286	2.857	3.786	3.857	
	Sides from little finger						
Medial:	3.571	3.429	3.143	2.857	3.214	3.786	3.714
Lateral:		4.071	4.214	3.643	3.571	3.357	
	Palms from fingers						
Medial:	3.643	3.714	4.429	4.214	4.929	4.500	4.571
Lateral:		3.571	3.429	3.786	4.071	4.286	

TABLE 4
Mean Awkwardness Ratings of Feet in Experiment A ($N = 7$)
(Scale: 1 (Easy) to 5 (Awkward))

	Picture plane OD						
	0	30	60	90	120	150	180
	Tops in picture plane						
Medial:	2.000	2.000	2.429	2.857	3.500	3.357	4.000
Lateral:		2.000	2.143	2.429	3.000	3.643	
	Soles in picture plane						
Medial:	3.357	3.500	3.571	3.143	2.714	3.071	1.929
Lateral:		3.786	3.571	2.571	2.429	2.357	
	Inside view						
Medial:	2.286	2.214	1.929	2.143	2.286	2.286	3.214
Lateral:		2.571	2.714	2.643	3.500	3.643	
	Outside view						
Medial:	2.214	2.571	2.643	2.857	3.500	3.786	3.357
Lateral:		2.500	2.643	2.571	3.000	3.357	
	Soles from heel						
Medial:	1.571	1.786	2.357	2.214	3.000	4.000	4.357
Lateral:		1.857	2.357	3.000	3.500	4.500	
	Tops from toes						
Medial:	4.000	4.000	3.714	3.929	4.143	3.643	3.929
Lateral:		3.857	4.071	3.929	3.714	3.786	

(r = .93, $F(1,70)$ = 445.17, $p < .0001$). This correlation was between .93 and .88 (in every case, $p < .0001$) for all but sides from little finger (.80, $p < .01$).

Feet. A comparable analysis for feet showed that ratings depended on OD for inside view ($F(4,24)$ = 3.46, $p < .02$), outside view ($F(4,24)$ = 8.89, $p < .001$), soles in picture plane ($F(4,24)$ = 3.51, $p < .02$), tops in picture plane ($F(4,24)$ = 6.95, $p < .001$), soles from heel ($F(4,24)$ = 10.89, $p < .001$), but not for tops from toes. Only for inside view was effect of OD on ratings different for lateral and medial orientations ($F(4,24)$ = 4.63, $p > .007$); no other effect involving medial and lateral orientations was reliable, though there were trends for such differences.

The correlation of feet ratings with RTs of left–right judgments of subjects in Experiment 3 for the same stimuli was .65 ($F(1,70)$ = 49.33, $p <$ .000); without tops from toes, this correlation was .85 ($F(1,58)$ = 154.74, $p < .0001$). For individual foot stimuli, this correlation was between .96 and .57 (every case, $p < .05$) for all but tops from toes, for which the correlation was .11.

There was also a strong correlation between mean awkwardness ratings for feet and mean RTs of subjects in Experiment 5, who imagined spatial transformations of their feet into orientations of the same stimuli, without having to make left–right judgments (r = .89 ($F(1,70)$ = 253.89, $p < .0001$).

Discussion

These results show important similarities between (a) subjects' ratings of the awkwardness of an orientation of a hand or foot and (b) RTs to make a left–right judgment of a hand or foot at that orientation and RT to imagine the spatial transformation of one's hand or foot to that orientation. The correspondence between the awkwardness of stimulus orientation and these RTs was weaker for feet than hands. This was true in particular for the foot's lateral and medial orientations where awkwardness measures show little variation. It is possible that ratings were insensitive to actual awkwardness, because in many cases subjects did not put their foot at the stimulus orientation when rating awkwardness, as they did with hands.

APPENDIX B: SPATIAL TRANSFORMATION PROCEDURES

This appendix describes in slightly more detail the three spatial transformation procedures discussed here (for a more formal treatment, see Parsons, 1987a). Each procedure requires a description of stimulus orientation in direction cosines. Tables 1 and 2 show the degrees of rotation for three procedures for spatial transformation of the hand or foot from its task orientation to the orientation of the stimulus. Spatial transformations of the hand originate where the back faces the observer and the fingers point forward or upward; spatial transformations of the foot originate where the top faces the observer and the toes point forward or upward). These values are used to compare RT in Experiments 1–3 for these three spatial transformation procedures.

Rotations by dimensions. A well-known example of a rotations-by-dimensions procedure is embodied in Euler angles which are used to describe differences in orientation (cf. Goldstein, 1950; Parsons, 1987e). The procedure here uses the following steps. (It assumes that the major principal axis of the body part is initially in the direction of positive Y axis. The positive Z axis is in the direction of the line of sight, the positive X axis is to the left, and the positive Y axis is upward.) (1) Determine in which quadrant of space the final orientation of the major principal axis of the body part is (e.g., forward, backward, leftward, and/or rightward). (2) Determine the angle from the final orientation of the body part's major principal axis to YZ and XY planes of the environmentally fixed frame with its origin at the body part's center of mass and aligned with the observer's visual reference frame. (3) Rotate the body part in either the YZ or XY plane (whichever is closer to the final orientation of the body part's major principal axis). This rotation should align the body part's major principal axis with the projection of the vector representing its final orientation onto the plane it is being rotated in (YZ or XY). (4) If necessary, rotate the body part about the vertical (i.e., Y) axis, so that the body part's major principal axis is in its final orientation. Finally, (5) if necessary, spin the body part about its major principal axis to put the minor and mean principal axes of the body part at their final orientations.

When the orientation difference is entirely in a principal plane of the observer's visual frame of reference, the rotations-by-dimensions procedure produces a path identical to that of the other procedures, if it uses principal axes of that frame.

A more efficient version of this procedure evaluates how much orientation difference is eliminated by a rotation about each principal axis and chooses that rotation, eliminating the most orientation difference overall. For some orientation differences, rotation about a principal axis will simultaneously eliminate orientation differences on two of three dimensions. (The orientation differences shown in Fig. 2 are like those for palms in picture plane and soles in picture plane; see Tables 1 and 2. For these stimuli, when α is greater than 90, this more efficient variant of the rotations-by-dimension procedure first rotates about the transverse axis lying in the plane of the hand and perpendicular to the hand's principal or long axis, then turns the hand to point the fingers correctly. The resulting difference in degrees of rotation from task (or canonical) to stimulus orientations for palms and soles in picture plane (see Experiments 2–5 and

Tables 1 and 2) is, for 0, 30, 60, 90, 120, 150, 180° ODs, 180, 210, 240, 270, 240, 210, 180°.)

A less efficient version of this procedure would randomly order the sequence of rotations about each principal axis on which there is an orientation difference. (The order of rotations is important because rotations are not commutative: different orders put the object at different final orientations.)

Spin precession. The spin-precession procedure discussed here spins the body part about its major principal axis. It simultaneously rotates (precesses) it about the environmentally fixed axis (i.e., in a transverse plane) that is the crossproduct of the vectors representing the initial and final orientations of the major principal axis. For simplicity, assume homogeneous motion, so that spin and precession rotations occur at coordinated rates proportional to the amount of rotation about each axis necessary to correct for the overall orientation difference. The precession angle is that between vectors representing initial and final orientations of the body part's major principal axis. The spin angle can be found by determining the amount of rotation necessary to align the minor and mean principal axes of the body part, once it has rotated through its precession angle.

The resulting spatial transformation is a rotation about an instantaneously changing axis. The total angle of rotation about this axis is equal to the precession angle plus the square root of the quantity 1 plus the square of the ratio of spin to precession angles (Parsons, 1987a). In principle, the spin can be about any axis, not just principal axes.

Shortest path. The shortest path procedure finds the axis (unique for each OD), about which the body part can be rotated by an angle absolutely minimizing the degrees of rotation. The usual method for solving this problem (e.g., Goldstein, 1950) is as follows. (1) Describe one orientation in terms of the other, using direction cosines. (2) Construct the (change-of-basis) matrix M by which the points described with respect to the initial reference frame can be described in terms of the final reference frame. (3) Set the major diagonal of this transformation matrix equal to 1 plus twice the cosine of θ, and solve for θ, the shortest path angle of rotation. (4) Find the eigenvector representing the axis of rotation.

The shortest path rotation (ignoring joint limits) of the subject's hand from its orientation in the task in Experiments 1 and A to the orientation portrayed by the palm in picture plane (Fig. 1) always requires 180°. This is because the change-of-basis matrix is

$$M = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -\sin(\alpha) & \cos(\alpha) \\ 0 & \cos(\alpha) & \sin(\alpha) \end{bmatrix}$$

where α is the angle of the hand's major principal axis from upright. Thus,

$$1 + 2\cos(\theta) = -1 - \sin(\alpha) + \sin(\alpha).$$

And $\cos(\theta) = -1$ or $\theta = 180°$, regardless of the value of α, the picture plane orientation of stimulus.

TABLE 5
Appendix C Experiment: Questionnaire on Subjects' Introspections in Left–Right Judgment of Hands*

	Mean	Standard error
1. On what percentage of the trials did you imagine your own hand in the orientation of the hand in the picture?	86.00%	6.78
2. On what percentage of the trials did you imagine your left hand in the orientation of the left hand in the picture and your right hand in the orientation of the right hand in the picture?	86.00%	6.00
3. Do you agree that some trials were harder than others because it was difficult to imagine your hand in the orientation of the hand in picture?	4 agree 1 disagree	
4. On what percentage of trials did you "accidentally" imagine your left hand at the orientation of a right hand in the picture (even when you eventually pushed the right hand button)?	6.25%	1.85
5. On what percentage of trials did you "accidentally" imagine your right hand at the orientation of a left hand in the picture (even when you eventually pushed the left hand button)?	7.00%	1.23
6. On the latter trials (in questions #4 and #5) when you accidentally imagined the "wrong" hand at the orientation of the stimulus, how often did you just notice it was the "wrong" hand and push the opposite button immediately without further thought?	80.00%	5.00

* Based on five subjects.

APPENDIX C

This appendix reports the results of an experiment designed to examine specific aspects of subjects' introspections about their left–right judgments. In Experiments 1–3, subjects were asked to describe (without guidance from the experimenter) their method for making their judgments. In the experiment reported in this appendix, subjects made left–right judgments like those in Experiment 2, and then responded to a questionnaire based on the introspections of subjects in Experiments 1–3. Five MIT undergraduates, who had not been in any related experiments, participated for $5.50 an hour in a replication of Experiment 2, and then responded to the questions in Table 5.

The pattern of subjects' RTs and errors were very similar to those in Experiment 2, and for brevity, are not reported. Subjects' responses to the questionnaire are consistent with the model of performance used in interpreting the results in Experiments 1–3. For most stimuli, subjects report imagining their own hand at the orientation of the stimulus. The exceptions were palms from fingers stimuli in which some subjects reported imagining "shaking hands" with the stimulus. Subjects reported using this "shaking hands" strategy because it was easier than imagining their hand in the "awkward" orientations of the palms from fingers stimulus. Subjects infrequently imagined the wrong hand in the orientation of the stimulus.

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