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Representation of Object Orientation in Children: Evidence from Mirror-Image Confusions

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Abstract

Although many cognitive functions require information about the orientations of objects, little is known about representation or processing of object orientation. Mirror-image confusion provides a potential clue. This phenomenon is typically characterized as a tendency to confuse images related by left-right reflection (reflection across an extrinsic vertical axis). However, in most previous studies the stimuli were inadequate for identifying a specific mirror-image (or other) relationship as the cause of the observed confusions. Using stimuli constructed to resolve this problem, Gregory and McCloskey (2010) found that adults' errors were primarily reflections across an object axis, and not left-right reflections. The present study demonstrates that young children's orientation errors include both object-axis reflections and left-right reflections. We argue that children and adults represent object orientation in the same coordinate-system format (McCloskey, 2009), with orientation errors resulting from difficulty encoding or retaining one (adults) or two (children) specific components of the posited representations.

Keywords

Spatial cognition; orientation; mirror images; object representation; development

The present study explores how young children represent and process the orientations of objects. Information about object orientation is important for perceiving and interacting with the visual world. For example, a child reaching for an object must accurately represent the object's orientation to position her hand appropriately, and the interpretation of a scene may be quite different depending upon whether two people in the scene are facing toward or away from each other. Nevertheless, little is known about how object orientation is represented or processed in adults or children. One potentially relevant observation is that adults and especially children frequently confuse mirror-image stimuli (e.g., Aaron & Malatesha, 1974; Biederman & Cooper, 1991; Davidoff & Warrington, 2001; Davidson, 1935; Farrell, 1979; Gibson, Gibson, Pick, & Osser, 1962; Gregory & McCloskey, 2010; McCloskey, 2009; McCloskey et al., 1995; McCloskey, Valtonen, & Sherman, 2006; Priftis, Rusconi, Umilta, & Zorzi, 2003; Riddoch & Humphreys, 1988; Rudel & Teuber, 1963; Sekuler & Pierce, 1973; Sekuler & Houlihan, 1968; Stankiewicz, Hummel, & Cooper, 1998; Stein & Mandler, 1974; Turnbull & McCarthy, 1996; Valtonen, Dilks, & McCloskey, 2008). In a classic study Rudel and Teuber (1963) tested children between 3 and 8 years old in tasks that required them to learn which of two stimuli had been arbitrarily designated the "correct" one. On each trial the two stimuli were presented simultaneously, the child chose the stimulus he or she believed was correct, and the experimenter provided feedback. When the stimuli were a horizontal bar and a vertical bar, even the youngest children learned the

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discrimination. However, when the stimuli were two mirror-image oblique bars (Figure 1A), few of the 3- to 5-year-olds learned to select the correct stimulus consistently, and many of the 6- to 8-year-olds also failed to learn the discrimination. Another manifestation of mirror-image confusion is the difficulty young children experience in learning to distinguish letters that differ only by mirror reflection, such as *b* and *d* (e.g., Davidson, 1935; Hildreth, 1932; Kaufman, 1980).

Gregory and McCloskey (2010) recently argued that despite the many studies of mirror-image confusion the nature and implications of the phenomenon remain unclear. Mirror-image confusion has typically been characterized as a tendency to confuse left-right mirror images (i.e., stimuli related by reflection across a vertical axis). This characterization is not, however, entirely satisfactory. A number of studies have shown that up-down mirror images are also subject to confusion (e.g., Huttenlocher, 1967; Sekuler & Houlihan, 1968). Moreover, as Gregory and McCloskey (2010 see also Howard, 1982; Rosenblith, 1965) pointed out, the stimuli used in most previous studies confound multiple spatial relationships, and so are not adequate to isolate a specific mirror-image (or other) relationship as the cause of the observed confusions. For example, the two oblique bars used by Rudel & Teuber (1963; see also Fisher, 1979; Over & Over, 1967; Schaffer, 1974; Serpell, 1971) are related not only by a left-right reflection but also by an up-down reflection, and by a 90° clockwise or counterclockwise picture-plane rotation.

Confounding of reflectional and rotational relationships occurs whenever stimulus objects are symmetric across one or both object axes. As illustrated in Figure 2A a bar may be thought of as an object with a principal axis of elongation and a secondary axis perpendicular to the principal axis. Because the bar is symmetric across these object axes, the outcomes of various reflections and rotations are indistinguishable. Consider in contrast the knife in Figure 2B, which is asymmetric across both principal and secondary object axes. Because of the asymmetries, the spatial relationships conflated in the case of the oblique bars can be differentiated. For example, a left-right reflection can be distinguished from a 90° counterclockwise rotation (see Figures 2C and 2D).

Also pervasive in studies of mirror-image confusion are confounds resulting from failure to dissociate object axes from extrinsic axes (i.e., axes not defined on the basis of the stimulus object, such as egocentric axes defined with reference to body parts or allocentric axes defined by environmental features). With the exception of the oblique-bar stimuli, virtually all of the stimuli in studies of mirror-image confusion have been presented with object axes parallel to extrinsic vertical and horizontal axes. For example, Figure 1B shows a line drawing of a pitcher and the copy made by AH, a woman with a developmental deficit in perceiving object orientation (McCloskey, 2004, 2009). The pitcher was presented with object axes parallel to extrinsic axes (e.g., AH's body axes, environmental axes defined by the walls of the testing room, or by the sheet of paper on which the stimulus was printed). Consequently, AH's error could be described as either a reflection across an extrinsic vertical axis, or a reflection across the pitcher's principal object axis. The same ambiguity attaches to confusions between mirror-image letters (e.g., b, d). Object- and extrinsic-axis reflections can, however, be unconfounded, by presenting (asymmetric) stimuli with object axes tilted relative to extrinsic axes. For example, given the tilted knife stimulus in Figure 2B, a left-right reflection across an extrinsic vertical axis (Figure 2C) takes a different form than a reflection across the object principal axis (Figure 2E).

As a first step toward clarifying the nature and implications of mirror-image confusion Gregory and McCloskey (2010) tested adults in tasks designed to elicit errors in memory for object orientation. Participants viewed pictures of tilted asymmetric objects such as the knife in Figure 2, and subsequently reported the orientation of each stimulus by drawing the object, or choosing an orientation on a forced-choice test. Across several experiments a consistent pattern emerged: Participants' errors were predominantly mirror reflections, but these did not take the form expected from the characterization of mirror-image confusion as a tendency to confuse left-right mirror images. The predominant error type was not left-right reflection (i.e., reflection across an extrinsic vertical axis, as in Figure 2C), but rather reflection across the object principal axis (as in Figure 2E). Gregory and McCloskey interpreted the systematic error pattern as evidence that object orientation representations are compositional—that is, composed of multiple independent elements, each of which represents a different aspect of an object's orientation. More specifically, they took the results as support for the COR (coordinate-system orientation representation) hypothesis proposed by McCloskey and colleagues (McCloskey et al., 2006; McCloskey, 2009). According to COR, visual representations of object orientation specify, by means of several independent components, the relationship between an object-centered frame of reference and one or more extrinsic reference frames.

In the present study we probed the representation and processing of object orientation in young children, focusing on two interrelated sets of questions. First, do young children's object orientation representations have the same compositional structure as those of adults, or are the children's representations different in some way (i.e., non-compositional, or compositional but with a different structure than in adults)? Second, do young children experience the same difficulties as adults in processing object orientation information, and so show the same form of mirror-image confusion (i.e., a predominance of object-axis reflections); or do children suffer from different or additional difficulties, leading to a different error pattern?

In the following sections we first survey the COR hypothesis and its interpretations for various forms of mirror-image confusion. On the basis of this discussion we then offer several predictions about young children's orientation errors, and present three experiments testing these predictions.

The COR Hypothesis

The COR hypothesis conceives of an object's orientation as a relationship between an object-centered frame of reference and a reference frame extrinsic to the object (McCloskey, 2009; McCloskey et al., 2006). As illustrated in Figure 3, the object-centered frame is defined on the basis of the object's shape, with a principal axis of elongation and a secondary axis orthogonal to the principal axis.[1] The extrinsic frame may be defined by axes of the observer's body (e.g., vertical and horizontal head axes), or on the basis of environmental features (e.g., the walls of a room, the edges of a computer monitor). For current purposes we simply assume an extrinsic coordinate system with vertical and horizontal axes, without considering the basis for defining the axes.

The two ends of each object and extrinsic axis are distinguished by polarity representations. For object axes we assume that polarity representations are based upon visual object features (e.g., shape, color, texture). In the case of the knife, for example, the polarity representations might conceivably be something like [pointed] and [blunt] for the object principal axis, and [curved] and [straight] for the secondary axis. (We use brackets to indicate that the polarity representations are non-linguistic feature representations, and not representations of words.) For extrinsic axes we assume that polarity representations are grounded in visual or more abstract spatial features of the environment or the observer's body. For instance, [up] and

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[1] Although the COR hypothesis can be applied to three- as well as two-dimensional objects and reference frames, we limit our discussion to two-dimensional representations because these are the representations relevant to our experiments.

[down] representations might be assigned to the poles of an extrinsic vertical axis by reference to the up-down distinction provided by the ceiling versus the floor of a room, or the head versus the feet of the observer. For an extrinsic horizontal axis, [left] and [right] polarity representations could be assigned by reference to the left and right sides of the observer's body.[2]

According to COR, an object's orientation relative to an extrinsic reference frame is represented by specifying the relationship between the axes of the object-centered frame and those of the extrinsic frame. For example, the orientation of the knife in Figure 3 could be represented by relating the knife's principal axis to the extrinsic vertical axis, and its secondary axis to the extrinsic horizontal axis (Figure 3).[3] COR assumes that the relationship between object and extrinsic axes is specified by *polarity correspondence* and *tilt* parameters. The polarity correspondence parameters specify how the poles of each object axis are related to the poles of the corresponding extrinsic axis. In Figure 3, for example, the knife's principal axis is positioned with its [pointed] pole toward the [up] pole of the corresponding (vertical) extrinsic axis, and the [straight] pole of the knife's secondary axis maps onto the [right] pole of the extrinsic horizontal axis.

The tilt component of an orientation representation specifies the tilt of the object axes relative to the extrinsic axes. COR assumes that tilt is represented by specifying the magnitude and direction of the angular displacement between the object's principal axis and the corresponding extrinsic axis. Tilt magnitude is simply an angle (e.g., 45° for the knife in Figure 3). However, tilt direction is somewhat more complex, in that specifying this parameter requires reference to polarity representations for extrinsic axes. For example, the direction of tilt for the knife could be represented by specifying that the object principal axis is tilted away from the [up] pole of the extrinsic vertical axis toward the [right] pole of the extrinsic horizontal axis (or, equivalently, away from the [down] pole toward the [left] pole). This description may seem an awkward means of specifying a clockwise tilt direction. However, *clockwise* and *counterclockwise* are only shorthand expressions for more complex descriptions that refer to polarity representations. For example, to say that a wheel is rotating clockwise relative to an observer means that each point on the wheel is moving from up to right to down to left (i.e., from the up pole of an extrinsic vertical axis to the right pole of an extrinsic horizontal axis, and so forth).

Given these assumptions the orientation representation for the knife in Figure 3 might look something like the following:

POLARITY CORRESPONDENCE

Principal-Vertical:	[pointed]↔[up]
Secondary-Horizontal:	[straight]↔[right]

TILT

Magnitude:	45°
Direction:	[up]→[right]

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[2] Previous discussions of COR simply assumed that one end of each axis was designated positive (+), and the other negative (−). However, this assumption leaves unanswered a question that turns out to be important in exploring the causes of some orientation errors: On what bases are polarity representations assigned to the ends of axes? The modified assumptions about polarity representations presented here are aimed at addressing this question.

[3] The COR hypothesis assumes that orientation representations include a parameter specifying which object axes are represented in relation to which extrinsic axes (McCloskey et al., 2006). However, this parameter of the posited representations is not central to the issues addressed in the present article.

Interpreting Mirror-Reflection Errors

The COR hypothesis assumes that orientation errors result from failures in encoding, retaining, or processing one or more components of the posited orientation representations, with the type of error determined by which components are affected. Mirror-reflection errors are attributed to failures affecting polarity representations.

Object-Axis Reflections

Object-axis reflections are assumed to result from errors affecting the representation of polarity correspondence between object and extrinsic axes. More specifically, polarity correspondence errors involving one object axis lead to reflections across the other object axis. Suppose that for the knife in Figure 3, the polarity correspondence between the secondary object axis and extrinsic horizontal axis ([straight]-[right]) were forgotten in the interval between presentation of the picture and a subsequent test. The degraded representation would fail to distinguish between the original orientation and its reflection across the object principal axis (see Figure 4A vs. 4B). Similarly, forgetting of the [pointed]-[up] polarity correspondence between the object principal axis and the extrinsic vertical axis could lead to an error involving reflection across the object secondary axis (Figure 4C).

In the Gregory and McCloskey (2010) study object principal axis reflection errors (Figure 4B) were much more frequent than object secondary axis reflections (Figure 4C). Gregory and McCloskey suggested that this difference arose from the properties of the stimulus objects. For most of the objects, the features differentiating the two sides of the object principal axis were more salient than the features distinguishing the sides of the secondary axis. The knife is typical in this respect: The blade and handle sides of the object principal axis are more distinctively different than the sharp and dull sides of the secondary axis. As a consequence, creating polarity representations that clearly distinguished the two ends of an object axis may have been more difficult for secondary axes than for principal axes (and/or the lower salience of the secondary-axis features may have caused less attention to be focused on secondary than principal object axes). Given weak polarity representations for secondary axes, polarity correspondences may have been more difficult to encode and retain for these axes than for principal axes. In this way the higher rates of object principal axis reflection errors (which result from secondary-axis polarity correspondence failures) than object secondary axis reflection errors (caused by principal-axis polarity correspondence failures) may be understood.

Extrinsic-Axis Reflections

Reflections across an extrinsic axis (see Figure 4D and 4E) may also be interpreted by reference to polarity representations. According to COR, extrinsic-axis reflections arise from errors in assigning polarity representations to extrinsic axes, or in using the extrinsic-axis polarity representations to establish relationships between extrinsic reference frames. Failures affecting horizontal-axis polarity representations lead to extrinsic vertical axis reflections (left-right reflections as in Figure 4D), whereas failures involving vertical-axis polarity representations cause extrinsic horizontal axis reflections (up-down reflections as in Figure 4E).

Imagine, for example, that an individual encoding the orientation of the knife in Figure 4A mistakenly reversed the assignment of [left] and [right] polarity representations to the poles of the extrinsic horizontal axis, assigning [left] to the right pole, and vice versa. The resulting orientation representation would specify not the correct orientation but instead the extrinsic vertical axis reflection (i.e., the left-right reflection shown in Figure 4D). Extrinsic-axis reflection errors were infrequent in the Gregory and McCloskey (2010) study, suggesting that the adult participants had little difficulty with extrinsic-axis polarity representations.

Orientation Representations and Errors in Young Children

Landau and Hoffman (2005) have argued that young children represent at least some aspects of space compositionally. Accordingly, we propose as a working assumption that young children's object-orientation representations have the same compositional structure as those of adults. Given this assumption, the COR hypothesis and the Gregory and McCloskey (2010) results from adults suggest predictions about children's orientation errors. First, if adults have difficulty encoding or retaining some component of an orientation representation, we obviously expect young children also to have difficulty with that component. Gregory and McCloskey (2010) argued that the adults in their study had difficulty encoding or retaining polarity correspondences between object secondary axes and extrinsic axes, because most stimulus objects lacked salient features differentiating the two secondary axis poles. Accordingly, we predict that young children will experience the same difficulty (assuming the children are tested with the same or similar stimulus objects), leading as in adults to object principal axis reflection (OPA) errors.

As the interpretation for OPA errors illustrates, the COR hypothesis implies that difficulty differentiating the poles of an (object or extrinsic) axis will lead to orientation errors. This point raises the possibility that in addition to OPA errors young children may evidence a type of extrinsic-axis reflection error. In particular, young children may have some difficulty distinguishing the poles of extrinsic horizontal axes, leading to extrinsic vertical axis (EVA) reflection errors (i.e., left-right reflections). Distinguishing the poles of an extrinsic vertical axis is presumably a simple matter even for a young child, because the up and down poles of vertical axes have salient distinguishing features (e.g., head vs. feet of the body, sky vs. ground of outdoor environments, ceiling vs. floor of rooms). As many theorists have noted, however, the poles of horizontal extrinsic axes are much more difficult to distinguish: The left and right sides of the body are far more similar than the upper and lower halves, and most environments do not have features as salient as sky vs. ground or ceiling vs. floor to distinguish the ends of a horizontal axis (e.g., Bornstein, 1982; Corballis, 1988; Corballis & Beale, 1976, 1983; Farrell, 1979; Goldmeier, 1936, 1972; Rock, 1973; Sutherland, 1960). Consequently, distinguishing the poles of a horizontal extrinsic axis may be especially challenging for young children. In other words, young children's [left] and [right] representations may be less distinct than their [up] and [down] representations (as well as less distinct than adults' [left] and [right] representations), leading to difficulties in assigning or using horizontal-axis polarity representations. According to COR, such difficulties result in extrinsic vertical axis (EVA) reflections (i.e., left-right reflections).

We predict, then, that young children will evidence both the type of mirror-reflection error made by adults (OPA reflection), and the type of error typically assumed to be implicated in mirror-image confusion (EVA reflection). Note that we predict differences in error pattern between children and adults not because we assume that children and adults represent object orientation differently, but rather because we assume that one aspect of orientation representation (differentiating the poles of extrinsic horizontal axes) is likely to be more difficult for children than for adults.

EXPERIMENT 1

In this experiment young children performed an orientation-matching task that imposed minimal demands on memory. On each trial a target picture was presented, and remained in view while the child attempted to find the picture with the same orientation in a forced-choice array.

Method

Participants—Sixteen four- to five-year-olds participated in the experiment (*M* = 4;6; Range = 4;1 – 5;0), and each received either pay or a toy. Each child tested in the present study participated in only one of the three experiments.

Stimuli & Design—Stimuli were photographs of eight familiar objects (flashlight, toothbrush, hairbrush, scissors, kitchen knife, comb, ice cream scoop, key) selected from those used in the Gregory and McCloskey (2010) study of adults. Each object was photographed under uniform lighting with its axis of elongation parallel to the camera's sensor plane, and each photograph was asymmetric along both planar object axes. All objects were poly-oriented (Leek, 1998). In contrast to mono-oriented objects, poly-oriented objects have no canonical upright orientation and are regularly viewed at a variety of orientations (although some orientations may be more common than others). Poly-oriented objects were chosen to minimize response biases that might occur with mono-oriented stimuli (e.g., a bias toward responding with a canonical orientation).

Each object appeared in 16 different orientations, consisting of all possible horizontal, vertical, and diagonal orientations of the original (vertical) photograph and its reflection across the object principal axis (see Figure 5). The complete stimulus set included 128 photographs (8 objects × 16 orientations).

On each trial a target stimulus was presented with an eight-alternative forced-choice test array. For oblique targets the test alternatives were the eight possible oblique orientations of the target object; for cardinal (i.e., horizontal and vertical) targets the test stimuli were the eight possible cardinal orientations. As shown in Figure 6 the target first appeared at the center of the display within a red circle. The test alternatives were then presented in a circular array around the target, with all test stimuli equidistant from the target. Each picture subtended a visual angle of approximately 6°. Each participant saw one of four response array types that differed with respect to which test orientations occupied which positions within the array.

Each participant received 64 trials, with all 128 possible targets presented across every two participants. Across the 16 participants each target was presented 8 times. For each participant the order of presentation was pseudo-randomized such that across every 8 trials, each object appeared once, and across every 16 trials each orientation appeared once. At least one trial intervened between successive presentations of the same object.

Procedure—The child was first shown a photograph of each stimulus object (at a randomly sampled orientation), and asked to name the object. The child was also asked to point out certain features of each object (e.g., handle and sharp edge for the knife), to ensure that he or she took note of the asymmetries within each object.

The child was seated approximately 45 cm from a computer screen. On each trial a fixation cross was first presented in the center of the screen (see Figure 6). The child was next shown the target object in a red circle and instructed to look carefully at its orientation. When the child was ready to continue, the circular test array was presented, with the target remaining on the screen. The experimenter encouraged the child to check all of the choices. The child responded by pointing to one of the test alternatives, taking as much time as needed. Eight practice trials preceded the 64 test trials; feedback was provided on practice but not test trials. Eleven of the 1024 trials were lost due to computer malfunctions; the reported results are for the remaining 1013 trials.

Results

Children chose the correct orientation from the test array on 75% of the trials (764/1013). Accuracy did not differ significantly between oblique (74%) and cardinal (77%) targets, $p > .1$.

Error analyses were carried out separately for the oblique and cardinal targets. For oblique targets seven error types may be distinguished, corresponding to the seven incorrect response alternatives presented on each trial. As shown in Figure 7, four of the seven error types are mirror reflections. In object principal axis (OPA) errors the target object is reflected across its principal axis of elongation, and in object secondary axis (OSA) errors the object is reflected across its secondary axis. In extrinsic vertical axis (EVA) errors the target is (left-right) reflected across an extrinsic vertical axis, and in extrinsic horizontal axis (EHA) errors the target is (up-down) reflected across an extrinsic horizontal axis. The three remaining error types are picture-plane rotations of +90°, −90°, and 180° (+ indicates clockwise and − counterclockwise rotation). (Note that Experiment 3 considered additional error types, as each stimulus was tested with all 16 possible target orientations.)

Mirror-image confusion has typically been assumed to involve difficulty distinguishing orientations related by left-right reflection; such difficulty would manifest in the current experiment as a high rate of EVA reflections. In contrast Gregory and McCloskey (2010) found that adults' errors were predominantly OPA reflections, with no systematic tendency toward EVA reflections.

Figure 8A presents the distribution of the children's errors across types for the oblique stimuli. Errors were distributed non-uniformly across types, $F(6, 90) = 10.4$, $p < .001$. (All ANOVAs reported in this article were Greenhouse-Geisser corrected for non-sphericity.) Object principal axis reflections (OPA errors) were more frequent than all other error types ($p < .01$ by Tukey's HSD test). EVA errors were somewhat more common than the remaining error types, but this effect fell short of significance ($p > .1$).

For cardinal target stimuli the possible error types are somewhat different than those for the oblique targets. Mirror reflections across object and extrinsic axes are confounded for cardinal targets: any reflection error could be described either as a reflection across an object axis or as a reflection across an extrinsic axis. As Figure 9 illustrates, four types of mirror-reflection error are possible for cardinal targets, but two of these can occur only for vertical stimuli and two can occur only for horizontal stimuli. For vertical stimuli the possible reflections are OPA/EVA errors, which could be reflections across either the object principal axis (OPA) or an extrinsic vertical axis (EVA), and OSA/EHA errors, which could be reflections across either the object secondary axis (OSA) or an extrinsic horizontal axis (EHA). For horizontal stimuli, the possible reflections are OPA/EHA errors (reflections across the object principal axis or an extrinsic horizontal axis) and OSA/EVA errors (reflections across the object secondary axis or an extrinsic vertical axis). In addition to mirror reflections, errors for cardinal stimuli can take the form of picture-plane rotations (+90°, −90°, 180°) or mixed (reflection plus rotation) errors.

Figure 8B presents the distribution of errors across types for the cardinal stimuli. Because possible error types differed for horizontal and vertical targets, error frequencies are shown separately for the horizontal and vertical stimuli. Errors were distributed non-uniformly across types, $F(8,120) = 10.5$, $p < .001$. Reflection errors potentially interpretable as object principal axis reflections (OPA/EVA plus OPA/EHA) were more frequent than other reflections (OSA/EVA plus OSA/EHA), $p < .025$ by Scheffé test, consistent with the large number of OPA errors with oblique stimuli. Also, the error types potentially interpretable as extrinsic vertical axis reflections (OPA/EVA plus OSA/EVA) were significantly more frequent than other reflections (OPA/EHA plus OSA/EHA), $p < .01$, suggesting that EVA as well as OPA errors were occurring systematically. In other words, the distribution of errors across the four reflection error types suggests that two underlying forms of error—object principal axis reflection (OPA) and extrinsic vertical axis reflection (EVA)—gave rise to the observed pattern. OPA/EVA errors were most frequent, because both underlying forms of error contributed to this observed error type; OPA/EHA and OSA/EVA errors were intermediate in frequency, because one underlying error type (OPA or EVA) contributed to each of these observed error categories; and OSA/EHA errors were very infrequent because neither underlying form of error contributed to this category.

Discussion

Despite the limited memory demands, children had some difficulty with the orientation-matching task, erring on one-fourth of the trials. The children's errors were not, however, random; the error pattern was highly systematic, with the vast majority of errors involving (some form of) mirror-image confusion. As expected, the young children, like the adults in the Gregory and McCloskey (2010) study, showed a strong tendency to confuse orientations differing by reflection across the object principal axis (OPA errors). Also consistent with predictions, the results suggest that children, unlike adults, may have a tendency to confuse orientations differing by (left-right) reflection across an extrinsic vertical axis (EVA errors). For oblique stimuli EVA errors were more frequent than any other type of error except OPA reflection (although the effect fell short of significance); and for cardinal stimuli the significant differences among reflection error types suggested that underlying EVA as well as OPA reflections were contributing to the observed error pattern.

Young children may, then, be subject to both the type of mirror-reflection error made by adults (OPA reflection), and the type of error typically assumed to be implicated in mirror-image confusion (EVA reflection). The conclusions about EVA errors must, however, be considered tentative, because these errors were not significantly more frequent than other error types for oblique targets, and because of the ambiguities inherent in reflection errors for cardinal stimuli. Experiments 2 and 3 provide additional evidence about the status of EVA errors, as well as speaking to the consistency of children's error pattern across task variations.

EXPERIMENT 2

In Experiment 2 the task's memory demands were increased by removing the target stimulus on each trial before presenting the forced-choice test array. In addition, we tested not only 4-year-olds but also 6-year-olds and adults to explore developmental differences in the quantitative and qualitative patterns of performance.

Method

Participants were sixteen four-year-olds (*M* = 4;6; Range = 4;0–5;0), sixteen six-year-olds (*M* = 6;7; Range = 6;0–6;11), and sixteen adults (Johns Hopkins University undergraduates who received extra credit in a course).

For the four- and six-year-olds the design and procedures were the same as in Experiment 1, except that the target stimulus disappeared on each trial immediately before the forced-choice test array was presented. The procedure for adult participants was slightly different, to ensure that the adults made a sufficient number errors to allow comparison of adults' and children's error patterns. Each adult received 128 rather than 64 target stimuli, and two different targets were presented on each trial. The targets were presented one at a time for 500 ms each, with a 250 ms pattern mask immediately following each target. The screen was then blank for 1.5 s, after which the test array for the first target stimulus was presented, and finally the test array for the second target. The two targets on each trial were always different objects (e.g., key and hairbrush).

Results

Removing the target before presentation of the test array substantially increased the difficulty of the task for young children. Nine four-year-olds failed to perform at a level significantly above chance; these participants were replaced, and the reported results come from 16 four-year-olds with reliably above-chance accuracy. Even with the exclusion of the at-chance participants, four-year-olds' accuracy (41%) was much lower than in Experiment 1 (75%), $t(30) = 6.18$, $p < .001$.

The six-year-olds in Experiment 2 showed higher accuracy (61%) than the four-year-olds, $t(30) = 4.44$, $p < .001$, and no six-year-olds were excluded for chance performance. Accuracy was higher still for adults (83%) despite the procedural differences that rendered the adult task more challenging (e.g., two targets per trial rather than one).

Both the four- and six-year-olds were less accurate for oblique than cardinal targets (four-year-olds: 32% vs. 49%; six-year-olds, 57% vs. 66%), $t(15) = 6.05$, $p < .001$ and $t(15) = 3.34$, $p < .01$, respectively. Adults showed no significant accuracy difference between oblique (82%) and cardinal (85%) stimuli, $t(15) = 1.78$, $p = .10$.

Four- and Six-Year-Old Children—Errors for oblique stimuli were non-uniformly distributed across types for four-year-olds, $F(6, 90) = 9.26$, $p < .001$, and six-year-olds, $F(6, 90) = 12.9$, $p < .001$ (see Table 1). In four-year-olds, object principal axis reflections (OPA errors) were more frequent than all of the other error types except EVA errors, and for six-year olds OPA errors were the most common errors (*ps* < .05 by Tukey’s test). EVA errors ranked second in frequency for both four- and six-year-olds, and occurred significantly more often than some other error types (rotations of −90° and 180° for four-year-olds; EHA errors and rotations of +90° and 180° for six-year-olds), *p*s < .05. These results indicate that four- and six-year-olds have a systematic tendency to make both OPA and EVA errors.

Table 2 presents the distribution for cardinal stimuli. For four- and six-year-olds, reflection errors potentially interpretable as extrinsic vertical axis reflections (OPA/EVA plus OSA/EVA) occurred significantly more often than other reflection errors (OPA/EHA plus OSA/EHA), $p < .01$ by Scheffé test. Potential OPA errors (OPA/EVA plus OPA/EHA) were significantly more frequent than other reflection errors (OSA/EVA plus OSA/EHA) for six-year-olds, $p < .05$. This pattern of more potential OPA than other reflection errors was also apparent for the four-year-olds though the difference did not reach significance ($p > .10$).

Adults—For oblique targets adults’ errors were distributed non-uniformly across types, $F(6, 90) = 13.5$, $p < .001$ (see Table 1). Consistent with Gregory and McCloskey’s (2010) results OPA errors occurred more often than all other error types ($p < .05$), but EVA errors did not occur significantly more frequently than any other error type. Furthermore, for cardinal stimuli (see Table 2), errors potentially interpretable as OPA errors were significantly more frequent than other reflection errors, $p < .01$ by Scheffé test, whereas potential EVA errors were not significantly more frequent than other reflections ($p > .99$). In sum, the adults’ pattern of error was different from the children’s and replicates the previous results from adults.

Discussion

The present results confirm the finding from Experiment 1 that young children, like adults, have a strong tendency to confuse orientations that differ by an object principal axis (OPA) reflection. In addition Experiment 2 provides stronger evidence than Experiment 1 that children are prone to confuse orientations that differ by a left-right reflection—that is, by an extrinsic vertical axis (EVA) reflection. Finally, the Experiment 2 results confirm that the error pattern for adults (OPA errors only) differs from that for young children (OPA and EVA errors).

EXPERIMENT 3

The purpose of this experiment was to ensure that the error pattern observed in Experiments 1 and 2 was not the result of some idiosyncratic feature of the task in these experiments (e.g., test alternatives presented in a circle surrounding the target). In Experiment 3 targets and test stimuli were presented on opposite sides of the participant. Also, the forced-choice test for each cardinal and oblique target included both oblique and cardinal test orientations. Finally, target and test stimuli were presented on paper rather than on a computer monitor.

Method

Participants were 16 four-year-olds (*M* = 4;6; Range = 4;0–5;0). Target and test stimuli were the same as in Experiments 1 and 2, except that the forced-choice test for each target included all 16 possible orientations (8 cardinal and 8 oblique orientations). Two loose-leaf binders were propped up in front of the child (see Figure 10). One binder displayed the target stimuli (with each target centered on a 27.9 × 21.6-cm sheet of paper), and the other binder presented the forced-choice alternatives. For half of the participants the target binder was on the left, and for the remaining half the targets were on the right. The response alternatives were arranged into four groups (horizontal, vertical, left oblique, right oblique) to simplify the process of searching the response array. Each participant saw one of four response array types that differed in placement of orientations within the array. The design was otherwise the same as in Experiments 1 and 2.

On each trial, the target and response alternatives were presented at the same time, and the child responded by placing a sticker on the chosen response. Participants were encouraged to look back and forth between the target and test stimuli as many times as necessary. The 64 test trials were preceded by six practice trials involving stimulus objects different from those in the test trials. The number of response alternatives was increased from four to eight and finally to sixteen during the practice trials so that the child would not be initially overwhelmed by the large response array. Feedback was provided on practice but not test trials.

Results and Discussion

Four children who failed to complete the task due to inattention were replaced. The reported data come from the 16 participants who completed the task (excluding three trials lost due to procedural mishaps). Overall accuracy was 69% (701/1021), and cardinal targets showed higher accuracy (74%) than obliques (63%), $t\,(15) = 5.37$, $p < .001$.

Because the response arrays included 16 rather than 8 alternatives, the number of possible error types is greater than in Experiments 1 and 2. For each target stimulus four additional picture-plane rotations (+45°, −45°, +135°, −135) and four additional mixed (reflection plus rotation) errors were possible on each trial. Figure 11A presents the distribution of errors across types for oblique stimuli. Errors were non-uniformly distributed, $F(14,210) = 14.46$, $p < .001$, with OPA and EVA errors occurring significantly more often than the remaining error types ($p < .05$ by Tukey's HSD tests). Also, rotations of +90° occurred more often than rotations of +/−135° and mixed errors ($p < .05$).

Errors for cardinal stimuli (Figure 11B) were also distributed non-uniformly across types, *F*(16,240) = 14.92, *p* <.001. Potential EVA errors (OPA/EVA plus OSA/EVA) were significantly more frequent than other reflection errors (OPA/EHA plus OSA/EHA, *p* < .01 by Scheffé test). Potential OPA errors (OPA/EVA plus OPA/EHA) were also more frequent than other reflection errors (OSA/EVA plus OSA/EHA) but the difference was not significant (*p* > .10).

Despite the procedural changes, the present experiment replicated the pattern of mirror-image confusions observed for young children in Experiments 1 and 2: Children confused stimuli differing by reflection across the object principal axis (OPA errors), and also stimuli differing by reflection across an extrinsic vertical axis (EVA errors).

GENERAL DISCUSSION

The present study explored mirror-image confusions in young children, with the aim of elucidating children's representation and processing of object orientation information. In three experiments mirror-reflection errors occurred more often than other forms of orientation error. Among the possible types of reflection error, object principal axis (OPA) and extrinsic vertical axis (EVA) reflections were far more frequent than object secondary axis (OSA) and extrinsic horizontal axis (EHA) reflections. This error pattern both resembles and differs from the pattern observed for adults in Experiment 2 and in Gregory and McCloskey (2010). Children, like adults, confuse orientations differing by reflection across an object principal axis (OPA errors). In contrast to adults, however, children also confuse orientations differing by (left-right) reflection across an external vertical axis (EVA errors).

Most previous discussions have taken for granted that mirror-image errors (in children and adults) take the form of left-right (EVA) reflections. However, our results clearly indicate a need to revise this assumption. Children, but not adults, make the EVA errors typically assumed to be implicated in mirror-image confusion; in addition, both children and adults also make OPA errors, a form of mirror-image confusion not previously considered.

The observed pattern of mirror-image reflection errors can be interpreted within the framework of the COR hypothesis (McCloskey, 2009; McCloskey et al., 2006). According to COR, the OPA errors observed in both children and adults arise from failures in encoding or retaining polarity correspondences between object secondary axes and extrinsic axes. The higher frequency of OPA than OSA errors may be attributed to the properties of the stimulus objects used in the present experiments and in the Gregory and McCloskey (2010) study. Gregory and McCloskey pointed out that for most of these objects the two sides of the object secondary axis were less distinctively different than the sides of the principal axis. As a consequence, encoding and/or retaining polarity correspondences may have been more difficult for secondary than for principal axes, leading to higher rates of OPA than OSA errors.

The EVA errors observed for children but not adults may be interpreted by assuming that young children's mental representations of left and right are less well-differentiated than those of adults, with the consequence that the children occasionally have difficulty assigning polarity representations to the poles of extrinsic horizontal axes. When a child encodes the orientation of a stimulus, she may usually assign [left] to the left pole of the extrinsic horizontal axis, and [right] to the right pole. Occasionally, however, she may reverse this assignment, assigning [left] to the right pole, and [right] to the left pole. If the child is trying to decide whether two stimuli match in orientation, the inconsistency in assigning polarity to the horizontal extrinsic axis will lead to EVA (extrinsic vertical axis reflection) errors.

Consider, for example, the two stimuli in Figure 12, which differ by an extrinsic vertical axis reflection. If the child encodes the stimulus in panel A using the correct polarity assignment (i.e., [left] assigned to the left pole of the extrinsic horizontal axis and [right] to the right pole), but encodes the stimulus in panel B using the reversed assignment, the two stimuli will seem to match because both will have the same orientation representation:[4]

POLARITY CORRESPONDENCE
  Principal-Vertical: [pointed]↔[up]
  Secondary-Horizontal: [straight]↔[right]
TILT
  Magnitude: 45°
  Direction: [up]→[right]

EVA errors could result not only from inconsistency in polarity assignment, but also from simple failure to assign polarity representations to the ends of a horizontal extrinsic axis. In the absence of these polarity representations neither tilt direction nor polarity correspondence between the horizontal extrinsic axis and an object axis could be encoded. An orientation representation lacking these parameter values could not distinguish the target orientation from its reflection across an extrinsic vertical axis, and therefore could give rise to EVA errors. However, the impoverished representation would also fail to distinguish the target from certain other orientations, including 90° rotations that cross the vertical axis. Therefore, if extrinsic vertical axis reflections resulted solely from failure to assign polarity to the horizontal extrinsic axis, we would expect these 90° rotations to be as frequent as EVA errors. In all of our experiments, however, the rotation errors were much less frequent than EVA errors, indicating that the EVA errors did not result entirely from failure to assign polarity to the extrinsic horizontal axis. Accordingly, we suggest that the observed EVA errors resulted predominantly from inconsistency in horizontal-axis polarity assignment (which gives rise only to extrinsic vertical axis reflection errors), with occasional failures to assign horizontal-axis polarity perhaps also playing some role.

This interpretation can account for our two major findings concerning extrinsic axis reflection errors. First, the finding that children made EVA (extrinsic vertical axis) reflection errors far more often that EHA (extrinsic horizontal axis) errors is explained by the assumption that polarity assignment is more difficult for extrinsic horizontal axes (which typically do not have highly salient features distinguishing the two poles) than for extrinsic vertical axes (which usually do have salient distinguishing features). Second, the finding that adults rarely made extrinsic vertical axis reflection (EVA) errors can be explained by assuming that adults, in contrast to young children, have well-differentiated [left] and [right] representations, and can assign these consistently to the poles of horizontal axes. It is also worth pointing out that our interpretation for EVA errors is closely related to our account of OPA (object principal axis) reflection errors: We attribute both error types to difficulties in

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[4] This interpretation may appear to conflict with findings showing that even very young children can succeed at tasks requiring them to encode and retain left-right distinctions (e.g., Acredolo, 1978; Hermer & Spelke, 1994). For example, in reorientation tasks (e.g., Hermer & Spelke, 1994; Lee & Spelke, 2008) young children succeed in limiting their search for a hidden object to room corners with the appropriate left-right relationship between short and long walls (e.g., short wall on the left, long wall on the right). However, success in these tasks is defined as above-chance performance, and the results typically show that young children, while performing at levels well above chance, are by no means perfect. For example, Lee and Spelke (2008) found that 4-year-olds searched in a geometrically inappropriate corner (i.e., a corner with the wrong left-right relationship between short and long walls) on 22% of trials in a standard reorientation task (vs. 0% geometrically inappropriate searches for adults tested under comparable conditions in Hermer & Spelke, 1994). In our experiments children were similarly imperfect yet far above chance in distinguishing target orientations from extrinsic vertical axis reflections; collapsing across experiments EVA errors, although more frequent than most other error types, occurred on only about 10% of the trials.

representing or processing axis polarity that arise when the two ends of an (object or extrinsic) axis lack salient distinguishing features.

A remaining question is what factors lead to developmental changes in patterns of orientation errors. One possibility is that language has some role in shaping orientation representations, consistent with findings indicating an influence of language on spatial representation more generally (e.g., Dessalegn & Landau, 2008; Pyers, Shusterman, Senghas, Spelke, & Emmorey, 2010; Shusterman, Ah Lee, & Spelke, 2011). In particular, Kolinsky and colleagues (2011) demonstrated that acquisition of written language affects the ability to distinguish left-right mirror images. In our study, the four- and six-year-old children were likely in the process of learning to read, mastering the ability to identify letters (which requires distinguishing between mirror-image forms such as b and d), and beginning to acquire word identification and sentence reading skills (which require the use of left-to-right ordering of letters within words, and words within sentences). Thus, the difficulty that leads to EVA errors–inconsistent assignment of polarity to the left and right ends of horizontal axes –may fall out as the children become more skilled with written language. Future research should systematically examine this exploratory hypothesis regarding children’s orientation representations.

We conclude by making note of two additional implications of our results for understanding the representation and processing of object orientation in adults and children. First, the high rates of object-axis reflection errors observed in the present experiments suggest that for children, as for adults, object-centered representations play a central role in representation of object orientation. As we have seen, object-axis reflections can be interpreted straightforwardly given the assumption that orientation representations map an object-centered frame of reference onto an extrinsic frame. How the object-axis reflections could be explained in the absence of this assumption is not at all clear.

More generally, the results of the present study support the fundamental assumption that object-orientation representations are compositional, consisting of multiple independent components that each represent a different aspect of an object’s orientation. This conclusion follows from the finding that the errors of both children and adults were systematic: Some error types were much more frequent than others, and the common error types could be attributed to failures affecting specific components of the posited representations.

Acknowledgments

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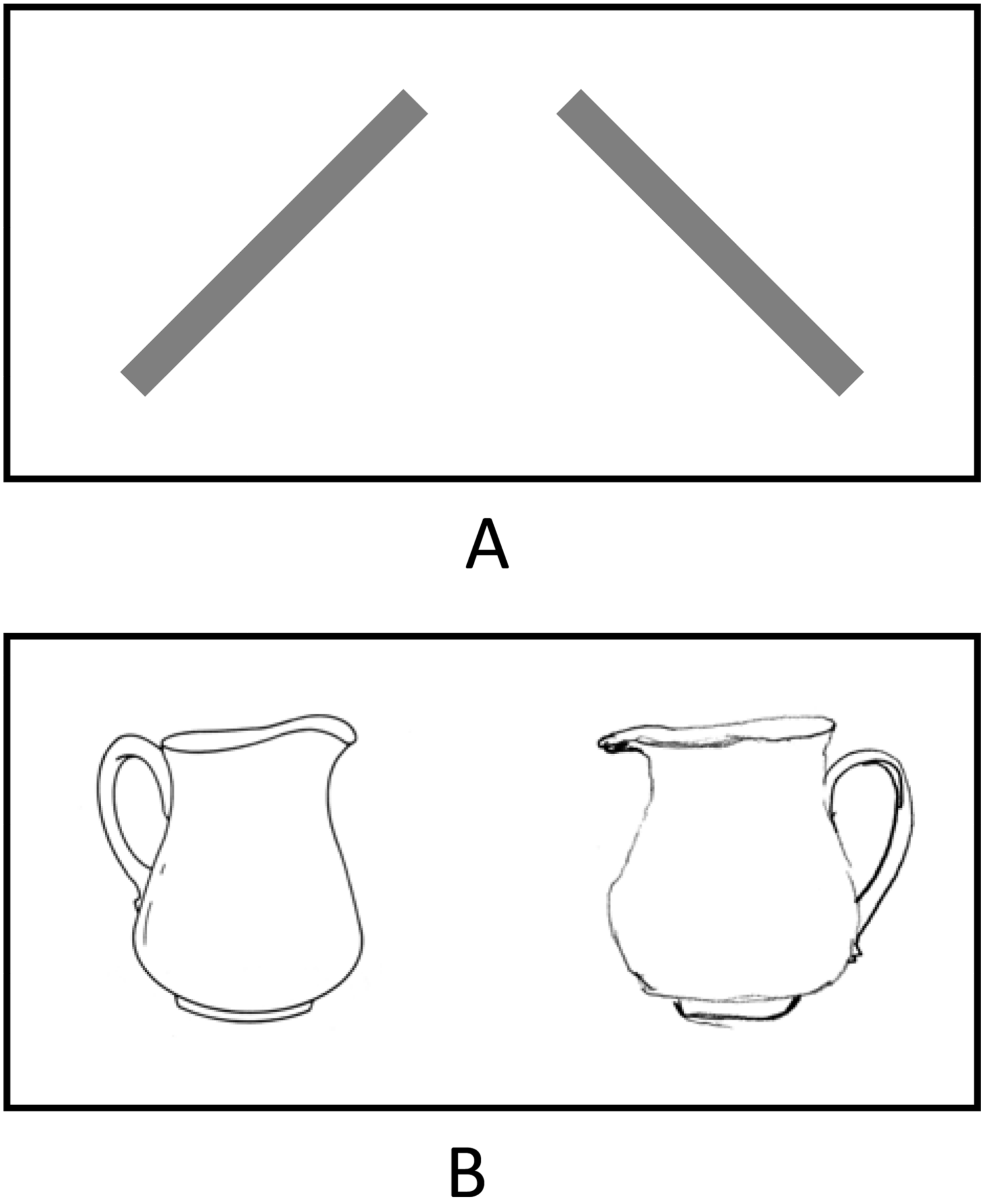


Figure 1.
Examples from prior studies of mirror-image confusion.

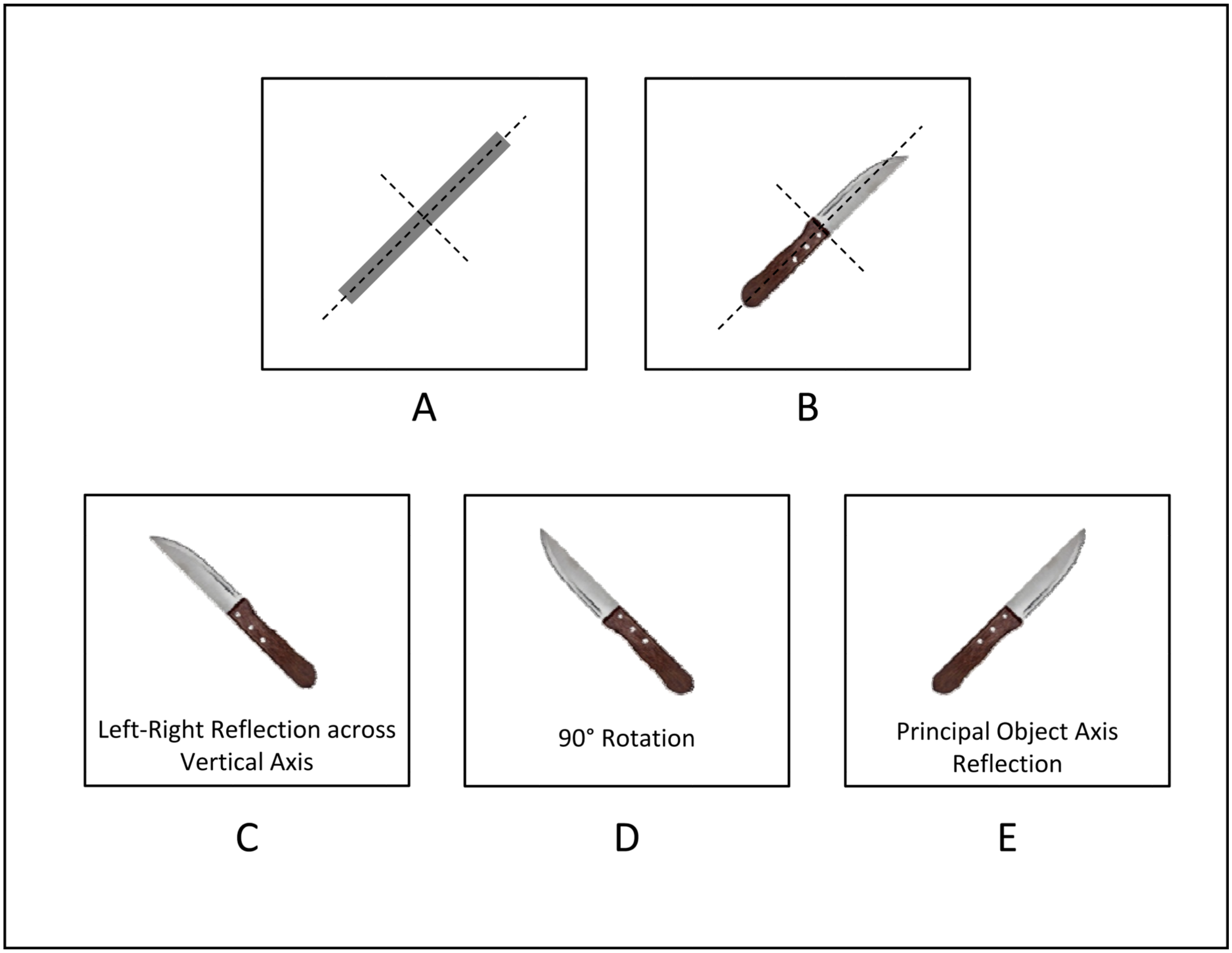


Figure 2.

A. An oblique bar stimulus, illustrating its symmetry across principal and secondary object axes. B. A stimulus that is asymmetric across both principal and secondary object axes. C. Left-right reflection (reflection across an extrinsic vertical axis) of the stimulus in (B) D. 90° counterclockwise picture-plane rotation of the stimulus in (B). E. Reflection of the stimulus in (B) across its principal axis.

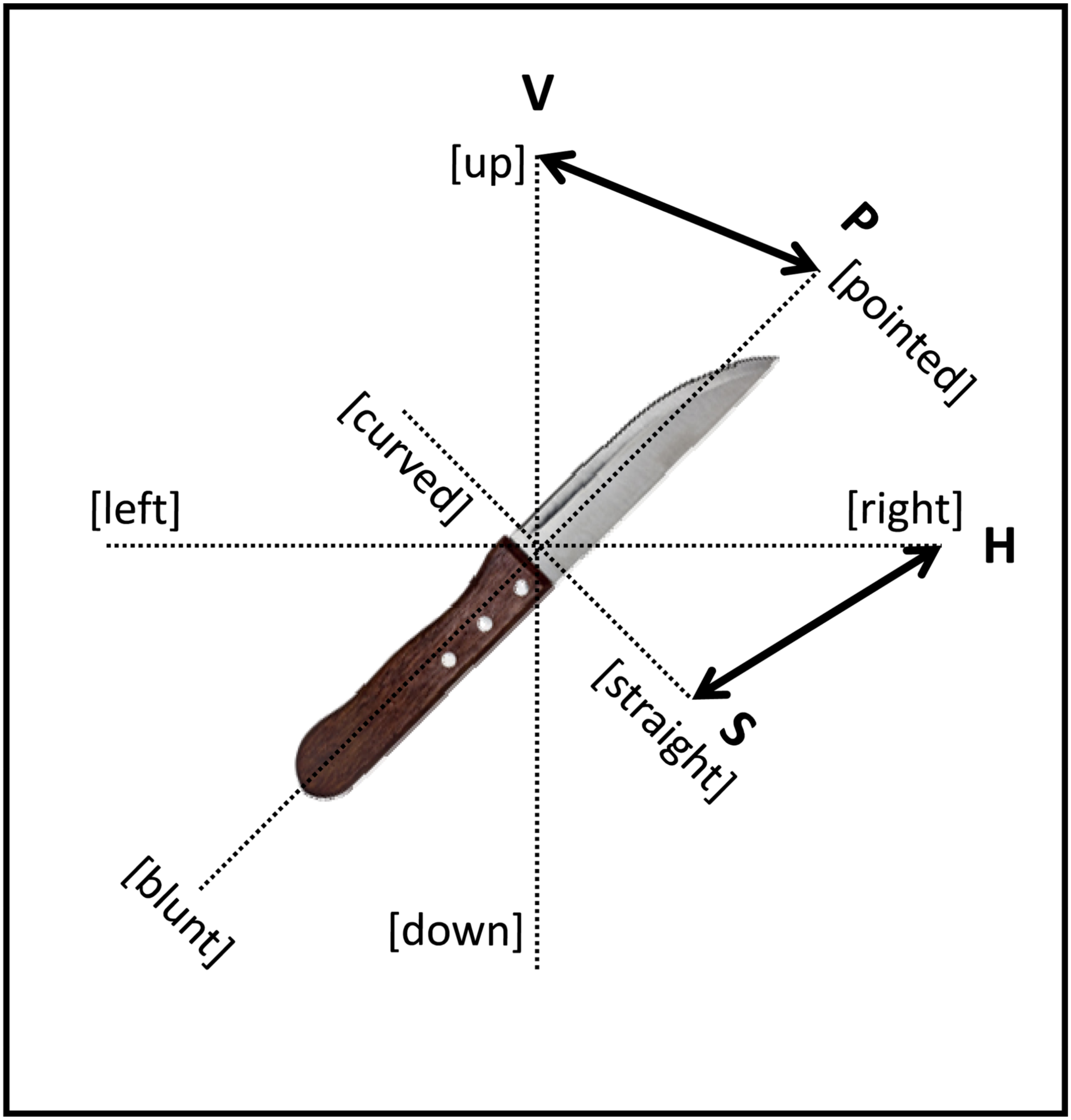


Figure 3.

Representing polarity correspondence between object and extrinsic axes. The [pointed] pole of the object's principal axis is mapped onto the [up] pole of the extrinsic vertical axis, and the [straight] pole of the object's secondary axis is mapped onto the [right] pole of the extrinsic horizontal axis. (V = extrinsic vertical axis; H = extrinsic horizontal axis; P = object principal axis; S = object secondary axis)

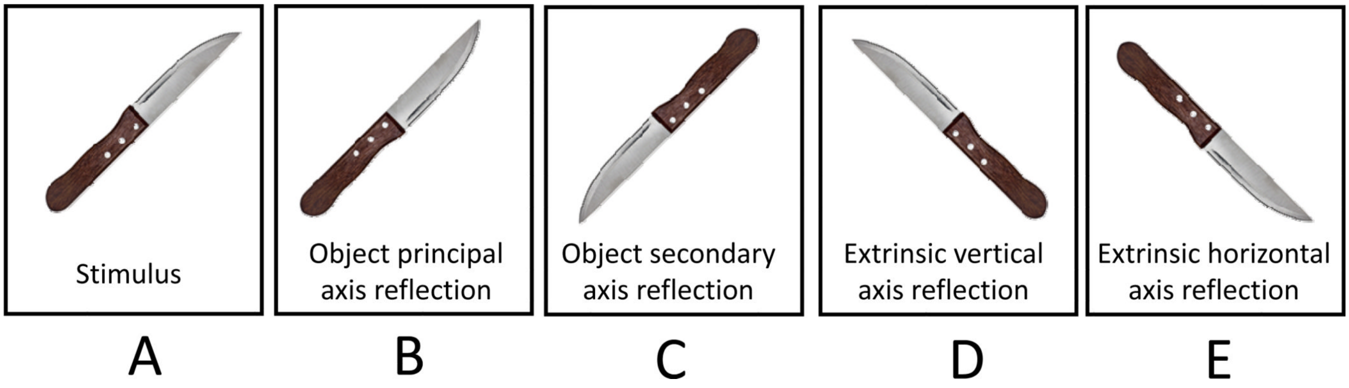


Figure 4.
Stimulus and possible reflection error types for oblique stimuli. A. Stimulus. B. Object principal axis reflection. C. Object secondary axis reflection. D. Extrinsic vertical axis reflection. E. Extrinsic horizontal axis reflection

Figure 5.

The 16 orientations at which stimuli were presented in Experiments 1, 2 and 3.

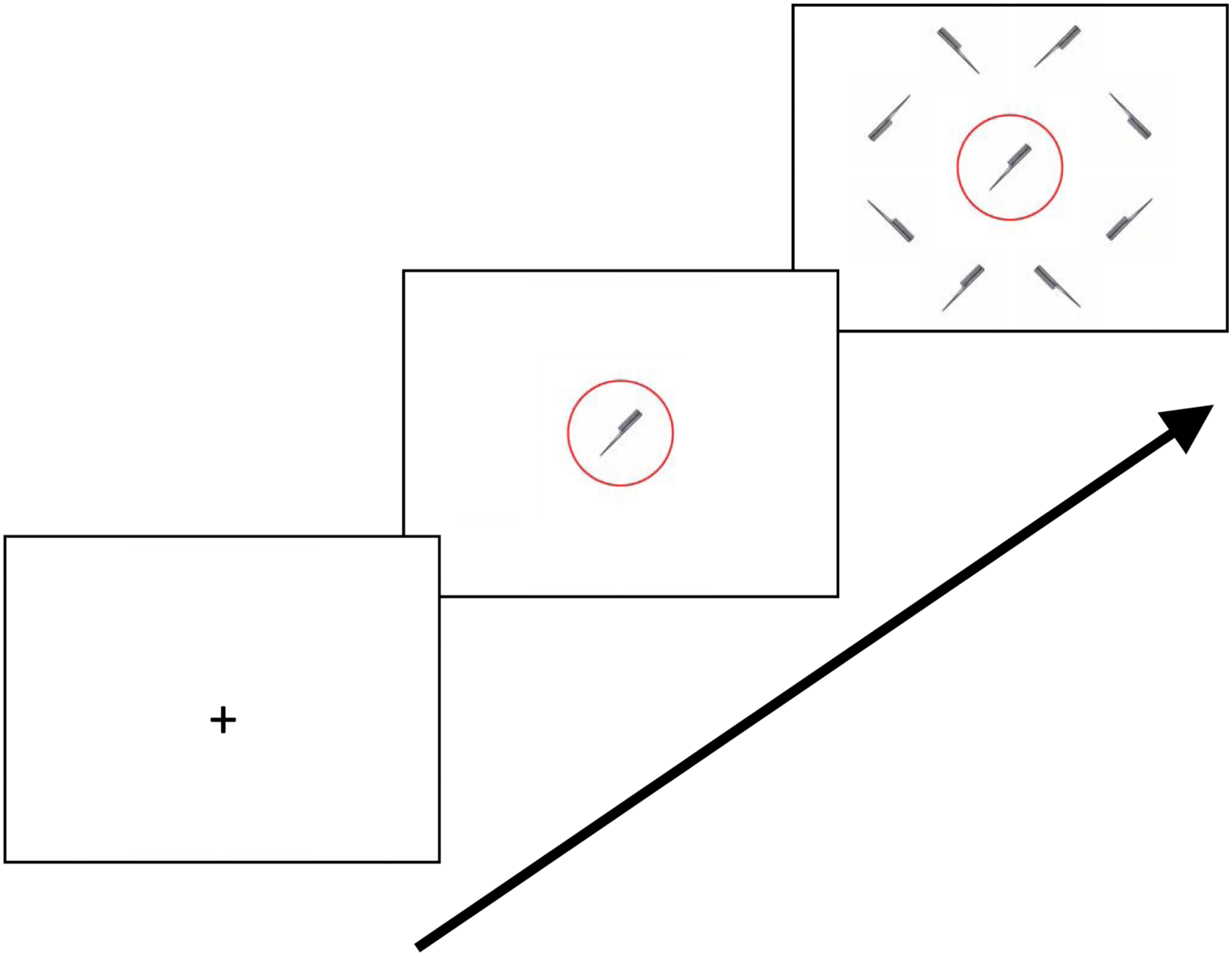


Figure 6.
Sequence of events on a trial in Experiment 1.

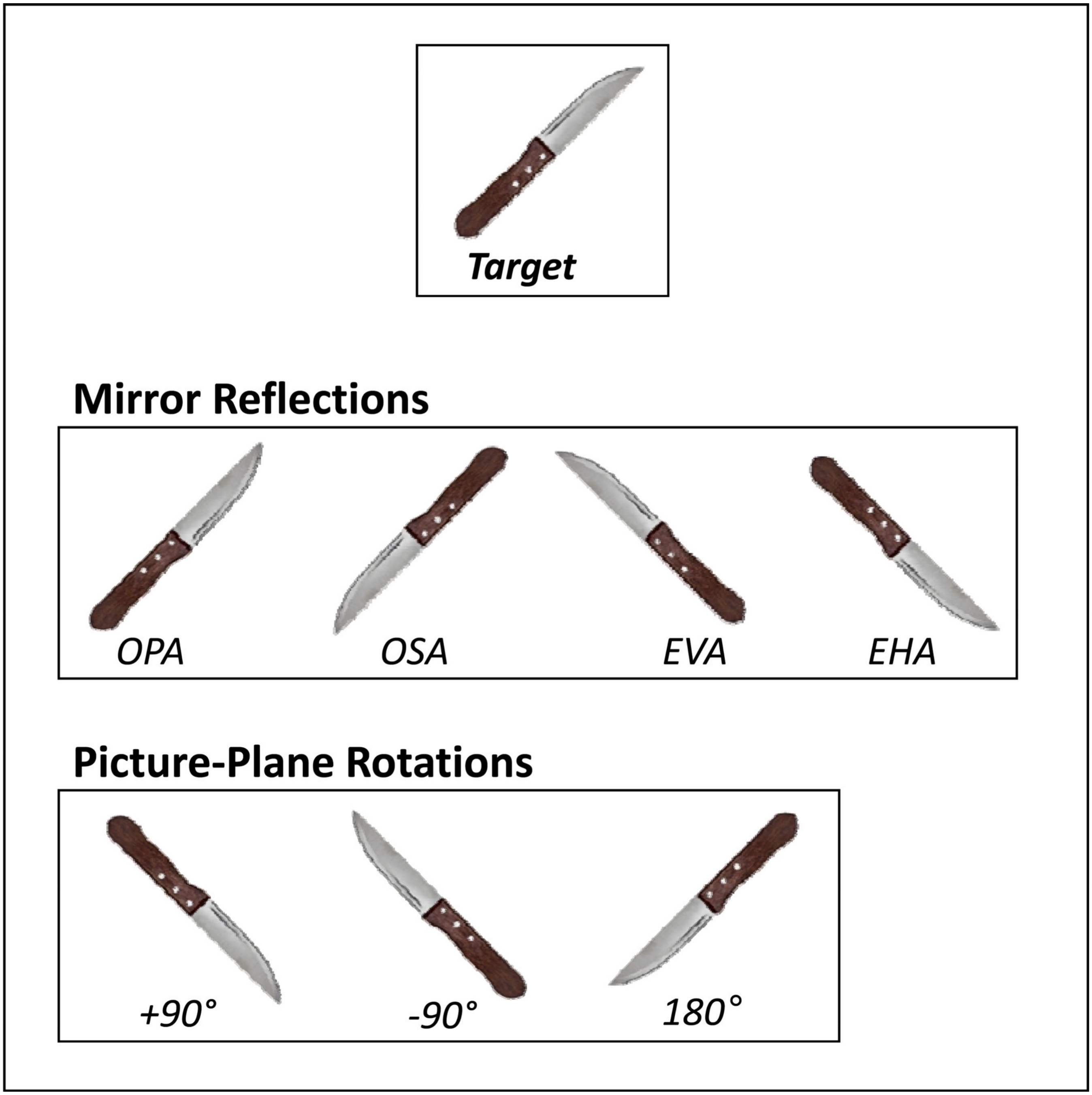
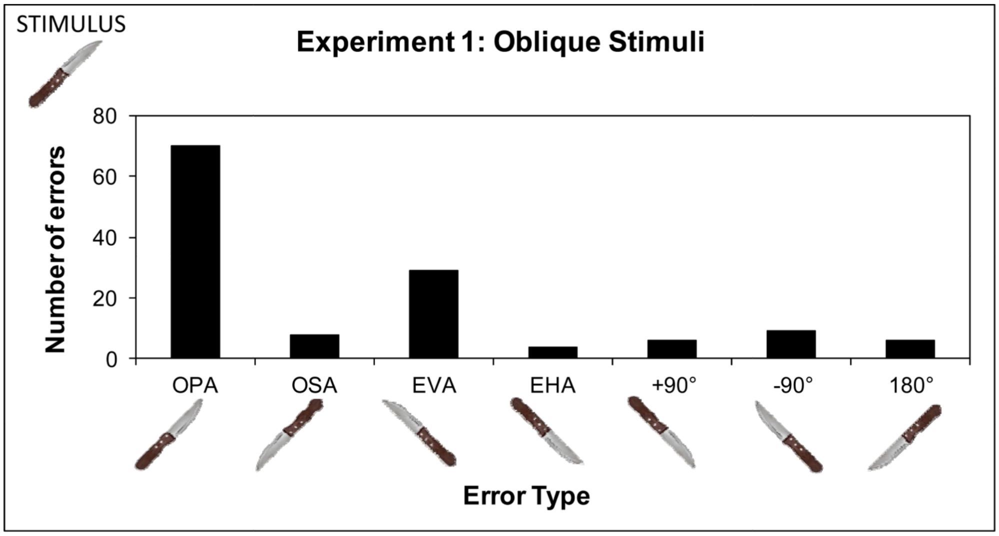
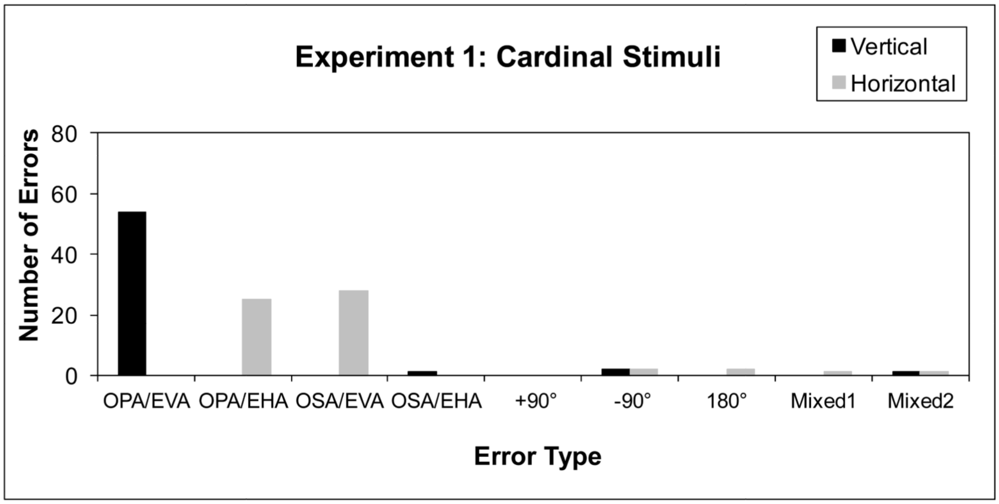


Figure 7.

Possible orientation error types for oblique stimuli, divided into two categories: mirror reflections and picture-plane rotations. For the picture-plane rotations, + indicates rotation in the clockwise direction, and − counterclockwise rotation. (OPA = object principal axis reflection; OSA = object secondary axis reflection; EVA = extrinsic vertical axis reflection; EHA = extrinsic horizontal axis reflection)



A



B

Figure 8.

A. Error distribution for oblique stimuli in Experiment 1. B. Error distribution for cardinal stimuli in Experiment 1.

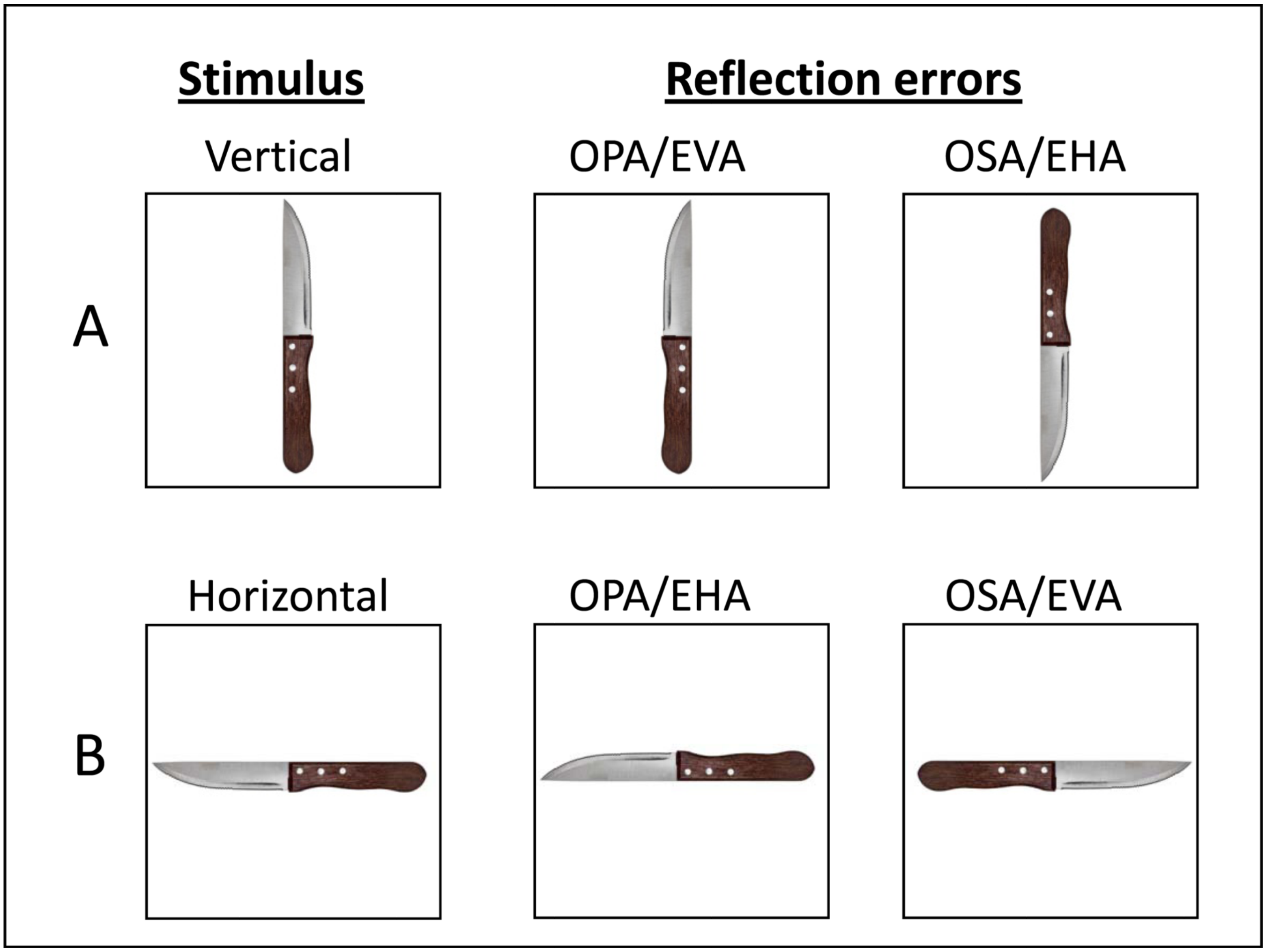


Figure 9.

Possible reflection error types for cardinal stimuli. A. Possible reflection errors for vertical stimuli. B. Possible reflection errors for horizontal stimuli.

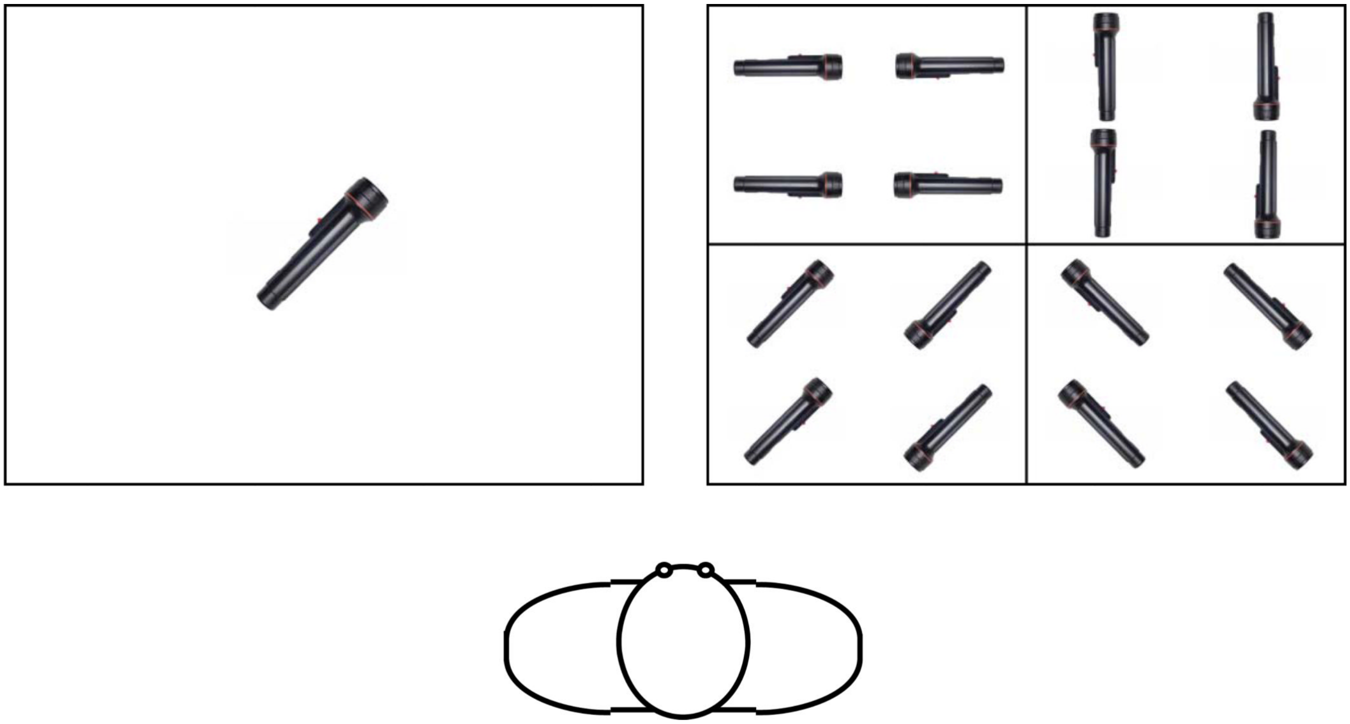


Figure 10.
Example of a trial in Experiment 3.

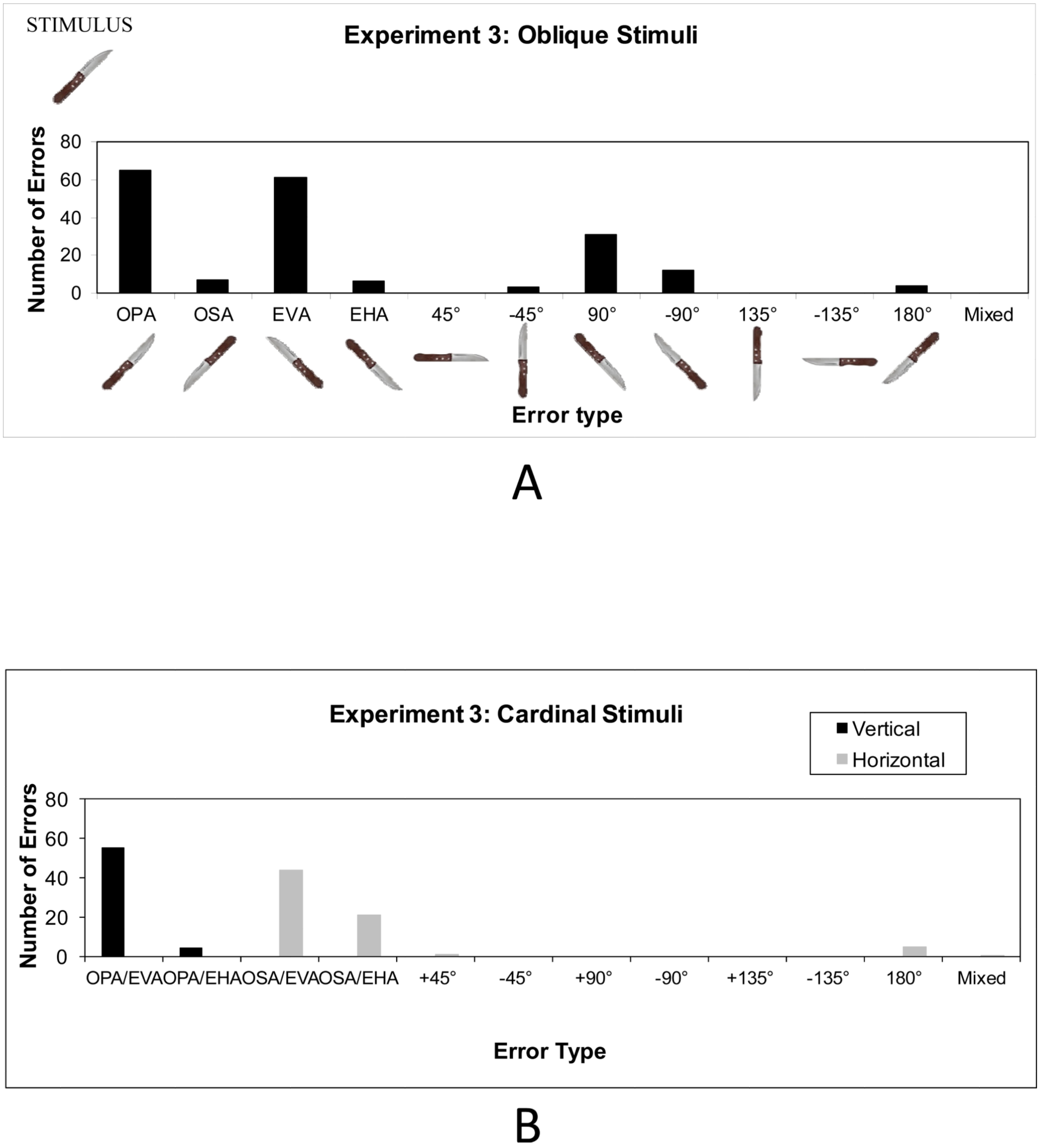


Figure 11.

A. Error distribution for oblique stimuli in Experiment 3. The value for mixed errors is the mean across the four individual forms of mixed error. B. Error distribution for cardinal stimuli in Experiment 3. The value for mixed errors is the mean across the six individual forms of mixed error.

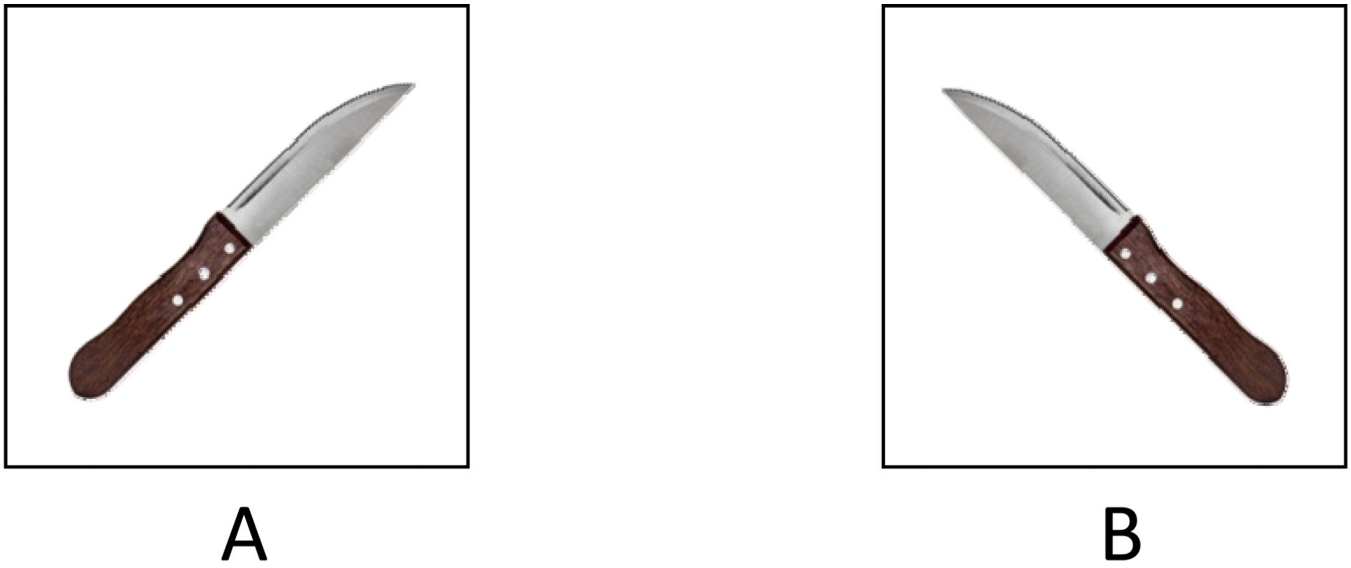


Figure 12.
A stimulus and its extrinsic vertical axis reflection.

Table 1

Error distributions for oblique stimuli in Experiment 2 for 4-year-olds, 6-year-olds and adults.

	Number of errors		
Error type	**Four-year-olds**	**Six-year-olds**	**Adults**
OPA	98	78	78
EVA	70	48	24
OSA	36	28	24
EHA	36	14	12
+90°	53	20	21
−90˚	29	23	20
180°	26	11	7

Table 2

Error distribution for cardinal stimuli in Experiment 2 for 4-year-olds, 6-year-olds and adults.

Error type	Number of errors					
	Four-year-olds		Six-year-olds		Adults	
	Vertical Stimuli	Horizontal Stimuli	Vertical Stimuli	Horizontal Stimuli	Vertical Stimuli	Horizontal Stimuli
OPA/EVA	83	--	59	--	31	--
OPA/EHA	--	34	--	33	--	38
OSA/EVA	--	64	--	42	--	16
OSA/EHA	11	--	9	--	7	--
+90°	6	4	7	2	4	7
−90˚	4	6	4	3	8	7
180°	7	14	4	4	5	5
Mixed	8	6	1	4	9	4

Note. The values for mixed errors are means across two individual forms of mixed error.