Theoretical Notes

Much ado about mirrors

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Takano (1998) has suggested four different kinds of reversal to explain why mirrors reverse left and right and not up and down or back and front. In fact, mirrors perform only one kind of reversal: They simply reverse about their own planes, and reflection about one plane is equivalent to reflection about any other, plus a translocation and rotation. The reflection of an object is termed its enantiomorph. Perception of the enantiomorphic relation normally requires an act, either physical or mental, of alignment. In deciding whether two objects are enantiomorphs, there is a tendency to align them so that the reversal is about the axis of least asymmetry. But in deciding whether a single object is one of two possible enantiomorphic forms, people generally rotate it to some canonical orientation. In the case of objects with defined top–bottom, back–front, and left–right axes, the canonical orientation is determined by the top–bottom and back–front axes, leaving the left–right axis to carry the reversal. The main reason for this, I suggest, is that the top–bottom and back–front axes have functional priority, and the left–right axis cannot be defined until top–bottom and back–front are established. This means that the latter two axes have priority in establishing the canonical orientation. The left–right axis is usually, but not always, the axis of least asymmetry.

As Alice long ago discovered, the world in the mirror is very like the real world, but there are some subtle changes. People who wear their watches on their left wrists are now seen wearing them on the right, writing is miraculously reversed, and American automobiles seem to have become anglicized, with their steering wheels on the wrong side. Although Lewis Carroll (1872) did not explicitly mention it, the obvious interpretation is that everything in the mirror world has been *left–right* reversed. There has been much discussion as to why mirrors should single out the left–right dimension, and not the up–down or back–front ones, for special treatment. In the most recent attack on this vexed problem, Takano (1998) has identified six past hypotheses as to why this might be so, suggested that none of them is adequate, and then proposed

that mirrors accomplish no fewer than four different kinds of reversal, which he calls Type I reversal, Type II reversal, Type III–I reversal, and Type III–II reversal.

Takano essentially argues that the nature of the mirror image relation can be understood differently depending on where the mirror is located and on what it is that is viewed in the mirror. In particular, he distinguishes between a mirror that is facing a person and a mirror that is beside the person, and between the person's perception of him/herself and the perception of printed words held up to the mirror—it is the combination of these four conditions that make up Takano's four cases. Thus, Type I reversal is the reversal that we see when we directly confront a mirror, Type II reversal is the reversal of alphanumeric characters held in front of a mirror, Type III–I reversal we see when we stand shoulder to the mirror, and Type III–II reversal is the reversal of script on a page held by the viewer standing alongside the mirror.

One objection to this approach is simply its lack of parsimony. If taken to the limit, it would imply a different account for every placement of the mirror, including a mirror that is directly above or underneath the viewer (which Takano does briefly consider), or indeed at any other angle. Further, Takano seems to restrict his analysis to a self-reflection in the mirror and to the reflection of print on a page held up by the viewer, thereby neglecting what mirror reflection does to the myriad of other objects that populate our lives. More importantly, I believe that he has failed to grasp that the relation between an object and its mirror image has a quality that is quite independent of where the mirror is placed. Indeed it is this relation that is very often seen as a left–right reversal regardless of the location of the mirror.

Before I elaborate this point, let us consider what mirrors actually do.

What Mirrors Actually Do

A mirror simply reflects about its own plane; or, to put it another way, it reverses the direction of the axes perpendicular to its surface. If you face a mirror it reverses back and front, so that your eyes in the mirror are looking back in the direction opposite to that in which your actual eyes are looking. If you stand on top of it, it reverses up and down. Only if you stand *beside* the mirror does it actually reverse left and right. Mirrors also translocate, so that the mirror image of an object is moved to a virtual location behind the mirror.

Every reflection is also equivalent to every other reflection, plus a rotation and translocation. Consider, for example, your mirror image as you stand in front of a mirror, facing it. That image is optically a back–front reflection of yourself, so let's call this mirror person B.F. Now

I am grateful to John T. Wixted, Reg Morris, Bill Ittelson, and an anonymous referee for helpful comments. Bill Ittelson continued to correspond with me, and was especially generous in helping me clarify several points, although we continue to disagree on a relatively minor issue. Correspondence should be addressed to M. C. Corballis, Department of Psychology, University of Auckland, Private Bag 92019, Auckland, New Zealand (e-mail: m.corballis@auckland.ac.nz).

consider your reflection as you stand beside a mirror; this image is optically a left–right reversal, so let’s call this image L.R. B.F. and L.R. are the same (virtual) person, except that they are moved and rotated into different positions—one is in front of you and facing you, the other is shoulder to shoulder, beside you. This means that we can *interpret* every reflection as a left–right reflection, provided we are willing to allow a rotation and translocation. Normally, rotations and translocations are taken for granted, since we are ourselves free to move around in space, as are most of the objects we see about us—and even if we are not free to move things physically, we can *mentally* move both ourselves and the objects around us. The fact that the face in front of us in the mirror has been turned around is something we do not normally even bother to remark on; what is more noticeable is that the mole that used to be on the left side is now on the right.¹

If we disregard the rotation and translocation caused by the mirror, we are left with the reflection, and this is the crux of the problem. The mirror reflection of an object is called its *enantiomorph*. Mirrors themselves are incidental to the problem of understanding the relation between an object and its enantiomorph, and enantiomorphs exist in plenty in the real world. For example, your shoes are at least approximate enantiomorphs, and regardless of how they are oriented with respect to one another we are apt to regard one as the *left–right* reflection of the other. So it goes for the relation between any pair of enantiomorphs in the real world, or that are created by mirror reflections, with the proviso that there is a defined left–right axis (on which more later).

The enantiomorphs of an object can also be created by turning it over in one dimension higher than the dimensionality of the object itself. For example, if you write a word on transparent paper and flip it over, the word is now reversed; thus a two-dimensional shape is “mirrored” by rotating it 180° through the third dimension. This has led to some confusion: Noting that a word is reversed when flipped over, Gregory (1998) argues that a similar flip explains why we appear to be left–right reversed when we view ourselves in the mirror. He writes “A mirror shows *ourselves* left–right reversed (reversed from how others see us without the mirror) because we have to turn around to face it” (p. 101). But unlike words, we are three-dimensional, not two-dimensional, and to create the mirror image of oneself one would need to turn around in the *fourth* dimension! Gregory seems persistently to confuse the enantiomorph with the real thing.² Your image in the mirror is not *you* turned around, it is your *enantiomorph*, turned around to face you. Simply appealing to the turning around will not do; to see the enantiomorph in the mirror as a left–right reversal, you have to compare it to yourself, with either you or the enantiomorph turned around so that both face the same way.

At this point it is useful to distinguish between two different reference systems—an *environment-centered* one and an *object-centered* one. In the environment-centered system, as we have just seen, every placement of the mir-

ror results in a different transformation. But in the object-centered system, every placement of the mirror produces the same result: The reflection, whatever its orientation in space, is your enantiomorph. Just as there is only one you, there is only one enantiomorph of you, and indeed every object has just one enantiomorph. In the case of objects with one or more axes of symmetry, an object and its enantiomorph are identical. In what follows, therefore, I focus on the enantiomorphic relations of asymmetric objects in object-centered space, rather than on mirror reflections in environment-centered space.

As Immanuel Kant (1783/1997) long ago observed, asymmetrical enantiomorphs invite the paradox that they appear to have the same shape; for every edge, corner, or surface on one, there is a corresponding edge, corner, or surface on the other.³ Yet they are not the same, since you cannot align them point for point by a rigid rotation and translocation. Your shoes *look* much the same, yet you cannot have one occupy the space that the other has previously occupied. The enantiomorphic relation has nothing specifically to do with mirrors or where they are placed. In describing the relation between enantiomorphs, we are usually (but not always) compelled to see one as the *left–right* reversal of the other, even though, from a geometric point of view, we can equally describe the reversal as being about any other plane.

The compulsion to see enantiomorphs as left–right reversals of each other is so strong that the reader may not find it easy to understand that reversal about any other plane will also do the trick. You are therefore invited to imagine a back–front reversal of yourself, with your nose, face, eyes, and so forth pushed through to the back of the head, and your back somehow oozed through to the front. You might then “feel” your watch as having remained on the left wrist (say), while back and front have reversed. However it is likely that you will also experience a strong compulsion to recalibrate your internal axes, and then feel the watch to be on the right wrist. In short, a back–front reversal is reinterpreted as a left–right reversal. If that demonstration does not work, here is another exercise that may help convince you: Imagine that the heel and toe of your left shoe are exchanged, while the top and bottom of the shoe, and its left and right sides, remain unchanged. This back–front reversal again produces the enantiomorph of your left shoe, which happens to be the same as your right shoe. Manufacturing processes that produced shoes as back–front mirror images or as top–bottom mirror images would serve the nation’s feet just as well as a process that produced left–right mirror images.

The real question, then, is not “Why do mirrors reverse right/left but not up/down?” as Block (1974) put it, but rather “Why are enantiomorphs generally perceived as left–right reversals and not as reversals along some other axis?”

The Role of Symmetry

One hypothesis, as Takano mentions, is that many objects, including people and animals, are more or less bilaterally symmetrical. Since the symmetry is usually

manifest along the left–right axis, it is easier to see the change as a left–right reversal than as a reversal of up and down or back and front (e.g., Corballis & Beale, 1976). In the case of your own enantiomorph, the left and right hands are both seen as *hands* and are themselves mirror images, so it is simpler to suppose that the watch is now on a right wrist instead of a left wrist than to suppose, say, that it is back and front that have been reversed. But even if you can succeed in the exercise of imagining a back–front reversal of yourself, you will no doubt find it easier to feel the reversal to be a left–right one. One obvious explanation for this is that the symmetry of the body means that left–right reversal is easier to understand or envisage.

There is good empirical evidence that this symmetry, or near symmetry, is indeed an important factor in determining how we perceive enantiomorphs, although I shall argue below that it does not cover all cases. Ittelson, Mowafy, and Magid (1991) had people adjust enantiomorphs in ways that would reveal their perceived relation to the originals. The objects included rectangular blocks with differently colored sides, unfamiliar three-dimensional shapes, and familiar shapes including books, letterhead stationary, and stamped envelopes, and the general conclusion was that “an object appears to differ from its enantiomorph by an apparent reversal along the axis of least perceived asymmetry” (p. 567).

This conclusion was not entirely unequivocal, however. Some of the objects presented by Ittelson et al. (1991) were arbitrary shapes without canonical axes; that is, they had no clearly defined top and bottom, back and front, or left and right. Clearly, such objects could not be seen as left–right reversed. In these cases, the subjects did indeed tend to align enantiomorphic pairs in such a way that the relation was seen as a reflection about the axis of least asymmetry. But when the subjects were not given the opportunity to manipulate the objects physically, the perceived relation depended on how the objects were presented. For example, if an object and its enantiomorph were positioned as though reflected along some axis, and if the subjects were not free to realign them, they saw the objects as reflected along the axis that they were in fact reflected along, even if this axis was not the axis of least asymmetry. Further, in the case of objects with conventionally defined top–bottom, back–front, and left–right axes, such as books, letterhead stationary, or stamped envelopes, there was a marked tendency to see the enantiomorphs as left–right reversed, even if the left–right axis was not the axis of least asymmetry. Ittelson et al. suggested that such exceptions might still be subsumed under the principle of least *perceived* asymmetry if it may be supposed that the axis of least perceived asymmetry is not necessarily the axis of least *actual* asymmetry, but can be influenced by canonical axes and social usage.

Navon (1987, p. 281) objects to the symmetry argument on the grounds that the enantiomorph of a “congenitally asymmetrical cripple” would still be recognized as left–right reversed. This might be so, for example, if

the cripple had lost an arm and a leg, and was at least arguably more asymmetrical with respect to left and right than with respect to back and front. It seems likely that the perceived reversal would again be influenced by canonical axes and be seen as a left–right reversal, regardless of relative asymmetry along different axes.

Takano (1998) argues against the symmetry hypothesis on the grounds that alphanumeric characters that are symmetrical about a horizontal axis, such as the letter C, are seen as left–right reversed rather than top–bottom reversed if viewed in a mirror. However, this is not really a fair example, precisely because a shape that is symmetrical about the horizontal is exactly the same as its enantiomorph. That is, the enantiomorphic relation is one of identity, and there is no reversal, at least with respect to object-centered coordinates. A better example might be a mirror-reversed R, which is seen as “backward,” or left–right reversed, even though it is grossly asymmetrical—and is indeed more symmetrical with respect to top and bottom than with respect to left and right. Here is a case, then, in which the axis of apparent reversal is *not* that of the least asymmetry. Although it might conceivably be argued that the letter R is *perceived* as less asymmetrical about the vertical than about the horizontal (even though it is not objectively so), it is perhaps more likely that the principle of least perceived symmetry is overruled by the tendency to see enantiomorphs as *left–right* reversed. This can only occur, of course, if the shape has identified left and right sides. The enantiomorphs of other asymmetrical characters, such as the letters G, J, or L, or the digits 2, 4, or 5, are also seen as left–right reversed, and I suspect that this has little to do with relative asymmetry about different axes.

The Role of Rotation

Although an asymmetrical object and its enantiomorph are different shapes, as Kant pointed out, they are often very difficult to tell apart.⁴ If you see a shoe lying on the floor, you will almost certainly recognize it as a shoe before you can discern whether it is a left or right shoe. Similarly, if an alphanumeric character, such as the letter R, is rotated away from the upright, observers can tell quickly what its identity is, but cannot immediately tell whether it is a normal or a backward R. In order to do so they typically rotate it, physically or mentally, to the upright (Cooper & Shepard, 1973). This suggests that discrimination of enantiomorphs depends critically on how they are aligned, and appropriate alignment often depends on an act of rotation.

When we can see both an object and its enantiomorphic reflection in a mirror, the mirror in fact aligns the two with respect to the axes of the mirror itself, but reverses them along the axis perpendicular to the mirror. In such cases, the relation is usually easy to perceive as a reflection along the axis perpendicular to the mirror. But when enantiomorphs are not systematically aligned, or only one of them is visible, then some kind of alignment process is necessary before the enantiomorphic relation

becomes apparent. For example, when you see yourself in a mirror, you do not see both your actual self and the reflection; all you see is your enantiomorph. In this case, the act of alignment might be either to mentally turn the enantiomorph around so that it faces the same way that you do, or to imagine one's own body turned around and moved to a frontal position, so that you can then compare your own body to the enantiomorph. These acts of alignment show the reversal to be a left-right one. It is this act of alignment that Takano (1998) considers in his Type I reversal.

This is but one example. Alignment, whether of one's own body as viewed in a mirror or of a shoe left casually on the floor, is a general problem in the perception of the enantiomorphic relation, and it is commonly accomplished mentally rather than physically. It is no coincidence that nearly all experimental studies of mental rotation have involved the discrimination of enantiomorphs. In the classic study by Shepard and Metzler (1971), the stimuli were pairs of drawings of three-dimensional objects, and the subjects were asked to decide whether they were the same or different. When different, the shapes were in fact enantiomorphs of each other. The time that it took the subjects to make "same" judgments varied linearly with the angular difference between the shapes, implying that the subjects mentally rotated them into alignment before making the judgment. Since Shepard and Metzler presented data only for the pairs that were the same, it is not clear from this experiment how people align shapes that are enantiomorphs, but the study by Ittelson et al. (1991) shows that, at least in the case of objects without canonical axes (top-bottom, back-front, left-right), the objects are typically aligned so that the reflection is about the axes of least asymmetry.

A more common mental rotation paradigm has been to present shapes singly in different angular orientations and ask subjects to decide whether each shape represents some standard form or not. The enantiomorphic discriminations involved in these studies have included normal versus backward alphanumeric characters, enantiomorphic polygons, pictures of the left versus right hands, pictures of human bodies in opposite poses, and pictures of left- or right-facing common objects (see Corballis, 1988, 1997, for reviews). These studies therefore provide further evidence of the importance of prior alignment in the discrimination of enantiomorphs. In most cases, the judgment is effectively converted to a judgment of asymmetry about the *left-right* axis. That is, a backward R is rotated to the upright so that it is then perceived as a left-right reversal of a normal R; a picture of a right hand is rotated so that the fingers are upward, and it is then perceived as the left-right reversal of a left hand; and so on. These studies therefore seem to confirm a preference to see enantiomorphs as left-right reversals of one another, and the left-right principle often overrides the principle of least asymmetry.

There is at least one case, however, in which rotation is carried out to accomplish a top-bottom reversal of enan-

tiomorphic pairs. Corballis and McLaren (1984) presented the lowercase letters *b*, *d*, *p*, and *q* in varying orientations. These four letters (in appropriate typescript) actually reduce to just two enantiomorphs—one may be regarded as either a *b* or a *q*, the other as either a *d* or a *p*. When asked to decide whether each letter was a *b* or a *d* (or, in another condition, a *p* or a *q*), the subjects mentally rotated them to the upright, so that the alternative forms were left-right mirror images. When asked to decide whether each was a *b* or a *p* (or, in another condition, a *d* or a *q*), the subjects again mentally rotated them to the upright, but in this case the alternative forms were *top-bottom* mirror images. Presumably because of their canonical orientations, people see the enantiomorphs *b* and *p*, *when labeled as such*, as top-bottom mirror images, not as left-right ones.

When canonical axes are defined, therefore, they may override any considerations of symmetry. Given any asymmetrical object, such as an alphanumeric character, a shoe, or an automobile (American or English), we rotate it to some canonical orientation before deciding which of two enantiomorphic forms it is. In the case of letters, for example, we rotate to the upright orientation, so that the only remaining difference between a normal and a backward letter is its direction along the left-right axis. With a shoe, we would rotate the shoe to its upright, face it forward (as though we are about to put it on), and then judge which shoe it is in terms of its left-right axis. But while this account may suggest that it is the canonical orientation that is important, and not the left-right axis *per se*, there is still a sense in which the left-right axis is the important one, and the one that generally carries the burden of the reflection.

Consider, for example, how we are to define the "normal" or canonical orientation of the letter R. One might say that the normal orientation of the letter R is such that the closed loop is at the top and the open loop at the bottom, and rotating to achieve this condition would indeed result in normal and backward Rs appearing as left-right mirror images. However, one might equally say that the normal orientation of the R is such that the straight portion is to the left and the rounded portion to the right. Rotating to achieve this condition would result in the normal and backward Rs being seen as *top-bottom* mirror images. We generally prefer to normalize with respect to the top-bottom and back-front axes, leaving the left-right axis to carry the reversal. What, then, is distinctive about the left-right axis?

The Nature of Left and Right

The identification of the canonical axes is more than just a matter of "social convention," as some authors have implied (e.g., Gardner, 1964). In most cases the left-right dimension axis of an object can only be identified once the top-bottom and back-front axes have been determined.⁵ The top-bottom and back-front axes are normally defined functionally, which generally leads in turn to structural differences. The top-bottom axis is

basically defined by gravity, which generally gives rise to strong structural asymmetries between top and bottom. Feet, for example, work best if they are in contact with the ground, while eyes are better placed high on the body surface, so as to maximize distance vision. It should be noted, though, that the top–bottom axis is not *necessarily* marked by asymmetry; for example, several letters of the alphabet (C, D, E, H, etc.) are symmetrical (or more or less so, depending on the typescript), so that asymmetry is not a *defining* characteristic of the top–bottom axis. Once the top–bottom axis is defined, the front–back axis is defined by motion, which again generally leads to structural asymmetries. Eyes are oriented toward the front rather than the back, feet point in the direction of motion rather than away from it, and knees bend in such a way as to facilitate forward rather than backward motion. Again, it is these functional properties rather than asymmetry *per se* that essentially defines the front–back axis. In some cases, the reference to front and back might be only indirectly related to motion, as in the front and back of a house. The reference to motion is essentially one of access to the house, rather than motion of the house itself. Again, the “front” of a page is the surface we can see, and so it is defined in terms of visual access.

In general, there are few such pressures to distinguish between left and right, either functionally or structurally, which is why most organisms and other objects that move, such as airplanes and automobiles and wheelbarrows, are largely symmetrical with respect to left and right. They *need* not be, of course, since there may be other considerations that dictate an asymmetry, although not necessarily a consistent one. An organism may function more efficiently if the two sides of the brain are specialized for somewhat different functions, or if its two claws are differently shaped, or if its internal organs are packaged asymmetrically—just as one might pack a suitcase in asymmetrical fashion simply to get all the stuff in.

There are some cases in which the left–right axis does have a consistent polarity. For example, the fundamental laws of physics have a consistent left–right bias, captured in the principle of the nonconservation of parity, but this asymmetry is subtle and was not in fact documented until the 1950s (Lee & Yang, 1956). A more obvious example is script, which in English (and many other scripts) proceeds from left to right, and requires symbols to be correctly oriented with respect to left and right. Even so, the left–right direction of script cannot be determined until back and front and top and bottom have been decided; the back–front axis is established by the decision as to which side of the paper you are going to write on, and the top–bottom axis by deciding which way up to form the script. There is still something of a tendency, probably innate, to treat left and right as arbitrary, since young children often have difficulty learning which way round script goes (see Corballis & Beale, 1976, for a review). This tendency may well derive from evolutionary pressures; to a freely moving animal, the left–right profiles of objects in the real world are often arbitrary, and are reversed by the simple expedient of viewing them

from the other side. The lability of the left–right dimension may therefore be partly a consequence of evolution in a world in which parity for the most part *is* conserved, notwithstanding the subtle asymmetries at the level of subatomic particles; that is, we have a built-in tendency to generalize objects to their left–right mirror images (see also Corballis, 1988). This innate disposition is also a consequence of the arbitrariness of the left–right dimension in the natural world, and it may augment our readiness to see enantiomorphs as left–right reversals rather than reversals of top and bottom or back and front.

I suggest, then, that the canonical orientation is usually defined in terms of top–bottom and back–front because these axes have logical priority over the left–right axis. Top–bottom and back–front have functional significance, and they are typically indicated by specific features within the object. These axes therefore serve as the basis for aligning an object, leaving the left–right axis to determine which of two enantiomorphic forms the object represents. When we see ourselves in the mirror, whether we stand in front of the mirror, beside it, or on top of it, we see the reflection as a left–right reversal because we normalize the reflection by envisaging it upright and facing the same way. It is then that we see that the mirror reflection is a left–right reversal—with the watch on the wrong wrist, the hair parted on the wrong side, and so on.

By aligning objects in this way, we generally do conform to the principle of Ittelson et al. (1991) that the objects are perceived as reflected about the axis of least asymmetry. I suggest, however, that in the case of objects with canonical axes, the driving principle is not the principle of least asymmetry, but rather the principle that top–bottom and back–front axes have priority over the left–right axis in establishing a canonical orientation. According to this interpretation, the fact that we align in this way is not a consequence of bilateral symmetry *per se*; rather, bilateral symmetry is itself a common consequence of the arbitrariness of the left–right axis. The priority of canonical axes over any symmetry principle is illustrated, I suggest, by the fact that we tend to see a reflected alphanumeric character as *left–right* reversed regardless of its angular orientation and regardless of relative asymmetry about the different axes. Critical three-dimensional examples are hard to find, since most three-dimensional objects with established canonical axes happen to be less asymmetrical about the left–right axes than about the other two axes. One possible example is an outrigger canoe, and I suspect that its enantiomorph would be seen as left–right reversed even though the axis of least asymmetry is the back–front axis. It remains possible, as Ittelson et al. (1991) suggest, that the left–right axis is nevertheless *perceived* as the axis of least asymmetry, but for this claim to be noncircular would require some measure of perceived asymmetry that is independent of the way that we perceive enantiomorphs.

Finally, a thought experiment: Imagine an object that comprises three rods at right angles to one another, connected at their midpoints. One is red, one is green, and

one is blue. Each has a small square attached to one end and a small circle attached to the other. The enantiomorph could be seen in terms of the reversal of any one of the rods, and there would be no meaningful sense in which it would be a *left-right* reversal. The very concepts of left and right require the prior establishment of the two other dimensions, and we can only describe the enantiomorph as a left-right reversal when this condition is met. But now suppose our colored rod device happened to be generally oriented with the red rod upright and the square attached to the ground. This would define a top-bottom axis. Suppose further that it always moved in the direction of the green rod, toward the square end. This would define a front-back axis. You might then be inclined to interpret the blue rod as defining the left-right axis, and the enantiomorph as left-right reversed. Symmetry, I suggest, need have nothing to do with it.

Summary And Conclusions

In summary, Takano's analysis fails to capture parsimoniously how we see the relations between objects and their mirror images. I suggest instead that the following more general principles may suffice to explain what mirrors do, and how we see the relations between real objects and their enantiomorphs:

1. A mirror does not in general reverse left and right. In environmental coordinates, it reverses about its own plane, along an axis perpendicular to that plane. This axis may or may not coincide with the left-right axis of the object that is reflected. Any reversal is equivalent to any other, plus a rotation and translocation. Provided the object has defined top-bottom, back-front, and left-right axes, we can always *interpret* its mirror reflection as a reversal along any one of these axes, although there is a strong tendency to see it as a left-right reversal.

2. With respect to object-centered coordinates, mirrors create *enantiomorphs* of the objects they reflect. Each object has only one enantiomorph—for every Tweedledee, there is only one Tweedledum. The looking-glass world visited by Alice was populated entirely by the enantiomorphs of objects in the real world.

3. We normally perceive the mirror-image relation between enantiomorphic pairs only when they are aligned in some way. Mirrors, for example, align them with respect to the two axes that define the plane of the mirror, but reflect them along the axis that is perpendicular to the mirror. If you can only see the object in the mirror (as when you see yourself in the mirror, but can't see your true self), then some act of alignment, either physical or mental, is necessary. Similarly, if you compare two visible enantiomorphs that are not aligned, you must align them in order to see the enantiomorphic relation. There is a marked tendency to align them in such a way that they are reflected about the axis of least asymmetry.

4. When an object has defined canonical axes, there is also a strong tendency to rotate it to a canonical orientation defined by its top-bottom and back-front axes, so that the difference between the object and its enantio-

morph is then seen as a left-right reversal. This may correspond to a reversal about the axis of least asymmetry, since many objects are approximately bilaterally symmetrical, in which case the axis of least asymmetry is in fact the left-right axis. There is at least some evidence to suggest that rotation to a canonical orientation, so that the reversal is generally seen as a left-right one, takes precedence over the principle of least asymmetry.

5. The left-right axis is special because it depends on the prior establishment of the top-bottom and back-front axes. This gives the top-bottom and back-front axes precedence in establishing the canonical orientation of an object, leaving the left-right axis to carry the burden of the reversal.

REFERENCES

- BLOCK, N. J. (1974). Why do mirrors reverse right/left but not up/down? *Journal of Philosophy*, **71**, 259-277.
- CARROLL, L. (1872). *Through the looking glass, and what Alice found there*. London: Macmillan.
- COOPER, L. A., & SHEPARD, R. N. (1973). Chronometric studies of the rotation of mental images. In W. G. Chase (Eds.), *Visual information processing* (pp. 75-176). New York: Academic Press.
- CORBALLIS, M. C. (1988). Recognition of disoriented shapes. *Psychological Review*, **95**, 115-123.
- CORBALLIS, M. C. (1997). Mental rotation and the right hemisphere. *Brain & Language*, **57**, 100-121.
- CORBALLIS, M. C., & BEALE, I. L. (1970). Bilateral symmetry and behavior. *Psychological Review*, **77**, 451-464.
- CORBALLIS, M. C., & BEALE, I. L. (1976). *The psychology of left and right*. Hillsdale, NJ: Erlbaum.
- CORBALLIS, M. C., & McLAREN, R. (1984). Winding one's *ps* and *qs*: Mental rotation and mirror-image discrimination. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 318-327.
- GARDNER, M. (1964). *The ambidextrous universe*. New York: Basic Books.
- GREGORY, R. (1998). *Mirrors in mind*. Harmondsworth, U.K.: Penguin.
- HERTZ, R. (1960). *Death and the right hand*. Aberdeen: Cohen & West.
- ITTELSON, W. H., MOWAFY, L., & MAGID, D. (1991). The perception of mirror-reflected objects. *Perception*, **20**, 567-584.
- KANT, I. (1997). *Prolegomena to any future metaphysics that will be able to come forward as science* (G. Hatfield, Trans.). Cambridge: Cambridge University Press. (Original work published c. 1783)
- LEE, T. D., & YANG, C. D. (1956). Questions of parity conservation in weak interactions. *Physical Review*, **104**, 254-258.
- NAVON, D. (1987). Why do we blame the mirror for reversing left and right? *Cognition*, **27**, 275-283.
- SHEPARD, R. N., & METZLER, J. (1971). Mental rotation of three-dimensional objects. *Science*, **171**, 701-703.
- TAKANO, Y. (1998). Why does a mirror image look left-right reversed? A hypothesis of multiple processes. *Psychonomic Bulletin & Review*, **5**, 37-55.

NOTES

1. Actually, this may be slightly misleading, since our internal images of our own faces are largely formed by mirror reflections, especially among the more vain of our species. We are apt to be surprised, not by our mirror images, but by true representations, as in photographs or videos. So it is our acquaintances, rather than ourselves, who appear most strongly to be left-right reversed in the mirror.

2. Takano (1998) also notes Gregory's confusion, and his Type I reversal gives a more adequate account.

3. The anthropologist Robert Hertz (1960, p. 92) once remarked, "What resemblance more perfect than that between the two hands! And yet what a striking difference there is!" He was not referring only to the

Kantian paradox, but also to the fact that most of us are much more proficient (dexterous) with one hand, usually the right, than with the other. The obsessive interest in handedness in all human cultures, ancient and modern, and more recently in cerebral asymmetry, no doubt owes something to the fact that our brains and bodies look symmetrical, yet function in strikingly asymmetrical ways.

4. A perfectly symmetrical organism would in fact be unable to tell them apart at all, but this is another story (Corballis & Beale, 1970, 1976).

5. Bill Ittelson (personal communication, January 1999) has suggested that a book is an exception. If we ignore the print, it might be

said that the first axis to be defined is the left–right one, since the binding effectively defines the left of the book (to a reader expecting English script, say, and not Japanese). However, one might equally argue that binding comes last, and that the axes are already defined by the text; the decision to start the text on a given page (or to print the title on a cover) defines the front, and the direction of text then defines the top–bottom and left–right axes.

(Manuscript received July 13, 1998;
revision accepted for publication February 17, 1999.)