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Relationship between frames of reference and mirror-image reversals

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Abstract. The mirror puzzle related to the perception of mirror images as left – right reversed can be more fully understood by considering an extended problem that includes also the perception of mirror images that are not left – right reversed. The purpose of the present study is to clarify the physical aspect of this extended problem logically and parsimoniously. Separate use of the intrinsic frame of reference that belongs to the object and one that belongs to its mirror image always leads to the perception of left – right reversal when the object has left – right asymmetry; on the other hand, the perception of left – right nonreversal is always due to the application of a common frame of reference to the object and its mirror image.

1 Introduction

Many authors have attempted to solve the mirror puzzle: "Why does the mirror reverse left and right, but not up and down?" (eg see the review by Gregory 1997), and the final solution seems to have been provided by Corballis (2000), Tabata and Okuda (2000), and McManus (2002) so long as the puzzle is restricted to the above question. However, one does not always perceive the mirror image as left – right reversed; sometimes it is perceived as reversed in the front – back or top – bottom direction, or as reversed in no direction at all (these latter three cases are called here left – right nonreversal). To understand the perception of mirror images completely, it is important to consider the extended mirror problem that includes both left – right reversal and nonreversal.

Psychological processes are involved in the perception of mirror images, but factors not related to these processes should be separated in analysing the extended mirror problem. In fact, Tabata and Okuda (2000) argued that the solution to the original mirror puzzle can be given essentially without recourse to psychology. In the present paper we give an explanation for the nonpsychological or physical aspect of the extended mirror problem to provide a basis for better understanding of the perception of mirror images.

2 Physical aspect of mirror reflection

The mechanism of mirror reflection is explained by geometrical optics as follows: A mirror reverses the axis perpendicular to the mirror plane, ie a mirror produces a plane-symmetric image of an object with respect to the mirror (eg Southall 1933/1964). In other words, an object and its mirror image are enantiomorphic to each other (eg Gardner 1964, 1990). An *enantiomorph* is defined as the object produced by reversing an asymmetric object along one or all three orthogonal axes. Left and right hands are typical examples of enantiomorphs.

We can treat the physical aspect of the extended mirror problem by considering the two types of frame of reference: the intrinsic frame of reference (IFR) and the common frame of reference (CFR). There is an IFR that belongs to the object and one that belongs to its mirror image, and each IFR is applied to the object and its mirror image separately (hereafter we call this simply "the application of the IFR"). The CFR is applied simultaneously to the object and its mirror image. Ittelson et al (1991), Corballis (2000), Tabata and Okuda (2000), and McManus (2002) referred in various ways to this IFR – CFR dichotomy. Ittelson et al (1991) pointed out that the study of mirror perception must take into account the two different sets of axes—the physical system fixed with respect to the stable features of the world and the object system fixed with respect to the object. Corballis (2000) called these two systems an environment-centred reference system and an object-centred one; the former is similar to our CFR, and the latter is the same as our IFR. Tabata and Okuda (2000) proposed a solution to the mirror puzzle by selecting the coordinate system *inherent* to the object and its mirror image, ie the IFR in our definition. McManus (2002) also proposed a solution to the mirror puzzle by applying *the principle of axis-determination order* (this principle is explained in the next section) to the top – bottom, front – back, and right – left of a mirror image, similarly to Corballis (2000) and Tabata and Okuda (2000). However, none of these authors referred to the critical roles of different coordinate systems in different perceptions of mirror images.

3 Approach to extended mirror problem

3.1 *IFR and left – right reversal*

The human body and many ordinary objects have built-in (intrinsic) asymmetry in the top – bottom and front – back directions, but are approximately symmetric in the left – right direction. Thus, it is an established practice that only after the top – bottom and front – back axes have been identified, is the third axis, left – right, fixed in applying an IFR. This practice is here termed the principle of axis-determination order.

When we are looking into a mirror, the principle of axis-determination order is used to match first top – bottom and front – back axes between the body and its mirror image, ie between the enantiomorphs, in order to compare their shapes. This corresponds to the application of an IFR to each, the object and its mirror image. As a result, we are forced to perceive that the direction reversed in the mirror image is the direction compared last in order, ie the left – right direction (Corballis 2000; Tabata and Okuda 2000; McManus 2002).

The above explanation holds true not only for solid objects but also for an asymmetric letter written on a sheet of paper. While the front – back axis of a letter is unclear, we can identify it by regarding the surface of the sheet of paper where the letter is written as the front and the reverse as the back. According to this reasoning, we can also explain the left – right reversal of an asymmetric letter in the same manner as that of asymmetric solid objects (Tabata and Okuda 2000).

Therefore, the original mirror puzzle: "Why does the mirror reverse left and right, but not up and down?" can be considered implicitly to assume the application of the IFR, as noted by Corballis (2000) and Tabata and Okuda (2000). Thus, we can conclude that the application of the IFR always leads to the perception of left – right reversal so far as the object has left – right asymmetry (left – right asymmetry is the necessary condition for the perception of left – right reversal).

3.2 *Examples of left – right nonreversal*

From the relationship between the perception of left – right reversal and the IFR, we can infer that the perception of left – right nonreversal is related to the application of a CFR to the object and its mirror image. On the basis of this assumption, let us consider typical examples in which we perceive left – right nonreversal:

Example 1. Standing before a floor mirror, almost all persons say that their image is reversed in the up – down direction.

Example 2. Some persons do not perceive left – right reversal in their mirror images with the right hand raised, for example, and state that the mirror image also raises the right(-side) hand.

Example 3. When seeing a motorbike shifting to its left in the rearview mirror of a car, a driver does not perceive left – right reversal, ie she/he observes the image of the motorbike as moving leftward, and identifies the movement correctly in real space (see figure 1).[(1)]

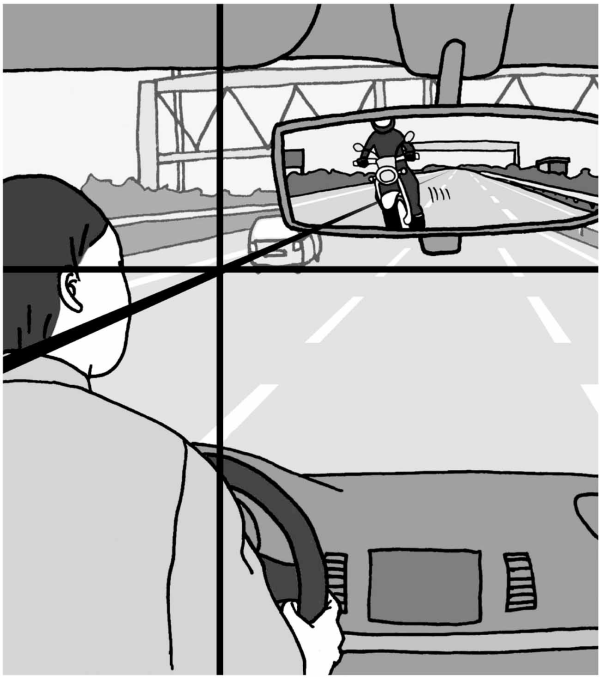


Figure 1. A motorbike in the rearview mirror of a car. A common frame of reference is applied to the real and mirror spaces.

Example 4. When applying make-up in front of a mirror, women do not make errors in penciling their eyebrow from left to right.

Example 5. There are objects that have none of top – bottom, front – back, and left – right intrinsic axes. An example is the three-dimensional object made of seven cubes used in the mental rotation paradigm developed by Shepard and Metzler (1971) (see figure 2). The importance of this example is that the seven-cube object does not have any intrinsic orientation in spite of being asymmetric in all the three orthogonal axes taken along the edges of the cubes. Except when this object is reflected by the side mirror, we do not perceive the left – right reversal of its mirror image. Thus, when the object is reflected by the front mirror, it is perceived as front – back reversed; and when reflected by the floor mirror as top – bottom reversed.

[(1)] When the left flashing indicator of the motorbike coming from his/her backside is on, the driver of the car will properly perceive that the *left-side* indicator is flashing according to the CFR. However, the driver may as well say that the right flashing indicator of the motorbike is on by applying an IFR to the image of the motorbike. The presence of the latter response does not invalidate the adequacy of example 3.

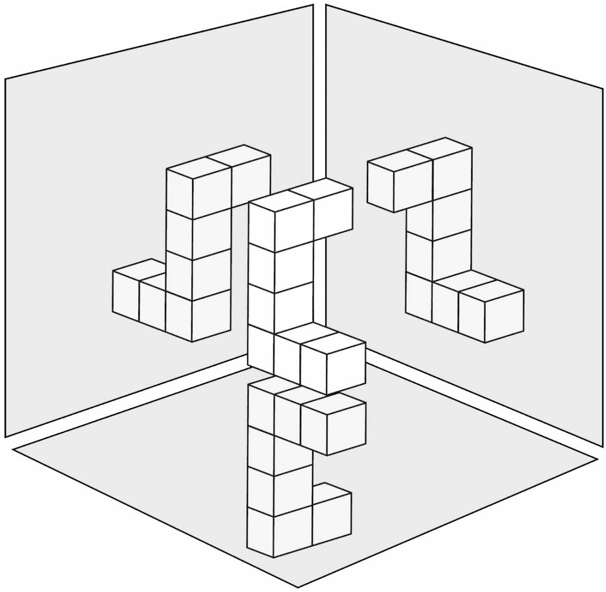
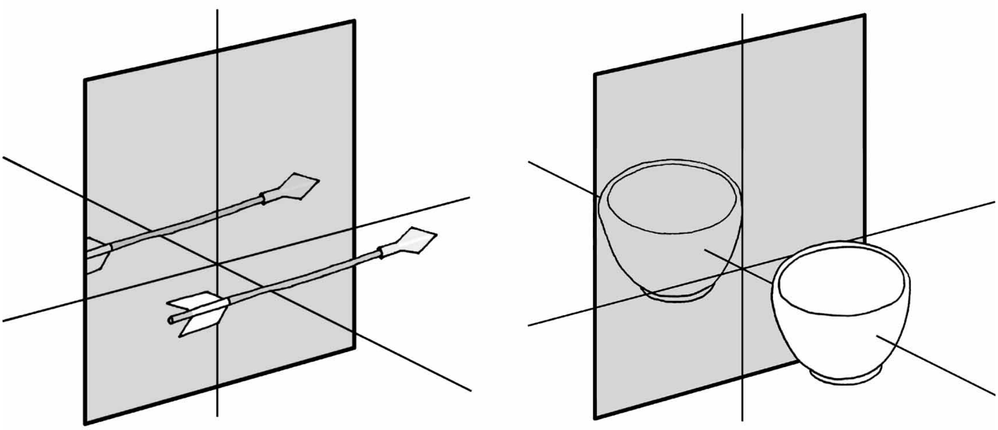


Figure 2. Three-dimensional objects made of seven cubes reflected in front, floor, and side mirrors. Mirror images are perceived to be reversed in the front – back, top – bottom, and left – right directions.

Example 6. Some ordinary objects have only a single intrinsic axis in either the top – bottom or the front – back direction. For example, an arrow (figure 3a) has the intrinsic front – back but not the top – bottom, and a nonpatterned cup (figure 3b) has the intrinsic top – bottom but not the front – back axis. Looking at the image of these objects in a front mirror, we never perceive them as left – right reversed, unlike the case of the object with three intrinsic axes. This might sound trivial, but makes it clear that the perception of left – right reversal needs all the three intrinsic axes.



(a) (b)

Figure 3. Examples of objects having only one intrinsic axis. (a) An arrow and its mirror image; a case having only intrinsic front – back. (b) A cup and its mirror image; a case having only intrinsic top – bottom.

Example 7. Consider the case in which a woman with a mole on the right cheek wants to confirm on which cheek the mole is located by looking into a mirror. Although the mirror image has the mole on its left cheek, she instantly finds that the mole is on her right cheek without giving any consideration to the left–right reversal of her mirror image.(2)

3.3 *CFR and left – right nonreversal*

When a woman states that the mirror image of her body is not left–right reversed (examples 1 and 2), she is applying a single observer-centred frame of reference that is common to real and mirror spaces. As mentioned earlier, we term this frame of reference common frame of reference (CFR). Similarly, when looking at a motorbike in the rearview mirror of a car (example 3), a driver applies a CFR for the real and mirror worlds as shown in figure 1. When applying make-up in front of a mirror (example 4), women also identify the left–right and top–bottom directions by the use of a CFR. Relying on the CFR, they do not perceive either left–right or top–bottom reversal, but are prompted to perceive front–back reversal as the logical consequence of enantiomorphism.

The IFR cannot be applied to objects without an intrinsic axis (example 5) or to those that have only a single intrinsic axis (example 6). Therefore, we are compelled to use a CFR for these objects. In example 7, the woman who perceives left–right nonreversal also relies on a CFR.

As mentioned above, the application of a CFR leads to nonreversal in the left–right axis in most cases. In some cases, however, it can lead to left–right reversal, one of the examples of which is the three-dimensional object made of seven cubes reflected by the side mirror in example 5.

3.4 *What CFR generally causes*

The direct consequence of the application of a CFR is not the nonreversal of the left–right axis, but simply the reversal of the axis normal to the mirror, according to geometrical optics. Examples 1 to 7 indicate that the left–right axis does not coincide with the axis normal to the mirror in most practical cases, in which one perceives the left–right nonreversal of the mirror image. On the other hand, when the normal to the mirror happens to be the left–right axis of the CFR adopted, the mirror image is perceived as left–right reversed.

Psychologically, a CFR can be based on one of the three types of orientation pointed out by Rock (1973): the environmental orientation, the egocentric orientation, and the intrinsic orientation of an object. In example 5, the CFR adopted would naturally be based on the egocentric orientation of the observer. In the side-mirror case of example 5, therefore, the left–right axis of the CFR coincides with the axis normal to the mirror, and left–right reversal is perceived in the mirror image. Similarly, left–right reversal is perceived also when the left–right axis of the CFR based on either the environmental orientation or intrinsic orientation of the object coincides with the axis normal to the mirror.

Thus, we can say that the perception of left–right nonreversal is due to the application of a CFR, but we cannot say that the application of a CFR always leads to left–right nonreversal as explained above. The relationship between the perception of left–right reversal or nonreversal and the application of the IFR or CFR can be drawn as a Venn diagram, as shown in figure 4. Areas A and B are clear, and we have also explained the occurrence of the cases that belong to area C.

Despite classifying the basis of mirror-image perception as the use of the CFR and IFR, we still allow the application of both kinds of frames of reference, and the application of a set of CFRs based on different orientations, to a single scene in a single instant. Applying make-up in the mirror, for example, a woman may well move

(2) A different response based on the use of IFR may also happen, but it cannot affect the perception of left–right nonreversal in this example.

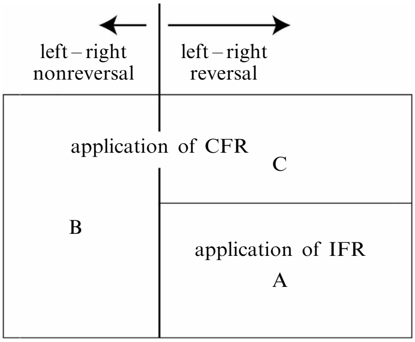


Figure 4. Relationship between the perception of left – right reversal and the application of the IFR or CFR.

the pencil left to right and top to bottom in accordance with what she sees in the mirror, controlled by a CFR. At the same time, she may notice that the writing on her T-shirt is left – right reversed. This is controlled by the IFR. We find a similar example of the dual control of frames of reference in a single scene in the context of a left – right visual reversal experiment. Kohler (1964) wrote about a subject's report of strange impression when wearing a left – right reversing device:

> "Inscriptions on buildings, or advertisements, were still seen in mirror writing, but the objects containing them were seen in the correct location. Vehicles driving on the 'right' (and the noise of the motor agreed) carried license numbers in mirror writing." (page 155)

Harris (1965) took this seriously and named it piecemeal adaptation. Thus our perceptual system may apply CFR and IFR simultaneously to objects or things in the same scene. It can also apply them to mirror images. Moreover, when we are looking at a mirror, there is a tendency for the locations of things to be perceived on the basis of CFR and the shapes of objects to be perceived under the control of IFR. However, this may not always be true, so that we do not say that this is a rule in mirror-image perception.

4 Concluding remarks

Our treatment of the extended mirror problem is based on the solution given by Corballis (2000), Tabata and Okuda (2000), and McManus (2002) to the original mirror puzzle. This solution has not met with any substantial and effective counterargument since its publication, and can be considered to have superseded all the previous hypotheses about the original puzzle, giving a firm foundation to the present treatment.(3)

Ittelson et al (1991) also pointed out the ambiguity of the mirror puzzle, but resolved it in a manner different from ours. They reformulated the puzzle into physical and perceptual problems, thus treating only the original mirror puzzle without extending it. They concluded that the perception of reversal occurs along the specific axis of the least perceived asymmetry (or greatest perceived symmetry), but their hypothesis was severely criticised by Corballis (2000). Therefore the analysis and conclusions of Ittelson et al are fundamentally different from ours despite apparent similarities between some of their descriptions and ours.

To predict exactly if an observer perceives left – right reversal or nonreversal of the mirror image under any situation, it is necessary to clarify the observer's psychological preferences for the IFR or CFR (with one of Rock's three orientation bases) in every conceivable type of situation. This would be a difficult problem that might not have a clear-cut solution because of the flexibility and insecurity of mental processes.

(3) One of the reviewers of this paper told us that Morgan's book (2003) already included a comprehensive solution to the original mirror puzzle, but we do not think so. Morgan's explanation of mirror reversal is quite similar to Gregory's (1987, 1997). The explanations of these two authors are criticised in the Appendix.

Therefore, the first critical step for understanding the extended mirror problem is the clarification of the physical conditions that lead to the left – right reversal and non-reversal. In the present study, this task was performed logically and parsimoniously.

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Appendix

Here we criticise Gregory's and Morgan's explanations of mirror reversals by comparing them with our treatment.

Gregory (1987) writes,

> "The mirror reflects top as top, bottom as bottom, right as right, and left as left: the mirror does not reverse right to left or up to down."

According to our treatment, this is a correct description so far as the use of a CFR is assumed. To observe left – right reversal, it is necessary to use an IFR for each of the object and its mirror image, ie a pair of enantiomorphs. Gregory's explanation lacks this step of elucidating the essence of left – right reversal. Thus it is unclear what he means by 'these mirror reversals' in his answer:

> "In all cases, it is object rotation that produces these mirror reversals in plane mirrors."

Gregory possibly considers the mirror image of the text seen in 'mirror writing' to be an example of left – right reversal, but he strangely and wrongly denies the appearance of mirror writing in one case by writing:

> "When, for example, a book is rotated around its horizontal axis to face a mirror, it appears upside-down, and not in 'mirror writing'."

After rotation around a horizontal axis, the text in the mirror surely runs from left to right as you saw in the real book before rotation. However, he fails to note that the mirror image of each asymmetric letter is a 'mirror letter' just like the case of rotation of the book around a vertical axis, and that the text in the mirror is actually mirror writing seen upside-down. Thus Gregory fails to explain the constant occurrence of mirror writing in a mirror.

Gregory (1997) makes the same error about the mirror image of ourselves by stating:

> "A mirror shows us *ourselves* right – left reversed (reversed from how others see us without the mirror) because we have to turn around to face it. ... But we can face the mirror by standing on our head—then, we are upside down in the mirror and not left – right reversed."

Here he gives a short explanation of what he means by 'right – left reversed', but he again fails to notice that the same right – left reversal is also seen when we stand on our head. Thus Gregory's hypothesis based on object rotation is far from being a valid solution to the original mirror problem. In our treatment, the occurrence of left – right reversal in mirror images in any relative configuration of asymmetric objects (including letters) with respect to a mirror can be explained as described in subsection 3.1 of the present paper.

Morgan (2003) explains the reversal of the mirror image of a text in the same manner as Gregory. The latter author attributed all the reversals to physical rotation, but Morgan has a somewhat different view about the reversal of the mirror image of ourselves, attributing it to mental rotation and making the hypothesis complicated without any improvement.

Morgan includes a consideration of an unusual case of looking at the image of a book in a mirror through our legs, and writes,

> "The text is no longer left – right reversed... Close inspection reveals that it is upside down."

The text is actually left – right reversed in the sense that it is in mirror writing, but Morgan misses this, following Gregory. In contradiction to the above passage, Morgan also writes:

> "[T]he impression of the writer is that objects such as chairs do not seem upside down [when looked at through our legs]."

This confusion comes from his lack of discrimination between the possible bases of the CFR, the environmental and egocentric orientations, in speaking of the up – down direction. In our treatment, the possible three bases of the CFR mentioned by Rock (1973) can naturally be accommodated as discussed in subsection 3.4.

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