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Reflections in art

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Abstract—When artists depict a mirror in a painting, it necessarily lacks the most obvious property of a mirror: as we move around the painting of the mirror, the reflections we see in it do not change. And yet representations of mirrors and other reflecting surfaces can be quite convincing in paintings. Here, we will examine the rules of reflection, the many ways that painters can break those rules without losing the impression of reflection and the rules that cannot be broken. The rules that govern the perception of reflection are a small subset of the physical rules of reflection.

Keywords: Reflection; symmetry; art.

INTRODUCTION

Reflections are not uncommon in natural scenes but until the development of mirrors, reflecting surfaces were limited to just a few materials such as still water, glassy minerals, and, of course, eyes. The highlights from eyes are salient enough to be incorporated into the eyespots often seen in animal mimicry. Snakes, frogs, fish, and most notably moths and butterflies often evolve eyespots to disorient predators. In many cases, these eyespots incorporate a white highlight (Fig. 1). Here we get a free insight into the visual system of the predators for the species that use highlights. True reflections from a curved surface move as the observer moves, but of course, the pigment on the mimicked highlight cannot. Any visual system that interpreted reflections based on the rules of optics would immediately notice that the mimicked highlight was not optically correct and that would be it for the prey. Clearly, the fake

Figure 1. (See color Plate I) The Peanut-head Bug (*Fulgora laternaria*) from rain forests of Central and South America demonstrates the effectiveness of mimicked highlights despite their obvious inability to move appropriately as the observer moves.

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highlight does work or it would not have survived eons of selection pressure. For the predator, the mimicked highlight must be conveying the additional realism of a reflection, and its immobility must not be breaking any of the rules for reflections actually implemented in the predator's visual system. Of course, the highlight also fools us — if we move our heads, the white spot does not lose its reflective quality. This example demonstrates that we can understand a great deal about the rules used by our visual system by identifying the inaccuracies of depiction, whether by animals or by painters, that we do not notice. In this article we explore the perception of reflection by studying artists' techniques for representing reflections; in particular, we are interested in what works despite deviations from the rules of optics (Cavanagh, 2005).

HIGHLIGHTS

When we consider reflections, it is helpful to divide them into two types: highlights on curved, glassy surfaces, and extended reflections on flat reflecting surfaces. The evidence from mimicry and the success of highlights in painting suggests that the analysis of highlights may be deeply embedded in our visual systems, as well as those of other species.

Beginning with the Greeks and Romans, artists have exploited highlights to add depth and realism to their paintings (see Miller, 1998, for a remarkable tour of reflections in art). Highly curved, reflective surfaces are the mirror equivalent of a fish-eye lens so much of the scene in front of the object is captured in the reflection and, optically, that should also include the scene around the observer outside of the picture space. Despite this obvious impossibility, almost anything can be put in the reflection as long as it is bright and curves appropriately for the reflecting surface curvature. A survey of medieval, Flemish, and modern paintings reveals any number of extraneous items in reflections that should not be there or items that are absent when they should be present. Fleming *et al.* (2003) showed that reflections need to have the statistics of real world scenes, including specifically some edges and bright light sources, but otherwise they do not have to match the objects that should actually be present for the reflecting surface to appear shiny. In a further article, Fleming *et al.* (2004) point out that reflections are compressed along the axis of maximum curvature and that this produces a signature of the surface shape over wide changes in the scene being reflected. The extreme case of this surface signature is seen in the extended highlights that run along the cylindrical portions of a reflective shape, a feature that was the first to be used by artists to capture surface curvature with reflections (see Gombrich, 1976, for his extraordinary analysis of the use of this cue by Greek painters).

The presence of a bright region of appropriate curvature does seem to naturally trigger the perception of a glossy, reflective surface (Beck, 1972), whereas the interpretation for a flat surface mirror does not seem to arise so readily (see below). A curved (convex) mirror is much more likely to pick up the reflection of a bright

window or other light source and artists of the Early Renaissance (when mirrors and highlights started to appear with some frequency) may have favored them over flat mirrors for this reason. Even a curved mirror may lose its reflective appearance and seem only a painting or ill-defined wall decoration if it does not include a particularly bright reflection.

Perhaps the most remarkable aspect of our perception of highlights in paintings is our tolerance of their lack of motion when we move our vantage point (and the tolerance shown by birds viewing the peanut bug of Fig. 1). The highlights are stuck at one point on the reflective object even though they should move. This tolerance vanishes if the depicted object itself is in motion (requiring a movie, not simply a painting). As Hartung and Kersten (2002) showed, the texture reflected on the glossy surface must not remain fixed on the object's surface or it is immediately interpreted as a surface texture belonging to the object and not a reflection. This difference between the effects of object motion and viewer motion will undoubtedly yield more insights with further study.

REFLECTIONS FROM FLAT SURFACES

Reflections from flat surfaces are optically much simpler, but because they are little different from the parts of the scene that they reflect, identifying them as reflections is a significant challenge. For an artist to succeed in capturing a convincing reflection that does not appear as some other part of the scene or a painting within a painting, the artist must exploit those cues that drive the inference of reflection. We will see that painters make use of symmetry in a variety of ways to indicate reflection.

Flat surface reflections may arise from natural surfaces like calm water or from human artifacts like mirrors. We should mention that our ability to recognize ourselves in mirrors is one of the criteria of higher order cognition that we share, apparently, only with some primates and dolphins (*cf.* Anderson, 1984; Hauser *et al.*, 1995; Reiss and Marino, 2001; Walraven *et al.*, 1995). Many species — monkeys, birds, fish — never understand mirrors and react aggressively to their own reflections (Zazzo, 1981). This result might suggest that the ability to identify flat surface reflections is a potential of a few species and that we have only recently become aware of it due to the advent of mirrors. However, this view ignores the presence of natural reflections in calm water. There are no accounts of animals, large or small, attacking their own reflections in the water surface, or even the reflections of other animals. There appear to be few if any cases of birds trying to fly through the water's surface to the clear skies reflected below — compare that to the many birds that die in attempts to fly through reflective, glass-clad buildings. Underwater species face similar challenges because of the total internal reflection occurring at the water–air boundary for angles of incidence less than 48.6° (creating a reflection of the underwater scene except for a large hole in the center above the observer, through which the above-water world is seen).

This anecdotal evidence suggests that there may be something special about horizontal, reflecting surfaces. Long experience with reflecting water surfaces may have led to some ability to discount mirrored scenes appearing on the air–water boundary. Evidence from species attacking their own reflection in vertical mirrors suggests that this reflection analysis does not transfer to vertically oriented mirrors or perhaps even to horizontal surfaces that are not at the water's surface.

On a flat reflective surface, such as a body of still water, the reflection creates a double-image where the bottom half is an inverted copy of the top half (Fig. 2). Because still water always forms a horizontal plane, the image has symmetry around the horizontal axis and any item in the upper half must always be in alignment vertically with its reflection.

This property underlines the point that symmetry is a basic optical cue to reflections from flat surfaces. When a reflecting surface is viewed at a shallow angle like the lake surface in Fig. 2, we see mirror symmetry where the reflected view is quite similar to the direct view, only inverted. However, when a reflecting surface is viewed more directly, at an angle that would allow us to see our own reflection, an object and its reflection are seen from opposite sides. For objects near the perpendicular from the observer's eye to the mirror, reflections show translation symmetry, at least for their silhouettes (but not, of course, for their internal detail): the outline of the object seen from behind is similar to the outline seen from the other side in the reflection, but it is shifted radially away from the reflection.

Figures 3 and 4 suggest that vertical alignment is a strong cue to reflection from horizontal surfaces and when this is violated, the perception of the reflection is degraded. In the altered photograph of Fig. 3, the reflection has been skewed from vertical and the patterns on the water now look more like a surface texture. In Fig. 4, the artist has placed the reflection of the sun (or perhaps the moon) significantly to the right of where it should fall. Many viewers note that something is wrong here, often without a clear understanding of what the error is (a second error is to show

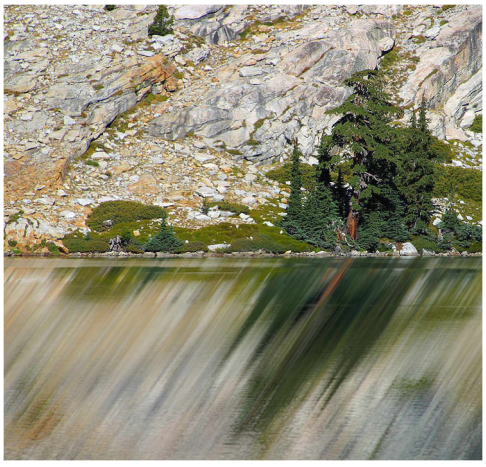
Figure 2. (See color Plate I) Reflections on a horizontal surface must align vertically with the object being reflected. In water with slight surface ripples, there is also blurring (appearing more in the vertical than horizontal direction because of the foreshortening of the ripple texture). The blurring does not interfere with the perceived reflectiveness of the water and the reflection is discounted — it is not seen as a pigment of the water surface but a reflection from it.

Figure 3. (See color Plate I) When the reflections are skewed to break the vertical alignment, they are seen more as a texture of the surface than a reflection on it.

Figure 4. (See color Plate II) The reflection of the sun (moon?) in this painting by Tosa Mitsunobu, 1536, is offset from vertical alignment and should not even be visible on the lake when the sun is at such a low angle (the line of sight to the sun, reflecting off the water, should be blocked by the intervening hills). The vertical misalignment immediately stands out as 'wrong' in some ill defined way but the impossibility of the reflection is not so easily noticed, it requires additional mental geometry.

P. Cavanagh *et al*., Figure 1.

P. Cavanagh *et al*., Figure 2.



P. Cavanagh *et al*., Figure 3.

the sun's reflection in the lake when it should be blocked by the intervening hills, but this is not often noticed).

The sensitivity to vertical alignment for the reflections from a horizontal surface does not translate to reflections from vertical surfaces. In Fig. 5 we see an artist's rendition of windowed door reflecting a balcony and outdoor scene. With a vertical reflection, the alignment of objects and their reflections depends on the orientation of the vertical surface relative to the direction of gaze in the pictorial space. The reflection of the horizon is always aligned horizontally with the visible horizon (as in Fig. 5) but other contours, even if horizontal in direct view only align horizontally under special circumstances (they are perpendicular to the reflecting surface and the reflecting surface is parallel to the direction of gaze to the vanishing point in the picture space). These complex constraints explain why we are not sensitive to when a reflection should be collinear or not (compare Fig. 5a and b).

Our visual systems are capable of detecting both mirror and translation symmetry in all orientations although mirror symmetry is more easily detected around the vertical axis than around the horizontal axis (Corballis and Roldan, 1975; Dakin and Hess, 1997; Palmer and Hemenway, 1978; Royer, 1981). The sensitivity to symmetry around the vertical axis may have emerged to simplify the recognition of animals that show a reflection of left and right body parts around the vertical midline, at least when viewed head on. The sensitivity to vertical alignment for reflections from calm water and insensitivity to deviations from horizontal alignment for reflections from vertical surfaces (see Fig. 5) also suggest an ecological origin for the reflection symmetry cue, but one that is independent of the symmetry sensitivity for objects.

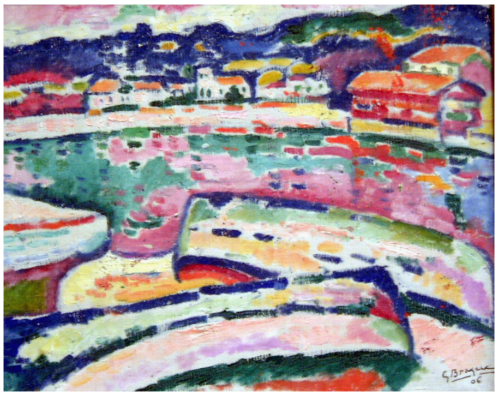
The effectiveness of the vertical alignment in horizontal reflections on water may arise, to some extent, from the vertical organization of the reflection, independently of its symmetry with the scene it ought to be mirroring. Displacing a reflection, or showing a repetitive vertical organization (mimicking the effect of broken reflections on surface waves) appears to be sufficient to generate some impression

Figure 5. (See color Plate II) In contrast to the sensitivity to vertical alignment in water reflections, reflections for vertical reflecting surfaces are more complex. In a vertical mirror, the horizon and its reflection must be aligned horizontally but that does not hold for other horizontal contours unless the vertical surface is aligned with the direction of gaze toward the vanishing point and the horizontal contour is perpendicular to the reflecting surface. Note that on the left, the railing heads off at an odd angle in the window reflection (but the horizon does not). On the right, the image has been altered so that the horizontal railings should align horizontally with their reflections, but still do not. It is hard to judge which is correct (the left one). The artist may have arranged the bent reflection deliberately. If the door and direction of view had been arranged to make the reflection aligned (as they should be on the right), the collinearity of contours would be a cue that the glass was transparent, giving a direct view of the outdoors, rather than reflecting it. However, the bent railing breaks the visual system's rules for transparency, eliminating this interpretation; apparently, the bend does not break the visual system's rules for reflection, and this is what we see. Clever artist. Of course, the bends of the reflected railings on the right do break the rules of physics for both reflection and transparency.

P. Cavanagh *et al*., Figure 4.

(a) (b)

P. Cavanagh *et al*., Figure 5.



P. Cavanagh *et al*., Figure 6.

of a reflecting water surface, even though it does not match the scene features that ought to be reflected (Fig. 6).

MIRRORS

The picture frame holding a painting separates the real world on our side of the frame from the painter's imagined world on the other side. But place a mirror in a painting and this neat division breaks down: many items depicted in the mirror ought to be lying about us in the real world, but of course are not. Clearly, artists can break this physical rule of mirrors and still represent a convincing mirror. What rules are required to successfully depict mirrors and what rules are optional? Possibly the first mirror depicted in art is in the famed *Alexander Mosaic* discovered in Pompeii (Fig. 7, see Miller 1998 for more of the history of mirrors in art). The mosaic shows a dying Persian contemplating his reflection in his polished bronze shield. This and other early representations of mirrors are more mirrors by deduction than by perception. An object in front of the mirror is duplicated within the mirror, a sort of conceptual symmetry. When there are two copies of an object in a painting, one explanation is that there is a mirror. If one of them has no pictorial space in which it could exist (e.g. the toast in Fig. 8 is in the space where the reflected cup would be if it were not a reflection), then that copy is a good candidate for a reflection. These conceptual cues lead to a deduction of a mirror more than a perception of a reflection. Later representations, starting with the Flemish realists, introduced more realistic cues (although conceptual cues still dominate) so that the perception of the mirror is more compelling and less based on deduction. What is it that makes these depictions convincing?

Clearly, high contrast of the reflected image is critical as well as some similarity between textures and objects in front of the mirror and in the reflection. However, items in the reflection do not have to match the items that are in the scene that ought to be in the mirror. Some very famous paintings include details in a mirror that are not visible in the space of the painting. The King and Queen are seen in a mirror in the rear of the room in Velàzquez's *Las Meninas* (Kemp, 1990) and a small dog is visible in the convex mirror of van Eyck's *The Betrothal of the Arnolfini* (L. Maloney, personal communication). Other cues carry the impression of the mirror quite well in van Eyck's case: the duplication of features in the room —

Figure 6. (See color Plate II) Even a hint of vertical organization helps organize a surface as a water reflection. The repeated daubs of color aligned vertically, trigger an interpretation of water even though the daubs are not aligned with anything in particular (Georges Braques).

Figure 7. (See color Plate III) *Alexander Mosaic* (100 BC). The fallen Persian sees his reflection in his shield.

Figure 8. (See color Plate III) Reflections do not have to match the reflected scene to be effective.

P. Cavanagh *et al*., Figure 7.

P. Cavanagh *et al*., Figure 8.

P. Cavanagh *et al*., Figure 9.

windows, doors, the couple seen from the back as well as their curvature carried in the convex surface. There are few supporting cues in the case of *Las Meninas* and the reflection might also be seen as a view through a portal into another room (Miller, 1998).

The various interpretations of *Las Meninas* make the strong point that, unlike highlights from shiny surfaces and reflections off flat horizontal surfaces, mirrors are purely cultural artifacts. We may learn the cues that trigger an interpretation of a mirror in a painting and some of these cues may be common to interpretations of reflections of all types. But others may be learned conventions — a paddle shaped object held in the hand in front of a person's face is probably a mirror because that's how people use mirrors. Many of the cues used to depict mirrors may therefore be telling us about our culture rather than our visual system.

NEUROPSYCHOLOGY OF MIRROR PERCEPTION

If symmetry detection underlies some part of the perception of reflection, brain injury that affects symmetry perception should also affect the understanding of mirrors. fMRI studies of symmetry judgment have found activity in the parietocentral region (Croize *et al.*, 2004; Jacobsen *et al.*, 2006). Other studies have implicated the lateral occipital complex (LOC), lying posterior to the parietal cortex, in symmetry judgments (Sasaki *et al.*, 2005; Tyler *et al.*, 2005).

Individuals who have suffered right parietal lesions sometimes exhibit a condition called 'mirror agnosia'. The right parietal patients who experienced left visual field neglect also often had trouble recognizing mirror reflections (Ramachandran *et al.*, 1997). When a vertical mirror is placed in the right visual field so that it shows the reflection of objects that are in the opposite, neglected field, these patients try to reach through the mirror to the reflections (which are in their good field) as if they were real objects and the mirror was an opening to them. A similar condition was found in one patient who had suffered a temporo-parietal lesion but had normal perceptual and object recognition capabilities. In an experiment, he had difficulty differentiating reflections from real objects (Priftis *et al.*, 2003). The parietal damage may lead to deficits in understanding mirrors by disrupting the analysis of symmetry. But this may arise either because the lesions directly affect regions that compute symmetry or because the attentional deficits in the neglected visual field disrupt the comparison of left and right visual fields that underlies symmetry analysis.

PSYCHOPHYSICS OF MIRROR PERCEPTION

Croucher *et al.* (2002) tested the commonly held belief that people should be able to intuitively recognize how mirrors work: their subjects were asked to identify when a reflection ought to become visible in a mirror and where to stand to see

a certain object in the reflection. However, their findings were surprising. Few of their subjects understood the optics of mirrors, greatly overestimating what is visible. These studies demonstrate why artists can get away with breaking the rules of optics when representing mirrors. Croucher *et al*. suggested that painters can see how reflections work in the scene they are depicting but they realize that they can use impossible but more aesthetically pleasing reflections to further their representation. The viewers won't notice.

The most obvious deviation from optics occurs in the representations of people looking at themselves in mirrors (Fig. 9). As described by Bertamini *et al.* (2003), viewers often assume that the person whose face is shown in the mirror is seeing him or herself at the same location as the viewer does. This is of course, optically impossible. They named this effect the 'Venus Effect' and it is in evidence throughout the history of art, most frequently in the many paintings of the indefatigable narcissist, Narcissus.

CONCLUSIONS

No matter how talented an artist is, a reflection can never be perfectly portrayed because a painting is flat, the images on a canvas cannot move with us, and any reflecting surface, parallel to the front plane of the picture, must show us, the viewers, as we stand before the painting itself. Clearly this does not happen. However, depictions of reflection in art are often very convincing and the checklist of requirements is short and tolerant (see suggestions in Table 1) — so tolerant that even glaring optical errors are ignored. We found that vertical alignment was critical for reflections on flat horizontal surfaces but horizontal alignment was less important for reflection in flat vertical surfaces. Items in the reflection do not have to match the objects that should be reflected. Some of the rules are perceptual and deeply embedded in the visual system. We would expect to see them in other species (like the birds preying on the peanut bug of Fig. 1). Other rules, specifically for mirrors, are more conceptual and a consequence of our familiarity with mirrors in our culture. We would expect to find these rules only in a few higher species and only for individuals given some experience with real mirrors. These rules that are used by our visual system appear to be a small subset of the physical rules that can be rapidly verified without extensive computation of identities, locations and views of items in the scene.

Figure 9. (See color Plate III) *Toilet of Venus,* Rubens. Venus's eyes appear to be gazing at her own face but that is impossible as the rules of optics require that if we see her in the mirror, she sees us (or the painter). Note the highlights on the beveled edge of the mirror as a cue to the glass of the mirror.

Table 1.
Perceptual and conceptual cues to reflection

Perceptual cues (part of visual system)	
Highlights on curved surfaces:	– lighter than the surface on which they are seen – distorted to correspond to surface curvature
Reflections in flat horizontal surfaces:	– vertical alignment, vertical repetition
Conceptual cues (part of culture)	
Mirror reflections:	– duplicate objects within and outside mirror – absence of picture space behind mirror for objects depicted in mirror – change of apparent lighting within the mirrored scene compared to surrounding surfaces (to rule out a painting of a painting)

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