The artist as neuroscientist

Artistic licence taps into the simplified physics used by our brain to recognize everyday scenes, says Patrick Cavanagh.

Although we rarely confuse a painting for the scene it presents, we are often taken in by the vividness of the lighting and the three-dimensional layout it captures. This is not surprising for a photorealistic painting, but even very abstract paintings can convey a striking sense of space and light, despite remarkable deviations from realism. The rules of physics that apply in a real scene are optional in a painting; they can be obeyed or ignored at the discretion of the artist to further the painting's intended effect. Some deviations such as Picasso's skewed faces or the wildly coloured shadows in the works of Matisse and other Impressionists of the Fauvist school are meant to be noticed as part of the style and message of the painting. There is, however, an 'alternative physics' operating in many paintings that few of us ever notice but which is just as improbable. These transgressions of standard physics — impossible shadows, colours, reflections or contours — often pass unnoticed by the viewer and do not interfere with the viewer's understanding of the scene. This is what makes them discoveries of neuroscience. Because we do not notice them, they reveal that our visual brain uses a simpler, reduced physics to understand the world. Artists use this alternative physics because these particular deviations from true physics do not matter to the viewer: the artist can take shortcuts, presenting cues more economically, and arranging surfaces and lights to suit the message of the piece rather than the requirements of the physical world.

In discovering these shortcuts artists act as research neuroscientists, and there is a great deal to be learned from tracking down their discoveries. The goal is not to expose the 'slip-ups' of the masters, entertaining as that might be, but to understand the human brain. Art in this sense is a type of found science — science we can do simply by looking.

Figure 1 **By 1467, artists such as Fra Carnevale had mastered consistent perspective but not consistent lighting. The people in the foreground cast deep shadows but those on the plaza above and to the left do not. The alcove on the right is brightly lit but the only opening in its left wall is a small door. The shadows on the right wall of the alcove rise mysteriously upwards. These severe inconsistencies are not evident or jarring to the human viewer. (Detail of *The Birth of the Virgin* by Fra Carnevale.)**

To count as a 'discovery' in this art-based neuroscience, deviations from standard physics must be mostly invisible to the human eye in casual viewing. A painting that, despite physical impossibilities in the depiction, gives an unhindered sense of the space and objects within it, says something about our brain. For example, a shadow that looks like a convincing shadow, even though its shape does not match the object that cast it, suggests the physics of light and shadow used by our visual brain is simpler than true physics[1,2].

This simplified internal physics employed by our visual brain is not used just to appreciate paintings, but to enable our rapid and efficient perception of the real world. Real shadows are subject to an extensive set of constraints, but few of these seem to be checked by our vision; that is why an artist can use an unrealistic representation with such great impact. It is important to note that the simplified rules of physics that interest us (and the artists' shortcuts that exploit them), are not based on the ever-changing conventions of artistic representation, as they hold for monkeys and infants[3,4], both quite immune to the conventions of art. These simplified rules are grounded instead in the physiology of the visual brain.

Darkness alone required

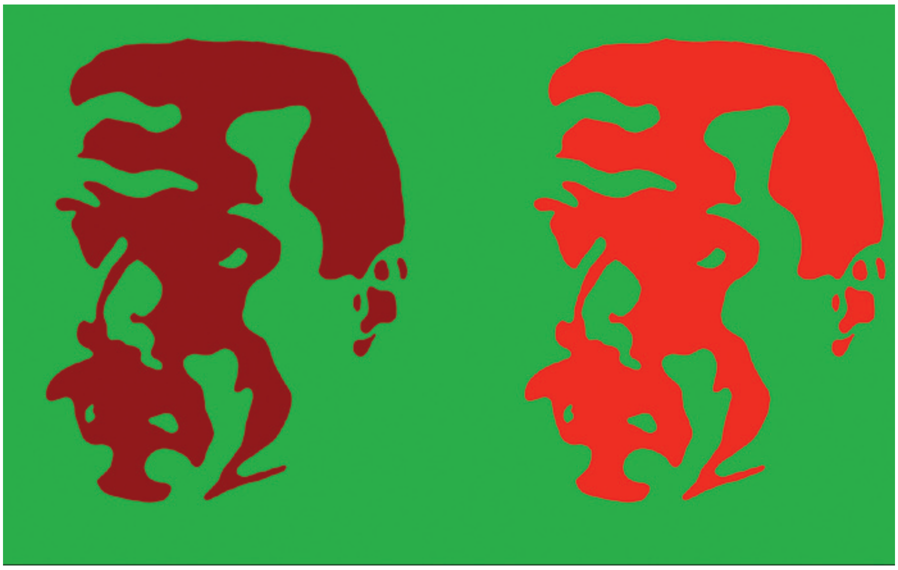
Cast shadows have appeared on and off in Western art from the early classical Greek[5] and Roman paintings and mosaics to the beginning of the modern era[6]. In contrast, with the exception of a single drawing, cast shadows did not appear in Eastern art until modern times[7]. Artists take many liberties when depicting shadows, using the wrong colour or shape, without disturbing the apparent light, space or form of the depicted scene. These physical impossibilities that slip by unnoticed (Fig. 1) are important for understanding vision. They reveal that the visual brain recognises shadows using only a

Figure 2 **Signorelli takes great liberty with shadows, but goes too far here in making the guard's shadow cross over the satyr's shadow as if it were paint. Although shadows can lie in the wrong direction and have the wrong shape, they cannot look opaque and still appear as shadows. (Detail from *The Assumption of the Virgin with Saints Michael and Benedict* by Luca Signorelli.)**

small subset of the criteria that constrain real shadows. Unsurprisingly, one criterion used unfailingly by artists is that the shadows must be darker than their immediate surroundings. This finding has been confirmed by perceptual experiments[1] that examine the recovery of shapes defined by shadows. Such experiments have also shown, as have artists many times over, that few if any other deviations from realism affect the recovery of shape from shadows. Exceptions to this broad tolerance can be found in paintings where shadows fail to be convincing. Specifically, shadows should not appear to have volume or substance of their own (Fig. 2), a criterion that has yet to be examined scientifically.

Scientific studies of the perception of shadows, and shape from shadows[1] have supported other discoveries made by painters. In the two-tone images of Fig. 3, the shadows below the nose, eyebrows and chin define the depth of the face. When the shadows violate the rules required by the visual system, the face is no longer seen as such a strong 3D structure. These studies show, for example, that the shadows must be darker, but do not have to be of physically possible colours. Studies of lighting direction support painters' intuition that inconsistent direction of lighting is not readily noticed. The cubes in Fig. 4 are all lit from one direction, with one exception. Subjects take a long time to pick out the oddly lit cube[8].

Figure 3 **The dark red areas of the two-tone image of a man's face on the left include both regions of dark shadow and dark pigment (eye brows, hair, mustache). These areas, in appropriate lighting, should be darker than the surrounding green areas. (If this is not the case, move to a location with fluorescent or natural lighting.) In the version on the right, the same red areas are now brighter than the green surround. Shadows have to be darker to support the recovery of object shape from shadow cues so the face on the right is much less 3D. But notice that the shadows, as long as they are darker, do not have to be the right colour[1] (the ambient red light seen in the shadows should also fall in the green areas, making them yellower than they are).**



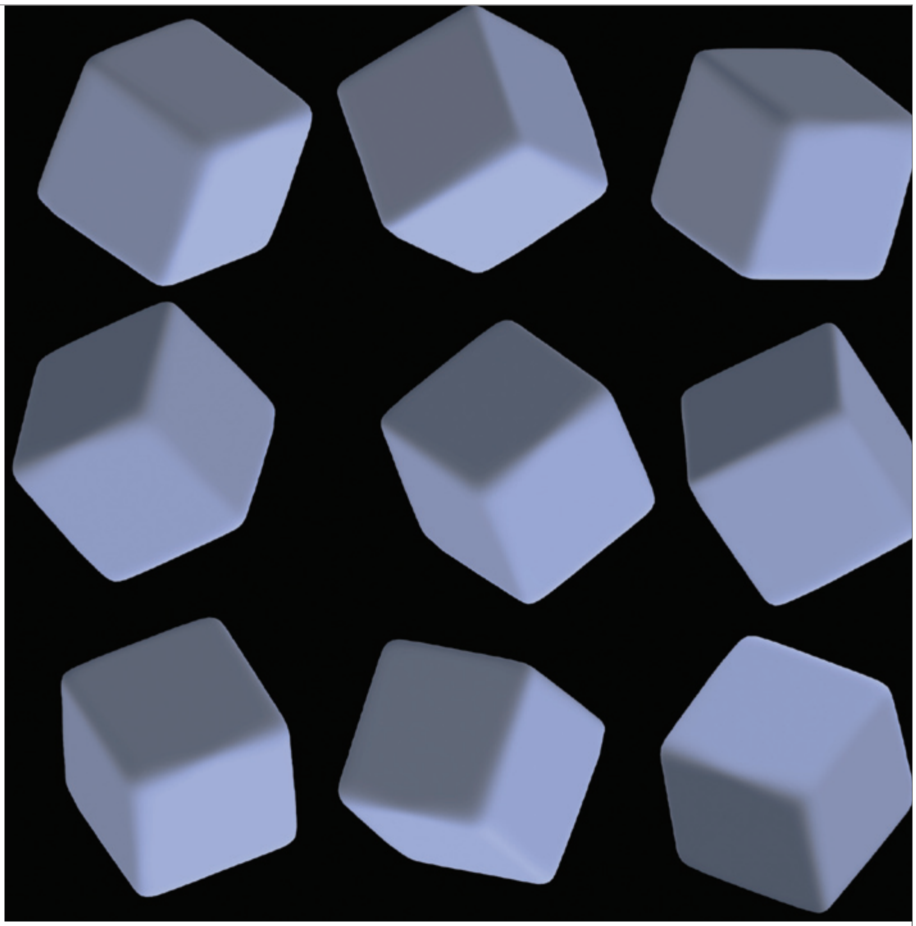


Figure 4 **An array of cubes all lit from one direction except one. Subjects take an average of eight seconds to find the odd item (bottom right here) and make many errors (30%), suggesting that inconsistent lighting is not readily noticed. (From ref. 8.)**

Surrogate boundaries

Much of our earliest recorded art takes the form of line drawings and, remarkably, the elements of this type of representation have remained unchanged. But given that lines do not divide objects from their backgrounds in the real world[9], why do line drawings work?

The effectiveness of line drawings is not simply attributable to learned convention, passed on through culture. Infants[10], stone-age tribesmen[11] and even monkeys[12] are capable of interpreting line drawings as we do. So what do lines represent to the brain? Artists do not just trace the brightness discontinuities in an image. Conventional line drawings do not include the outlines of cast shadows or pigment contours; rather, they trace out the contours that characterize shape (Fig. 5). Artists have discovered which key contours must be perceived by the visual brain for the viewer to identify the essential structure of an object. By studying the nature of lines used in line drawings, scientists may eventually gain access to this natural knowledge base.

Seeing through paint

It is not easy to draw or paint a material that is barely visible and through which background patterns are only slightly altered. Artists do this by making a reasonable version of the background surface appear through the transparent surface. This superposition involves crossing the contours of the transparent object with the contours in the background. For example, in Fig. 6 the front rim of the glass crosses the back waterline, and in Fig. 7 the hem of the sheer cotton garment crosses the outline of the legs that are visible both above and below the hem. Experiments by F. Metelli have shown how these crossings or 'X-junctions' are critical cues for the successful depiction of transparency[13]. When the X-junctions are misaligned, the impression of transparency is lost (Fig. 8).

Although the X-junctions must be present to successfully convey transparency, other properties of the transparent material are not critical. For example, in paintings of water and glass, gross deviations from the optics of refraction (Fig. 6) are rarely noticed by the viewer, indicating again that the visual brain only computes a small set of the possible

Figure 5 **Lines are used to convey the outer contours of the horses in a very similar way in these two drawings, one from 15,000 BCE (left: *Chinese Horse*, paleolithic cave paining at Lascaux) and the other from 1300 CE (right: Jen Jen-fa, detail from *The Lean Horse and the Fat Horse*, Peking Museum).**

Figure 6 **No optical distortion of the lemon in the water is shown here and yet the glass and the water appear convincingly transparent. (*Implement Blue*, M. Preston, 1927; oil on canvas on paperboard, 42.5 x 43 cm; gift of the artist 1960 collection; Art Gallery of New South Wales.)**

physical properties of a transparent material in assessing whether or not a surface is transparent.

Filling in the gaps

Many paintings only hint at the elements in a scene and depend on the viewer's memories to construct meaningful images from the fragments. Impressionism and Cubism in particular rely on this memory based reconstruction to complete scenes from partial representations. These paintings demonstrate the minimal skeletons of visual forms that are capable of evoking remembered images (Fig. 9).

No need for 3D

Flat paintings are so commonplace that we seldom ask why flat representations work so well. If we really experienced the world as 3D, an image seen in a flat picture would distort jarringly when we moved in front of it. But it does not as long as it is flat. A folded picture, in contrast, distorts as we move around it (Fig. 10). Our ability to interpret representations that are less than 3D indicates that we do not experience the visual world as truly 3D (refs 14–16), and has allowed flat pictures (and movies) to dominate our visual environment as an economical and convenient substitute for 3D representations. This tolerance of flat representations is found in all cultures[10], infants[3], and in other species[4] so it cannot result from learning a convention of representation. Imagine how different our culture would be if we could not make sense of flat representations. Visual art would all be 3D: there would

Figure 7 **(right) Egyptian artists were the first to depict transparency. They needed to show the elegance of the fine transparent cottons worn by the wealthy (Pharaoh Sethi I on the right). The transparency of the cotton tunic is captured through overlapping contours and contrasts.**

Figure 8 **(left) When a transparent surface covers a contour in the object behind it, the contour of the transparent surface and the underlying contour cross to form an X-junction. Two of these X-junctions are seen in the top panel. As Metelli showed[13], if the contours are displaced to eliminate the X-junction, as on the bottom panel, the same patches of light and dark look more opaque than transparent.**

be no paintings or movies. Our pockets would be bulging with little statuettes of loved ones rather than photographs.

Less is more

Impressionists used minimal detail in their paintings, yet their pieces evoke a strong sense of place and mood. A photograph of an equivalent scene might be unexceptional, but the inaccurate splashes of colour and hints of contour are often moving despite, or perhaps because of, discrepancies from a realistic portrayal (Fig. 11).

Why is this style so effective? Recent neuroscience studies of the connection between vision and the centres of emotion suggest a possible reason. Brain imaging[17] of subjects presented with faces expressing fear show that the amygdala (a centre of emotion) responds strongly to a blurry version of the faces. In contrast, areas responsible for conscious face recognition respond weakly to blurry faces and best to faces presented in sharp detail (Fig. 12). Impressionist works may connect more directly to emotional centres than to conscious image-recognition areas because the unrealistic patchwork of brush strokes and mottled colouring distract conscious vision (Fig. 11).

Figure 9 **Two dancers are made up of some of the isolated swatches of colour. The arrangements are sufficiently similar to familiar human shapes to trigger the integration of the marks as legs, arms, heads and bodies of single figures. Before the development of brain imaging, similarly disconnected images[23] were used by neurologists to identify brain injury to the parietal lobe. (*The Yellow Dancers* by Gino Severini, circa 1911–1912; oil on canvas, 45.7 x 61 x 2.3 cm.)**

Depicting reflection

Mirrors have been depicted in art since Greek and Roman times but, inevitably, artists commit fascinating errors when representing what is reflected by the mirror[18]. Having encountered reflections in mirrors throughout our lives, we might assume we understand how they work — what objects should be visible in the mirror given our position, the angle of the mirror and the location of other objects around us. Real mirrors never test this knowledge because they are always correct. But painters do test our knowledge of mirrors and reflection, and reveal that basically we have none. In a painting, almost any reflection will do, with only a few limits. Artists can depict people

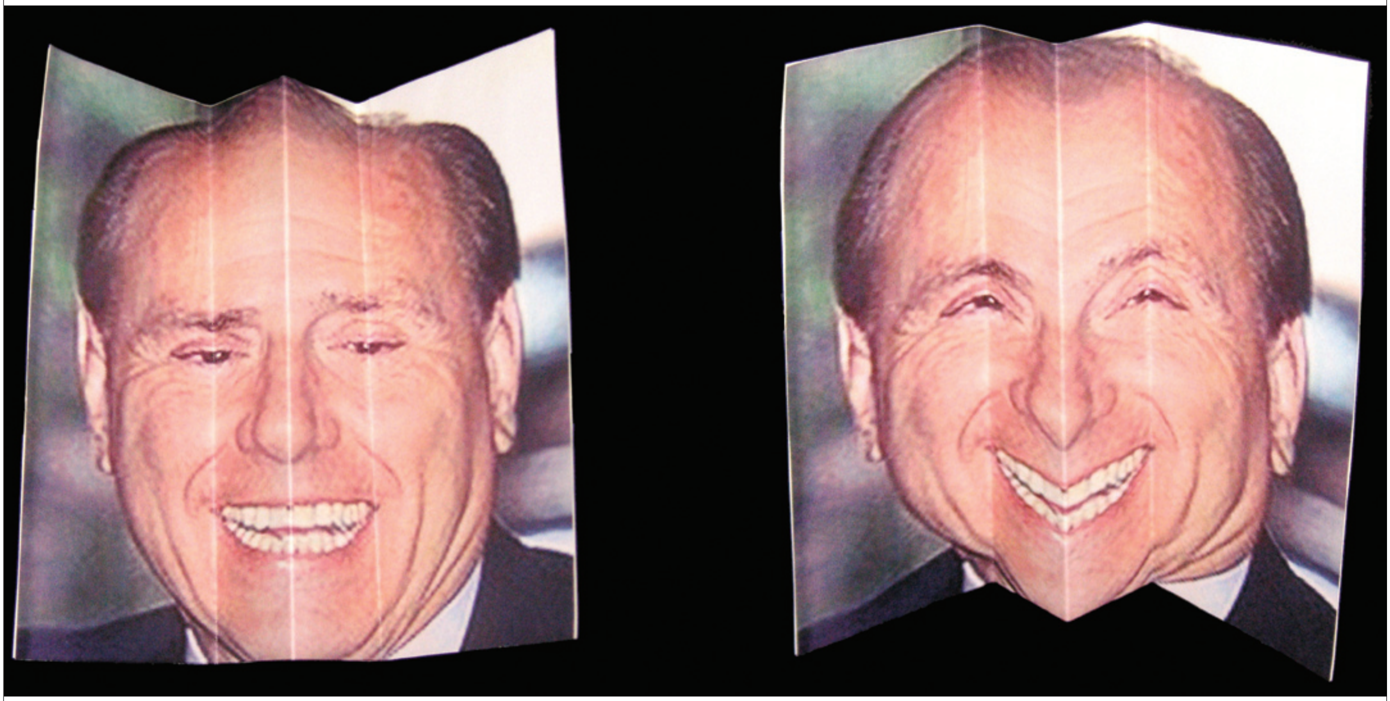


Figure 10 **When a flat picture is viewed from different angles, the 3D scene can still be perceived without jarring distortions. In contrast, when a folded picture of a face is tilted, striking changes of expression are seen. (From ref. 16.)**

Figure 11 **The blurry, global shapes and colours may convey emotional content directly to emotional centres of the brain while the irrelevant fine detail typical of Impressionist pieces distracts conscious perception. (Oil on canvas (55.1 x 65.9 cm), Potter Palmer Collection, The Art Institute of Chicago.)**

looking at their reflections and reveal both the person and the reflection, often when this is geometrically impossible (Fig. 13).

Recent vision research also demonstrates that people have little or no awareness of where reflections ought to be[19], or even of what they should look like[20]. Subjects in one experiment had to indicate on a drawing where, when walking into a room, they would first see the reflection of a particular object in a mirror. Even physics students were unable to do this with any accuracy. Experiments also show, as painters have known for centuries, that the pattern of reflection on a surface doesn't have to match the actual scene around it for it to appear as a reflection[21] (Fig. 14). The pattern only needs to match the average properties of natural scenes[20] and curve in concert with the implied curvature of the shiny surface[22].

The neuroscience of art

Paintings and drawings are a 40,000-year record of experiments in visual neuroscience, exploring how depth and structure can best be conveyed in an artificial medium. Artists are driven by a desire for impact and economy: thousands of years of trial and error have revealed effective techniques that bend the laws of physics without penalty. We

Figure 12 **Vuilleumier *et al.*[17] found that the blurry, fearful face on the right activated the amygdala more than the sharply detailed or unfiltered versions. This suggests that low spatial frequencies (gross detail) provide the amygdala, an important emotional centre of the brain, with coarse, but rapid, fear-related information. The face-recognition areas of ventral visual cortex showed less activation in response to the blurry versions than to the sharp or unfiltered images. Slower conscious analysis may therefore rely on the high spatial frequencies for face identification. Earlier studies[24] showed that the amygdala can respond to the fearful images even in a brief, masked presentation that subjects do not report seeing. The right amygdala has even been shown to respond to emotional facial expressions in a patient with no primary visual cortex and no conscious visual experience[21].**

Figure 13 **Try to determine where the woman is looking. Could she be looking at her own reflection or is that physically impossible?**

can look at their work to find a naive physics that uncovers deep and ancient insights into the workings of our brain. Discrepancies between the real world and the world depicted by artists reveal as much about the brain within us as the artist reveals about the world around us. ■

Patrick Cavanagh is in the Vision Sciences Laboratory, Department of Psychology, Harvard University, 33 Kirkland Street, Cambridge, Massachusetts 02138, USA.

1. Cavanagh, P. Leclerc, Y. G. *J. Exp. Psychol. Hum. Percept. Perform.* **15,** 3–27 (1989).
2. Casati, R. *The Shadow Club* (Little Brown, New York, 2004).
3. Yonas, A., Cleaves, W. T. & Pettersen, L. *Science* **200,** 77–79 (1978).
4. Bovet D. & Vauclair J. *Behav. Brain Res.* **109,** 143–65 (2000).
5. Bruno, V. J. *Form and Color in Greek Painting* (W. W. Norton & Company Inc., New York, 1977).
6. Hills, P. *The Light of Early Italian Painting* (Yale Univ. Press, New Haven 1987).
7. Gombrich, E. H. *Shadows* (Natl Gallery Pub., London, 1995).
8. Ostrovsky, Y., Sinha, P. & Cavanagh, P. *Perception* (in the press).
9. Kennedy, J. M. & Silver, J. *Perception* **3,** 313–322 (1974).
10. Yonas, A. & Arterberry, M. E. *Perception* **23,** 1427–1435 (1994).
11. Kennedy, J. M. & Ross, A. S. *Perception* **4,** 391–406 (1975).
12. Itakura, S. J. *Gen. Psychol.* **121,** 189–197 (1994).
13. Metelli, F. *Sci. Am.* **230,** 90–98 (1974).
14. Busey, T. A., Brady, N. P. & Cutting, J. E. *Percept. Psychophys.* **48,** 1–11 (1990).
15. Koenderink, J. J. & van Doorn, A. J. in *Looking into Pictures* (eds Hecht, H. Schwartz, R. & Atherton, M.) 239–300 (MIT, Cambridge, Massachusetts 2003).
16. Cavanagh, P., von Grünau, M. & Zimmerman, L. *IEEE Proc. 2nd Intl Symp. 3D Data Processing, Visualization and Transmission* 35–41 (2004).
17. Vuilleumier, P., Armony, J. L., Driver, J. & Dolan, R. J. *Nature Neurosci.* **6,** 624–631 (2003).
18. Miller, J. *On Reflection* (Yale Univ. Press, New Haven, 1998).
19. Croucher, C. J., Bertamini, M. & Hecht, H. J. *Exp. Psychol. Hum. Percept. Perform.* **28,** 546–562 (2002).
20. Fleming, R. W., Dror, R. O. & Adelson, E. H. *J. Vis.* **3,** 347–68 (2003).
21. Pegna, A. J., Khateb, A., Lazeyras, F. & Seghier, M. L. *Nature Neurosci.* **8,** 24–25 (2005).
22. Savarese, S., Fei-Fei, L. & Perona, P. *ACM Intl Conf. Proc. Series: Proc. 1st Symp. on applied perception in graphics and visualization.* 115–118 (2004).
23. Wasserstein, J., Zappulla, R., Rosen, J., Gerstman, L. & Rock, D. *Brain Cog.* **6,** 1–14 (1987).
24. Morris J. S., Ohman A. & Dolan R. J. Proc. Natl Acad. Sci. USA 96, 1680–1685 (1999).

Acknowledgments: I thank M. Bernson, E. Besancon, M. Carrio, A. Dietrich, H. Farid, L. Gay, A. Kiely, A. Lonyai, C. Pemberton, D. Wang, S. Hamlin and R. M. Shapley for their contributions to this work.

Figure 14 **These green billiard balls are all shown to reflect the scene that surrounds the ball on the left[20]. In the central and right examples, the reflections no longer correspond to the new surrounds but subjects perceive the balls to be as glossy as the one on the left. (From ref. 20.)**