square on top of 4 disks is assumed. Note that the completion of the boundaries of the Kanizsa square is accompanied by a surface filling-in process that leads to the square being perceived as brighter than the surrounding white background. In a related process, the black disks are completed "behind" the reconstructed surface. Filling-in and completion processes related to visible figures (the Kanizsa square) are referred to as "modal," while these processes are referred to as amodal when related to invisible parts of figures (the parts of the disks occluded by the Kanizsa square assumed in front by the visual system).

Figures 1(c) and (d) illustrate the existence of surface filling-in processes. Figure 1(c) shows that the physical gray levels in between the black bars are the same. When the black bars are removed, some regions in the stimulus are seen as much brighter and others as darker, an illusion referred to as the Craik-O'Brien-Cornsweet illusion. The difference in brightness in Figure 1(d) is due to the luminance difference (contrast) at the edges of the surfaces. Surfaces outlined by bright edges are perceived as much lighter than surfaces outlined by dark edges. This supports the idea that the surface features that define the edges are interpolated to reconstruct the percept of the surface (in this case brightness). Boundary and surface completion processes are also hypothesized to underlie filling in across the blind spot caused by the absence of retinal receptors where the optic nerve leaves the eye.

Future Research

The present entry on the topic of completion and filling-in cannot adequately reflect the full complexity of this research field. To do justice to some of the ongoing discussion on this topic, it must be mentioned that while the mechanisms of boundary completion are generally agreed upon, the view on surface filling-in in the present entry represents dominant concepts that are not shared by all investigators. For example, it has been suggested that a spread of surface information from the borders to its middle in retinotopic maps is not required. Instead, a mechanism might exist that simply "assumes" that surface properties just inside its edges should also be present in its middle. This is a symbolic (logical) operation that might be carried out in the high-level visual cortex. Some studies have failed to find evidence for the spread of information thought to underlie surface perception in early retinotopic visual areas, and this has been taken by some as support for symbolic theories of surface perception. Hence, further empirical work is required to test the traditional view as well as symbolic theories, and to resolve some inconsistencies in the findings among some studies. Because the traditional view and symbolic theories are not mutually exclusive, elements from both theories might find support in the future.

P. De Weerd

See also Consciousness; Gestalt Approach; Object Perception; Object Perception: Physiology; Perceptual Organization: Vision

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Visual Illusions

Visual illusions are subjective percepts that do not match the physical reality of the world. When we experience a visual illusion, we may see something that is not there, fail to see something that is there, or see something different from what is there. Visual illusions not only demonstrate the ways in which the brain fails to recreate the physical world, but they are also useful tools to identify the neural circuits and computations by which the brain constructs our visual experience.

The terms *visual illusion* and *optical illusion* are often used interchangeably. However, unlike visual illusions, optical illusions do not result from brain processes. Instead, an optical illusion is the perception of a distortion that results from the physical properties of light, such as reflection and refraction, and/or the optics of the eye. An example of an optical illusion is the phenomenon in which a pencil looks bent when it is placed upright in a glass of water, owing to the differing refraction indices of air and water. An example of a classical visual illusion is the Ebbinghaus illusion, named for its creator, Hermann Ebbinghaus. If two identical circles are placed side by side, one surrounded by large circles and the other surrounded by small circles, the first central circle will look smaller than the second one (see *Action and Vision,* Figure 2a). The Ebbinghaus illusion cannot be explained by the physical properties of the visual stimulus or by the optics of the eye. Instead, it is due to neural processes that compare a visual object with its context.

Only a fraction of the visual illusions known today have been developed within the framework of the visual sciences. Visual artists have often used their insights regarding perception to create visual illusions in their artwork. Historically, long before visual science existed as a formal discipline, artists had devised a series of techniques to "trick" the brain into thinking that a flat canvas was three-dimensional or that a series of brushstrokes was in fact a still life. Thus, the visual arts have sometimes preceded the visual sciences in the discovery of fundamental vision principles. In this sense, art, illusions, and visual science have always been implicitly linked. This entry describes various types of visual illusions.

How to Make Visual Illusions

Some visual illusions are developed intentionally by applying known visual principles to stimuli patterns and/or experimenting with variations of existing illusions. Other illusions are discovered completely by chance: An attentive observer may simply notice something strange about the way that the world looks and try to understand and replicate the underlying conditions leading to the unusual percept. Finally, illusions may be discovered through the application of known physiological principles of visual processing in the brain.

One example of this last method is the standing wave of invisibility, a type of visual masking illusion in which the visibility of a central bar (the target) is decreased by the presentation of flanking bars (the masks) that flicker in alternation with the target. This illusion was predicted (by Stephen Macknik and Margaret Livingstone) from the responses of visual neurons to flashing objects of varying durations. The Standing Wave of Invisibility illusion demonstrates that a set of masks can render a target perpetually invisible, even though the masks do not overlap the target spatially or temporally. The invisibility of the target results from the adjacent masks suppressing the neural responses normally evoked by the onset and the termination of the target.

Categories of Visual Illusions

Some attempts have been made to classify visual illusions into general categories with varying degrees of success. One substantial obstacle to classifications or taxonomies of visual illusions is that some visual illusions that seem similar may be due to disparate neural processes, whereas other visual illusions that are phenomenologically different may be related at a neural level. Taking these shortcomings into account, some representative categories and examples of visual illusions follow. When known, their underlying neural bases are also discussed. However, the reader should keep in mind that the neural underpinnings of many visual illusions—especially those discovered recently—are not understood. What follows is by no means an exhaustive list.

Adaptation Illusions

The first documented visual illusion was described in Aristotle's *Parva Naturalia*. This illusion, later known as the "waterfall illusion," can be observed while looking at a waterfall, river, or other flowing water. Watch the flowing water for a while (a minute or more works best), and then quickly shift your center of gaze to the stationary objects next to the water (for instance, the rocks to the side of the waterfall). The stationary objects will appear to flow in the opposite direction to that of the water. The illusion occurs because neurons that detect motion in a specific direction (for instance, downward motion if you stare at a waterfall) become adapted (that is, less active) in response to steady stimulation. Neurons that have not been adapted (such as the neurons that detect upward motion) are more active in comparison, despite having been at rest. The differential responses of both neuronal populations produce the illusion of the stationary rocks to the side of the waterfall flowing upward for a few seconds.

Brightness Illusions

Some visual illusions change the apparent brightness of objects. Brightness and color illusions often occur because the brain does not directly perceive the actual wavelength and light reflected from objects in the world. Instead, it compares them to those of other objects in the vicinity. For instance, the same gray square will look lighter when surrounded by black than when surrounded by white. Thus, for the brain, perception is often context dependent.

The Hermann grid is another classic example of a brightness illusion. In this phenomenon, a white grid against a black background shows dark illusory smudges in the intersections. Conversely, a black grid against a white background results in whitish smudges perceived at the intersections (see *Contrast Perception,* Figure 3a). In 1960, Günter Baumgartner measured the responses of visual neurons during the presentation of Hermann grid stimuli. He concluded that the illusion is due to differences in the firing of center-surround retinal ganglion cells to the various parts of the grid (intersecting versus nonintersecting regions). Thus, the Hermann grid illusion has been traditionally interpreted as a perceptual result of lateral inhibition. However, recent research suggests that the retinal ganglion cell theory is incomplete and that the illusion may be generated at the cortical level.

Color Illusions

These are illusions that modify the apparent color of an object. Some classical color illusions are based on simultaneous color contrast. For instance, a gray circle will take on a reddish hue when placed against a green background, and a greenish hue when placed against a red background. This local contrast effect is based on retinal lateral inhibitory processes. Other context-dependent color illusions, such as the "Rubik cube" created by R. Beau Lotto and Dale Purves, are more difficult to explain by local lateral inhibition at the level of the retina, and may thus reflect a more central origin.

Benham's disk, or Benham's top, was discovered in 1894 by C. E. Benham, a toymaker. A spinning top with a certain pattern of black and white lines appears to take on colors as it rotates. This illusion has been studied by vision scientists for over 100 years, and it continues to inspire novel research. The underlying neural processes are not well understood, but current theories point toward retinal circuits.

Illusions of Size

The apparent size of an object is changed, usually due to contextual cues. In the Ponzo illusion, two horizontal lines of the same length are superimposed on a pair of converging lines resembling train tracks. The upper line (closer to the converging end of the tracks) seems longer than the lower line (closer to the diverging end of the tracks). The illusion is probably due to the fact that the brain interprets the upper line as farther away than the lower line. The Moon illusion (the perception that the moon looks bigger when close to the horizon than when high up in the sky) might be at least partially related to the Ponzo illusion. That is, the moon close to the horizon may look larger because of accompanying contextual cues, such as trees and houses, indicating that the moon must be far away. Such contextual cues are absent when the moon is high up in the sky.

The Ebbinghaus illusion, discussed in the introduction to this entry, is another example of a classic size illusion.

Shape and Orientation Illusions

These are illusions in which an object appears to take on shapes or orientations that are different from the actual physical ones. Distortion effects are often produced by the interaction between the

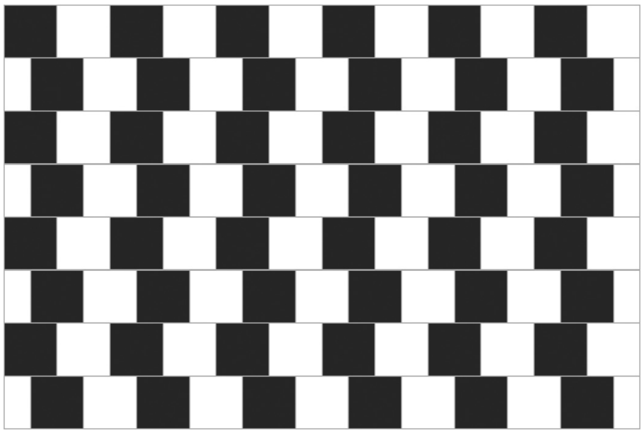

Figure 1 The Café Wall Illusion

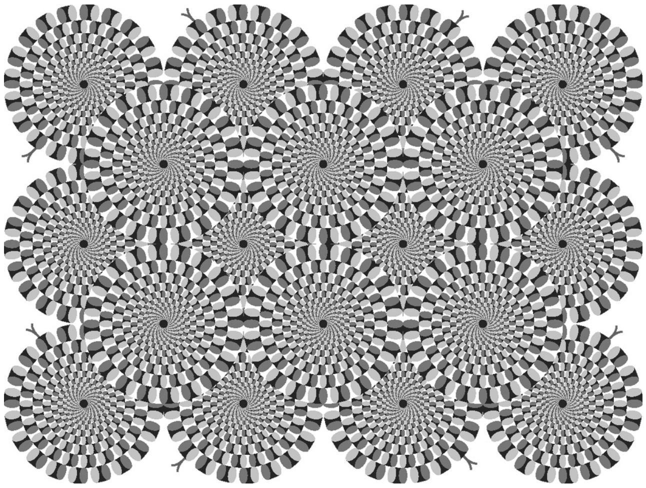

Figure 2 The Rotating Snakes Illusion

Source: Courtesy of Akiyoshi Kitaoka.

actual shape or orientation of the object, and the shapes or orientations of other nearby figures. A classical example is the Café Wall illusion, first discovered in a café in Bristol, England. The black and white tiles in the Café Wall are perfectly straight, but look tilted (see Figure 1).

Invisibility Illusions

In an invisibility illusion, observers fail to perceive an extant object in the physical world. In motion-induced blindness, the observer fixates the center of a display consisting of several stationary circles and a surrounding cloud of moving dots. Although the stationary circles remain physically extant on the display, they fluctuate in and out of visual awareness for the duration of the viewing (sometimes only one circle disappears, sometimes two, sometimes all of them). The neural mechanisms underlying this phenomenon are currently unknown.

The standing wave of invisibility, described earlier, is another example of an invisibility illusion.

Illusory Motion

Some stationary and repetitive patterns generate the illusory perception of motion. The illusory effect is usually stronger if you move your eyes around the figure. If you keep your eyes still, the illusion tends to diminish or even disappear completely. For instance, in the Rotating Snakes illusion created by Akiyoshi Kitaoka, the "snakes" appear to rotate. But nothing is really moving, other than your eyes. If you hold your gaze steady on one of the black dots on the center of each "snake," the motion will slow down or even stop (see Figure 2). Bevil Conway and colleagues showed that the critical feature for inducing the illusory motion in this configuration is the luminance relationship of the static elements. Illusory motion is seen from black to dark gray to white to light gray to black. When presented alone, all four pairs of adjacent elements each produced illusory motion consistent with the original illusion. Also, direction-selective neurons in macaque visual cortex gave directional responses to the same static element pairs, in a direction consistent with the illusory motion. These results demonstrated directional responses by single neurons to static displays and suggested that low-level, first-order motion detectors interpret contrast-dependent differences in response timing as motion.

Stereo-Depth Illusions

Your left eye and your right eye convey slightly different views of the world to your brain. Close your left and right eye in rapid alternation. You will see that the image shifts left to right. Your brain integrates these two images into a single stereo image, which conveys a sense of depth. This is the principle behind stereo-depth illusions. The wallpaper illusion is a classic example, which arises when observing a pattern of horizontal repetitive elements, such as in wallpaper. If viewed with the appropriate vergence, the repetitive elements appear to float in front or behind the background. The wallpaper illusion is related to the illusions portrayed in the famous Magic Eye books (the Magic Eye illusions are based on a special type of repetitive pattern, called a random dot autostereogram).

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See also Afterimages; Contrast Enhancement at Borders; Hallucinations and Altered Perceptions; Impossible Figures; McCollough Effect; Nonveridical Perception; Pictorial Depiction and Perception; Visual Masking

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Visual Imagery

How many windows are there in your home? Is the green of grass darker than the green of pine trees? How many straight and/or curved lines make up an uppercase letter E? If you have not thought about these questions before, it is likely that you experienced a visual image while finding their answers. For example, to determine the number of windows in your home, you might have imagined yourself standing in each room and counting the number of windows you "saw" in your mental image. *Visual imagery* refers to the experience of seeing something that is not physically present, so that there is no corresponding sensory input to your visual system. It is often referred to as "seeing with the mind's eye." Most people report that they experience visual images when answering the types of questions posed above, as well as when figuring out how to best pack suitcases in the trunk of their car or rearrange the furniture in their living room. Distinguished scientists and inventors, such as Albert Einstein, Nikola Tesla, and Richard Feynman, reported that their thought processes were accompanied by the experience of mental imagery. For example, Tesla reported that when he first designed a device, he would run it in his head for a few weeks to see which parts were most subject to wear. In what ways is visual imagery like seeing? In what ways is thinking with images different from other forms of thinking? These questions will be discussed in this entry, along with the perceptual characteristics of images, the physiological basis of imagery, the imagery debate, visual versus spatial images, and the functions of visual images.

Perceptual Characteristics of Images

Objective measures have shown that the experience of having a mental image is similar to the experience of seeing in many respects. The time to answer questions about objects in a mental image is related to the relative size of those objects, as if one has to "zoom" into the image to see the details of the object's appearance. For example, it takes longer to "see" whether a rabbit has whiskers if you imagine a rabbit next to a fly than if you imagine a rabbit next to an elephant. Time to scan between objects in a mental image is also related to the distance between these objects, just as it takes more time to scan between objects that are farther apart when looking at a real scene. For example, if you imagine a map of the United States, it takes longer to scan from San Francisco to New York