4-1-2006

Optical Illusions and Their Causes: Examining Differing Explanations

Sarah Oliver
Franklin W. Olin College of Engineering, Sarah.Oliver@alumni.olin.edu

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Sarah Oliver
AHS Capstone
9 May, 2006

Illusion is the first of all pleasures.
Oscar Wilde

Introduction

Optical illusions stimulate us by challenging us to see things in a new way. They are interesting within scientific disciplines because they lie on the border of what we are able to see. According to Al Seckel (2000), they "…*are very useful tools for vision scientists, because they can reveal the hidden constraints of the perceptual system in a way that normal perception does not."* Different kinds of optical illusions may be better explained by one discipline or another. Some optical illusions trick us because of the properties of light and the way our eyes work, and are addressed by biology and perhaps optics, while other illusions depend on a "higher" level of processing which is better addressed by psychology. Some illusions can only be fully explained using knowledge of more than one discipline. When there are both biological and psychological explanations, they may both be right. There is already a substantial body of work that specifically addresses optical illusions, however, there is still enough disagreement within disciplines and between disciplines to make this an interesting project.

One of the challenges of this project is the question of how to choose a satisfactory definition of "optical illusion." Every source has a different definition that includes or excludes phenomena as it suits the author's purpose. Gregory, one of the most well-known researchers of optical illusions, notes that illusion

> … may be the departure from reality, or from truth; but how are these to be defined? As science's accounts of reality get ever more different from appearances, to say that this separation is 'illusion' would have the absurd consequence of implying that almost all perceptions are illusory. It seems better to limit 'illusion' to systematic visual and other sensed discrepancies from simple measurements with rulers, photometers, clocks and so on. (Gregory, 1997)

Gregory addresses the difficulty in defining "illusion" in such a way that it includes everything that we think of as illusions, but excludes things like movies, which are illusions in the sense that they appear to depict motion while actually being composed of a series of static pictures.

A similar definition of illusion comes from Held:

> [We assume there is] a necessary correspondence between certain of the properties of the object (such as wavelength of reflected light, measured size, geometric shape) and those of its perceived image (color, apparent size, form)… [If] one or more of these assumed correspondences proves incorrect, we term the perception an illusion. Accordingly, the illusions simply indicate the inadequacies of the assumed correspondences. (Held, 1974)

Both of these definitions have a good level of specificity for the illusions that I wish to address. Other definitions, some more inclusive and some less so, can be found in Appendix I.

For the purposes of this paper, I will further narrow the definition of optical illusions to include only illusions that are two-dimensional and stationary in time. In addition, I will not address *all* illusions meeting these criteria, but will focus on those illusions for which multiple explanations have been proposed.

When considering a large set of illusions, it would be useful to organize these illusions in some meaningful way. The limited scope of this paper may make such a classification system less necessary than it would be in a larger project. However, a classification system will place my work in the context of other illusions, and may suggest future directions to pursue.

One of the most complete classification systems that I've found comes from Gregory (1997) (see Table 1).

	Physical		**Cognitive**	
Kinds	*Optics*	*Signals*	*Rules*	*Objects*
Ambiguity	Mist	Retinal rivalry	Figure-ground	Hollow face
Distortion	Mirage	Café wall	Muller-Lyer	Size-weight
Paradox	Mirror	Rotating spiral	Penrose triangle	Magritte mirror
Fiction	Rainbow	After-images	Kanizsa triangle	Faces in the fire

Table 1: Gregory's classification system, with an example of each type of illusion. Several of these illusions are addressed in this paper, but others are excluded because they fall outside of my definition of "illusion."

He starts with defining a simple division between physical and cognitive illusions. He further divides physical illusions into two categories: those due to optics (disturbance of light between objects and the eyes), and those due to the disturbance of the sensory signals of the eye. He then divides cognitive illusions into those that are due to general knowledge (or "rules"), and those that are due to specific knowledge of objects. This classification system seems to suggest that certain illusions would be better studied by particular disciplines. For example, it would not be useful to study cognitive illusions using one's knowledge of optics. It is tempting to throw all optical illusions into one of these categories. However, Gregory cautions that "[a]lthough [physical and cognitive illusions] have extremely different kinds of causes, they can produce some surprisingly similar phenomena," so it may not be wise to put seemingly similar illusions in the same category without looking at the research. In addition, some illusions may have aspects that place them in two or more categories.

This paper addresses such a small number of illusions that a classification system is not really necessary to make the project manageable. However, Gregory's classification system is useful for suggesting possible directions to pursue regarding various illusions. For example, illusions in the "cognitive" categories would probably be more thoroughly addressed in the literature of psychology or cognitive sciences than they would in the literature of biology.

Background

Since most of the research on optical illusions falls into the realm of either psychology or physiology, it may be useful to give some basic information about how each discipline views optical illusions, before examining specific illusions.

One of the sections of psychology that is relevant to optical illusions is that which studies stimulus inadequacy. Stimulus inadequacy usually applies to monocular vision but the relevant theories are useful for considering binocular vision as well. In general, stimulus inadequacy refers to the situation in which more than one distal stimulus (objects in the real world) produces the same proximal stimulus (image projected on the retina). See Figure 1:

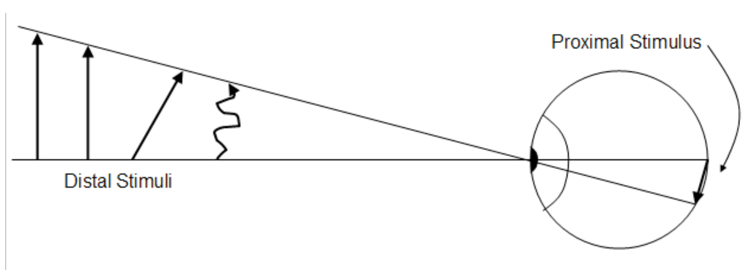

Figure 1: Stimulus Inadequacy: Multiple distal stimuli can produce the same proximal stimulus on the retina.

There are two main groups of theories that seek to explain how the mind deals with stimulus inadequacy. These are the empiricist and the psychophysical (or Gibsonian) views.

In the empiricist view, when the stimulus alone is inadequate, visual perceptions are unconscious inferences based on other knowledge, memories, assumptions, inferences, etc. (Gregory, 1997), (Hershenson, 2000). For an example of the use of knowledge to resolve a stimulus inadequacy problem, see Figure 2:

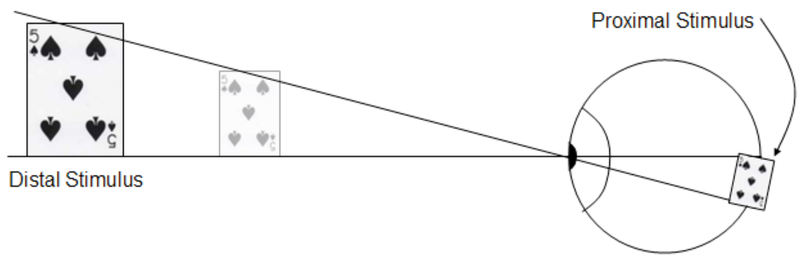

Figure 2: An empiricist resolution to stimulus inadequacy: When shown an extra-large sized playing card at a certain distance, the viewer will use their past experience with playing cards to interpret the proximal stimulus as being a normal sized playing card at a closer distance.

Gregory expands on this by saying, "we may say that knowledge is necessary for vision because retinal images are inherently ambiguous (for example size, shape and distance of objects) and because many properties that are vital for behaviour cannot be signalled by the eyes, such as hardness and weight, hot or cold, edible or poisonous." (Gregory, 1997).

The Gibsonian, or psychophysical, view is that stimuli are only inadequate when brought into the laboratory and removed from their natural context. Gibson believes that the stimulus contains all the information necessary, with no need for inferences[1].

In the natural world, Gibson argues, the eye is almost always positioned somewhere above the ground plane, and the human visual system evolved to take this into account (Hershenson, 2000). Figure 3 illustrates the difference between Gibson's analysis and the empiricist view. Empiricists would say that since points A, B, C, and D lie on the optic axis and therefore all stimulate the same point on the retina, there is no depth information present. In Gibson's view, points on the optic axis are upward projections of points on the

[1] It is relevant to this paper to note that if humans rely on acquired knowledge to recognize objects, we would be blind to new or unusual stimuli. Gibson did not recognize the phenomena of illusion (Gregory, 1997).

ground plane, and therefore would stimulate different points on the retina, providing depth information.

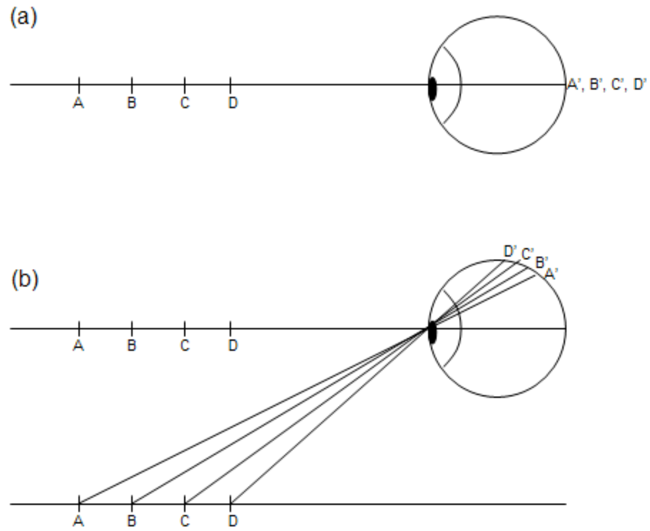

Figure 3: (a) represents the empiricist understanding of the perception of points which lie on the same optic axis: since all four points stimulate the same point on the retina, the visual system is unable to extract depth information from the stimuli. (b) represents Gibson's understanding of the problem. Points A, B, C, and D are at eye level, and they must be understood in relation to the ground plane. Projecting the points onto the ground plane yields a different proximal stimulus (A', B', C', D') on the retina for each point, allowing the visual system to extract depth information.

The details of these two opposing views will in general not be important when considering illusions. The important difference between them is that the Empiricist view assumes the need for inferences or past knowledge when understanding a stimulus, and the Gibsonian view argues that the stimulus can be understood without past knowledge, based solely on rules of perception that exist in the visual system.

Explanations for optical illusions are not addressed exclusively by psychology. There are compelling physiological causes for some illusions. It may be useful to briefly address the relevant anatomy of the human eye, as background for later discussions.

Although the human eye has many interesting structures, the part of the eye most relevant to this paper is the retina. The retina is made up of cells onto which light that passes through the lens is projected. Points in a person's peripheral vision would be projected on the edges of the retina, where the cells are larger and hence have lower acuity. Points in the center of a person's vision are projected onto the fovea, which is a part of the retina located near the optic nerve (see Figure 4). Over the entirety of the surface of the retina there are layers of cells that lie between the photoreceptors and the incoming light. At the fovea, however, these layers are much thinner, allowing the light to pass straight to the photoreceptors without interference. In addition, the photoreceptor cells are smaller and more closely packed in the fovea, allowing for higher acuity (Livingstone, 2002).

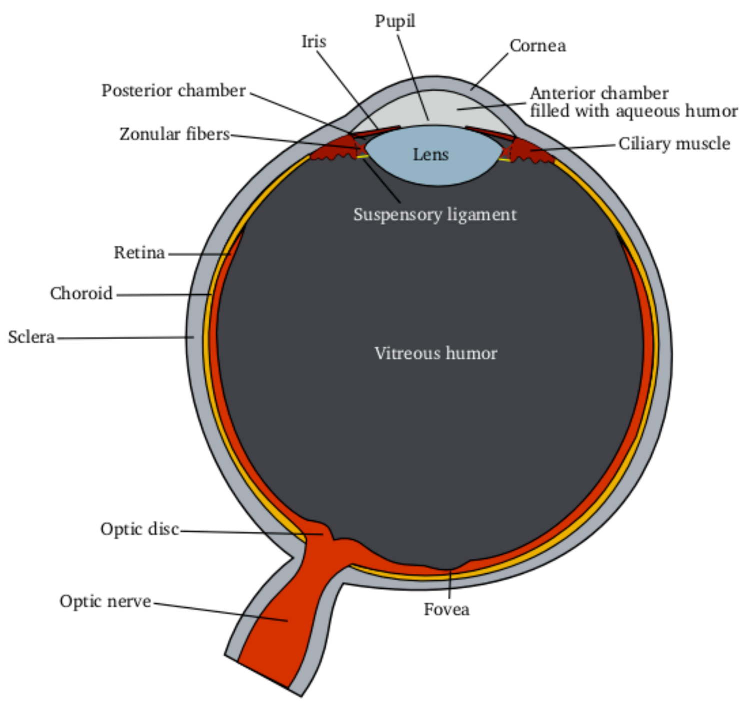

Figure 4: The parts of the eye most relevant to this paper are the retina (in red) and the fovea, which is a part of the retina near the optic nerve (image credit: Fovea, 2006).

Although the anatomy of the eye has certain parallels with the components of a camera and has often been explained in those terms, the analogy is misleading because it gives an impression of the brain as a passive receiver of projected images, which fails to credit to the role of the brain in visual perception (Zeki, 1999). Frisby points out that optical illusions can actually be used to deconstruct the camera analogy (1979). He offers Fraser's spiral as an example (see Figure 5).

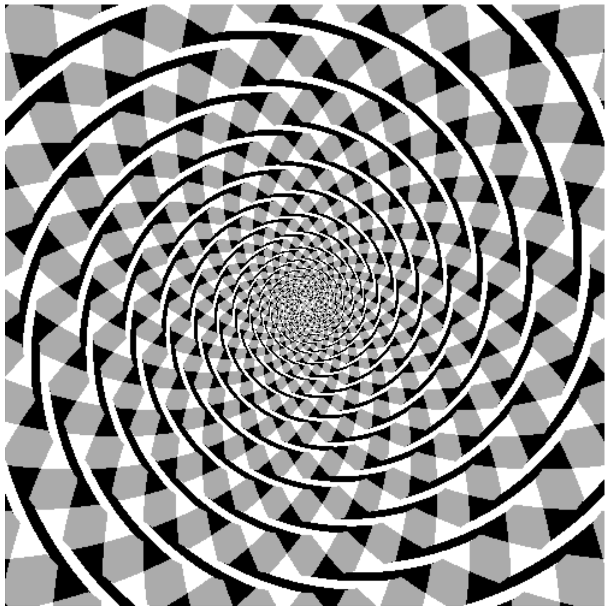

Figure 5: Fraser's spiral (actually a series of concentric circles) can be used to demonstrate how the human visual system differs from a camera (image credit: Fraser, 2006)

Fraser's illusion is made up of concentric circles that appear to be spirals. However, although the illusion can fool the human visual system, it can't fool a camera. The camera records the concentric circles, which can be confirmed by tracing the circles in the image with a finger. He concludes regarding the visual system that "[a] process which takes concentric circles as input and produces a spiral as output can hardly be thought of as 'photographic'" (Frisby, 1979). Further emphasizing the importance of knowledge in visual perception, Gregory notes that "[r]emarkably, there are more downwards fibres from the cortex to the lateral geniculate bodies (LGN) 'relay stations' than bottom-up from the eyes (Sillito, 1995), (Gregory, 1997). This is intriguing because it suggests that the brain may "tell" the eyes what they are seeing more than the eyes tell the brain.

The behavior and specialization of cells in the retina and cortex are especially relevant when studying optical illusions. The first major divergence in function begins in the retina.

There are large and small ganglion cells, corresponding to different kinds of visual information (Livingstone, 2002). The large cells mark the beginning of a pathway that is sometimes called the "Where" system. The smaller cells belong to the "What" system. The Where system is considered to be the older (evolutionarily speaking) of the two systems. This system is responsible for the perception of motion, depth, position, and figure/ground separation (Livingstone, 2002). The Where system is blind to color, but is highly sensitive to contrast or differences in luminance (brightness). The What system is only well-developed in primates, and is responsible for the perception of color and detail, and for the ability to recognize objects such as faces. Emphasizing the separation of these two systems, Livingstone (2002) offers that "[t]he areas of our brain that process information about color are located several inches away from the areas that analyze luminance—they are as anatomically distinct as vision is from hearing."

Most cells in the retina and thalamus are organized as "center-surround" in their selectivity for whatever feature they specialize in. Center-surround refers to the idea that each cell has a network of dendrites which collectively form the receptive field of the cell. Each cell or type of cell is selective for something, whether it be a color, or the presence of light, or a more complex feature. Let's consider a cell that is selective for light. The center of the cell's receptive field is stimulated by the presence of light, but the area surrounding the center is inhibited by light. Conceptually this can be understood as depicted in Figure 6. The center of the cell's receptive field is represented by + signs to indicate a positive response, and the surround is represented by – signs. Obviously the cell will produce the strongest signal when all of the "+s" and none of the "-s" are activated. This scenario is shown in Figure 6(b), where there is a small spot of light focused on the center of the cell's receptive field.

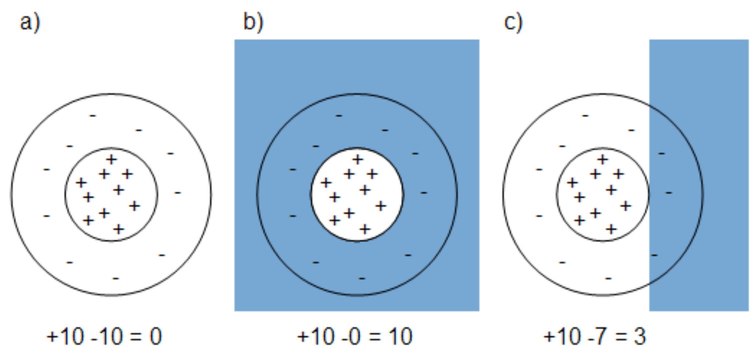

Figure 6: The center-surround organization of this cell means that it produces a strong signal in response to discontinuities, but not to ambient lighting conditions. In (a), which depicts bright lighting conditions, the cell produces no signal. Obviously the same would be true if the cell were exposed to darkness (+0 -0 = 0). The cell produces the strongest response when stimulated by a small point of light that falls on the center of the receptive field.

This cell behavior is important in the explanation of several illusions.

Some illusions have causes that are neither psychological nor physiological in nature. Examples of such illusions include rainbows, mirages, and the illusion that occurs when a stick is inserted into a glass of water (the stick seems to bend). Since most physical optical illusions don't meet my criteria (two-dimensional, stationary in time) they fall outside the scope of this paper.

Let us now examine several interesting illusions for which there exists more than one explanation. As you will see, for each illusion there is a variety of theories that complement or contradict each other.

Hermann Grid

An illusion interesting for the controversy surrounding it is the Hermann grid illusion. The classic grid, discovered by Ludimar Hermann in 1870 (Livingstone, 2002), consists of a white grid on a black background (see Figure 7):

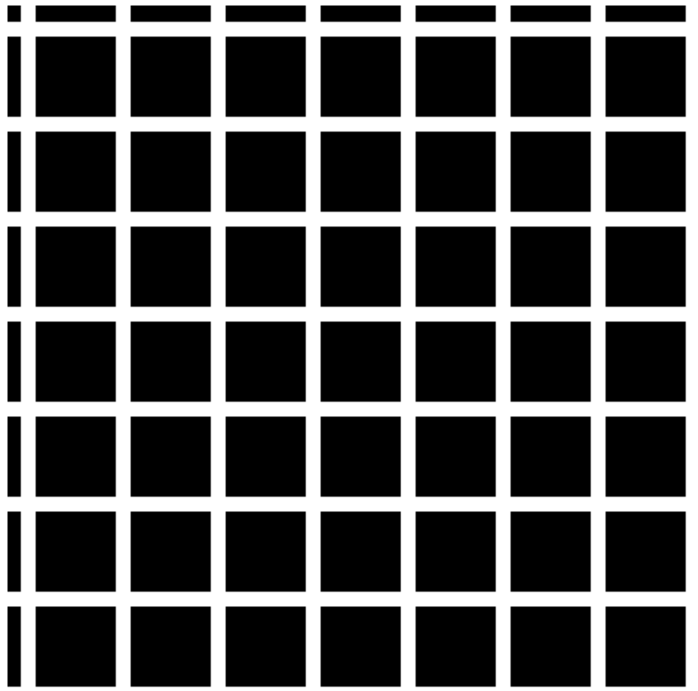

Figure7: The Hermann grid illusion. Gray spots should appear at the intersections of the grid when the viewer focuses his or her eye elsewhere

The viewer will notice that the intersection of two white lines appears white when she looks directly at it, but appears gray when viewed out of the corner of her eye.

The traditional explanation is a physiological one that uses the center-surround properties of ganglion cells to explain the effect of the illusion. This property of retinal ganglion cells was discovered in 1953 by Stephen Kuffler, who found through experimentation that cells responded better (produced larger electrical impulses) to small spots of light than to large spots (Livingstone, 2002). From this he deduced that cells are activated by light that reaches the center of their receptive field, but are inhibited by light that falls on the edges of the receptive field. Researchers later found that the center-surround organization also applies to cells in the thalamus. What this means is that the human visual system is more responsive to edges and discontinuities than to gradual changes in light levels.

When considering the Hermann grid, note that a cell whose receptive field is of a particular size will have its center stimulated equally by a point on a line and by a point on an intersection. However, the "surround" of the cell's receptive field will be inhibited more by the greater amount of white space present in the intersection (see Figure 8), resulting in a stronger signal from the point on a line. The reason why the effect is stronger in the viewer's peripheral vision is that retinal cells are smaller the closer they are to the fovea (Bach, 1999). Again, this is the most widely accepted explanation for the Hermann grid illusion. However, it is disputed by some.

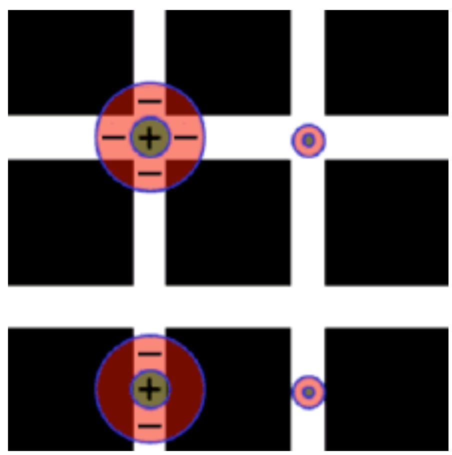

Figure 8: cells are more weakly stimulated by points in the intersections of the grid (image source: Bach, 1999)

In particular, Geier, Sera, and Bernath published a paper in 2004 offering a simple refutation of the traditional explanation. They point out that when a sinusoidal function is applied to the lines of the grid, the gray spots disappear (see Figure 9):

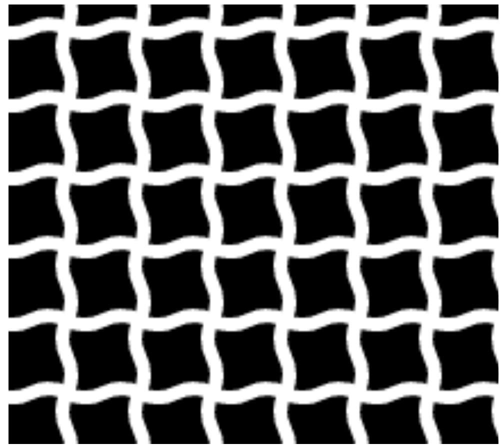

Figure 9: Hermann grid with a sinusoidal function applied. Note that the illusion disappears. (image source: Bach, 1999)

If the traditional explanation were correct, the illusion should still be present, since the cells that were inhibited/stimulated by a square grid would receive the same input from local sections of the sinusoidal grid, and the gray spots should still occur. Greier et al do not offer an alternative explanation, but they do conclude that the illusion seems to depend on the straightness of the lines of the grid, and not on the width of the lines. This is unexpected, based on the traditional explanation; thinner lines would be expected to strengthen the illusion because of the fact that the size of receptive fields of retinal cells increases with greater distance from the fovea. Thinner lines would result in more of the centrally-located cells getting weak signals which would in turn cause gray spots to appear closer to the center of focus. In addition, personal experimentation leads me to believe that the thickness of lines does make a difference. The illusion is stronger when the grid is viewed at a greater distance, as suggested by Livingstone (2002).

An alternative explanation for the illusion is offered by Schiller Lab at MIT. As additional evidence against the traditional explanation, Schiller notes that a grid of black lines on a white background produces the illusion as well as the classic coloring, which doesn't make sense if the centers of cells are stimulated by light and inhibited by darkness. However, this complaint doesn't seem to take into account the different types of retinal cells; there are cells that are sensitive to white, and there are also cells that are sensitive to black, and inhibited by white (Livingstone, 2002). Another point that Schiller brings up seems more valid: he notes that in a grid pattern with intersections designed to maximize the inhibition of cells, the illusion does not increase, as would be expected under the traditional explanation (see Figure 10):

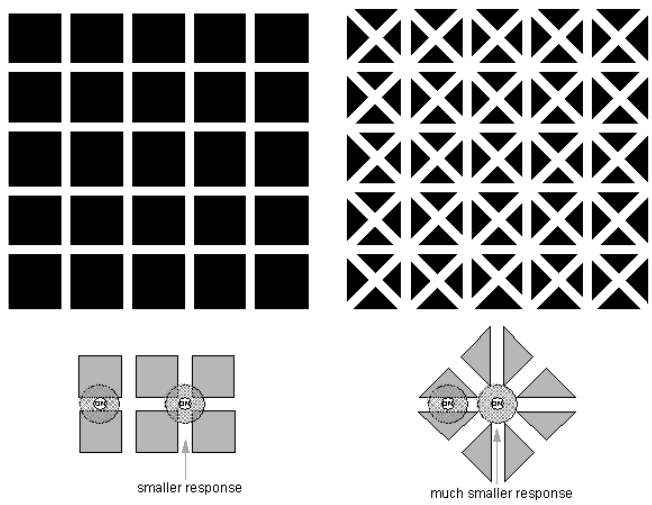

Figure 10: A grid designed to maximize inhibition does not increase the effect of the illusion. (image source: Schiller, 2005)

Schiller proposes that the Hermann grid illusion is due not to center-surround responses in retinal ganglion cells, but to the responses of orientation-selective neurons in the cortex. Cells that select for vertical lines "sum" the presence of a vertical line in the surround of the cell's receptive field, and if there is sufficient verticality present, the cell produces a signal that leads to the perception of activity at the *center* of the receptive field (see Figure 11):

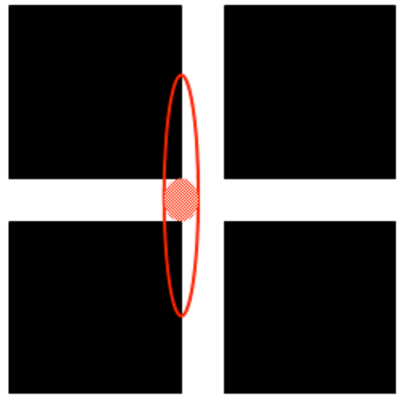

Figure 11: The vertically-selective cell (in red) responds to the presence of vertical lines in the surround of its receptive field by producing a response at the center of the field (solid red), where there actually is no vertical line.

In the case of the Hermann illusion, a cell that is selective for verticality could sum the signal above and below an intersection, and then cause a response in the intersection, even though there is no vertical line at that location. The explanation would of course also include the responses of horizontality-selective cells. This would explain the appearance of the gray areas at intersections.

There seem to be serious problems with the traditional explanation for the Hermann grid illusion, but it is currently more widely accepted than any of the alternate explanations. This may change as research progresses; the alternative explanations are relatively new and have not been extensively studied or published. The problem seems to be a very current one that will probably continue to be debated in the near future.

Equiluminance

Images displaying equiluminance don't often show up in books of optical illusions, but they are interesting, perhaps more for the theorized cause than for the effect. People viewing an image with various colors of equal luminance (apparent brightness) might notice that the shapes seem to shimmer. Also common is for viewers to report that the image makes their head hurt. One of the most well-known works making use of equiluminance is Richard

Anuszkiewicz's *Plus Reversed* (see Figure 12). Note that the point at which two colors are equiluminous varies from person to person as well as depending on lighting conditions, so this painting may not achieve perfect equiluminance for you, the viewer, but you should be able to see some of the effect.

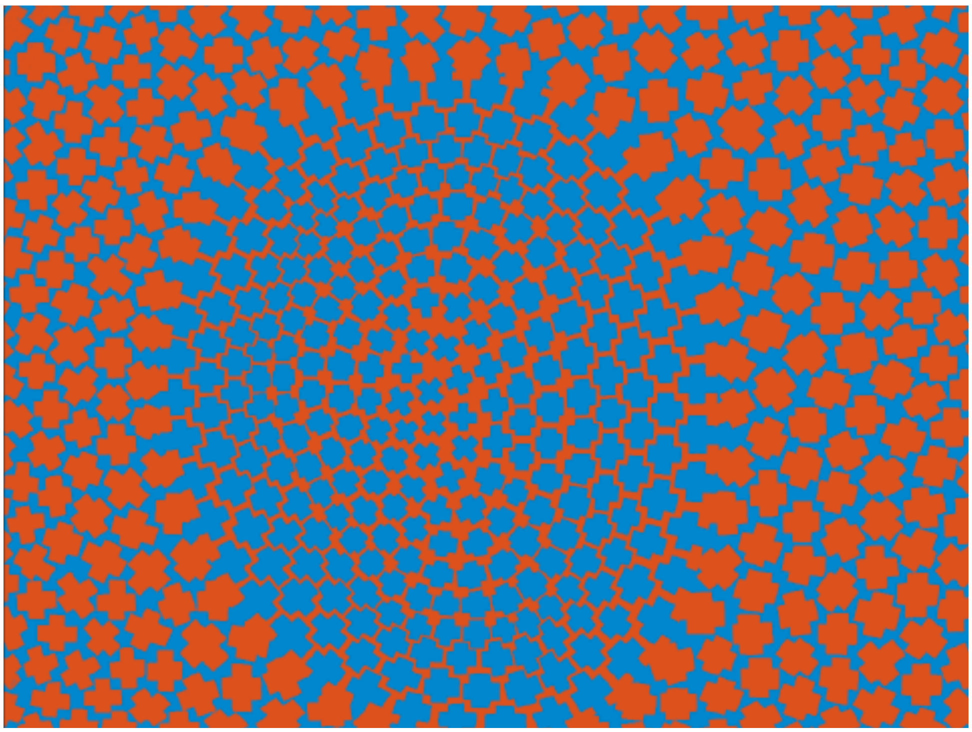

Figure 12: *Plus Reversed* by Richard Anuszkiewicz, 1960. The red and blue are equiluminous, making the image seem unstable (image source: Douma, 2006).

The most popular explanation for the visual effect of equiluminance is based on the idea that the human visual can be broken into two subsystems: the Where system and the What system.

When two colors are equiluminant, the Where system cannot differentiate between them. The What system is able to differentiate between the colors, but is unable to provide the position information that would normally come from the Where system. This is why the shapes in an equiluminous image may seem to shimmer or be unstable.

However, Cavanagh takes issue with the assertion that the visual system is incapable of perceiving position information in luminance-defined images (Cavanagh, 1991. He notes that while previous researchers have attempted to link the Where and What systems to two different kinds of cells (magnocellular and parvocellular, respectively), in fact both types of cells are involved in perceiving luminance. When luminance information is available, the visual system prefers to use luminance to determine position, but color can also convey position, although at a lower resolution. Cavanagh argues that because the What system has a lower resolution when perceiving position, many past experiments are invalidated because they used stimuli too small for the What system to perceive.

One interesting finding of Cavanagh's relating to illusions is that while *explicit* contours can be perceived in equiluminous images, *implicit* contours are not seen (see Figure 13).

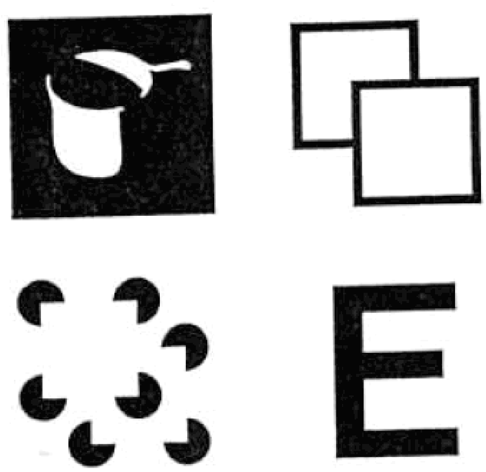

Figure 13: The two figures on the left are examples of implicit contours, while the figures on the right are explicit contours. Under equiluminous conditions, explicit contours are perceived but implicit contours are not. In the case of the figure in the lower left, the viewer would see seven partial circles instead of eight circles partially or fully occluded by two squares (Cavanagh, 1991).

While there are minor disagreements about the details of how we perceive equiluminous images, researchers seem to agree on the basics. Even if the What system is able, to some extent, to see edges defined by color, it is not as effective at processing edges and position, so the shimmering effect still occurs.

Impossible Objects: Penrose Triangle

Impossible objects include such illusions as the Penrose triangle, the impossible cube, and several of M. C. Escher's drawings, such as "Waterfall" (Figure 16). All of these figures have common attributes, so we will just consider the Penrose triangle in depth. It is interesting to note that the Penrose triangle and other impossible figures can be "constructed," in that a three dimensional model can be built and photographed in such a way that it appears to be an impossible object. Two such constructions are shown in Figures 14 and 15. Obviously the existence of these physical objects means that they are not impossible at all. So why, when we view a two-dimensional depiction of a Penrose triangle such as that in Figure 17, do we not automatically interpret the figure as one of the possible physical constructions? Why do we see the Penrose triangle as a paradox?

Figure 14: Penrose triangle

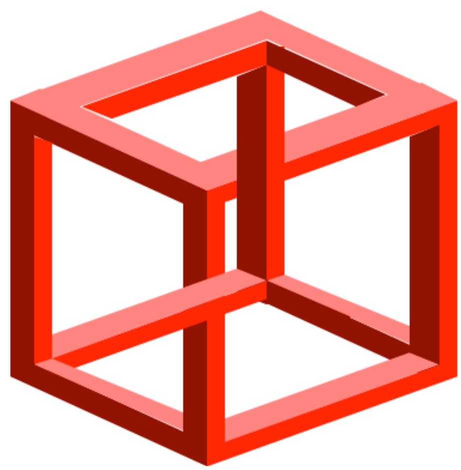

Figure 15: Impossible Cube

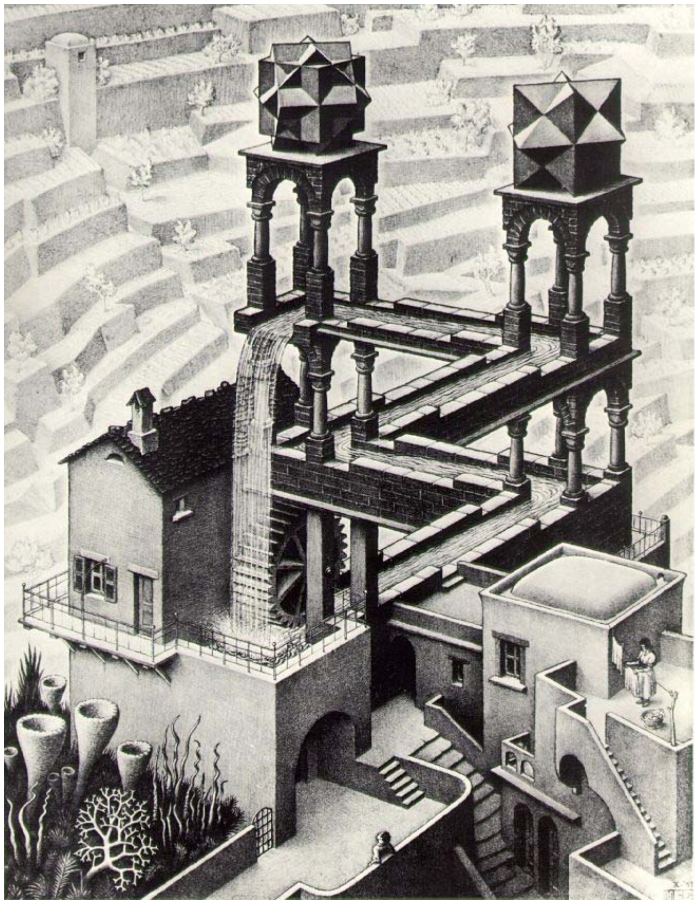

Figure 16: *Waterfall,* M. C. Escher. Lithograph, 1961.

Figure 17: The actual physical construction can be seen in the mirror. (image source: Impossible, 1997)

The physiological explanation for impossible figures is based on the levels of vision processing that take place in the brain. Certain cells are responsive exclusively to vertical lines, or horizontal lines, or corners, or points of light. Taking all of these responses together, the brain can determine, for example, that it is seeing a rectangle (responses from horizontal-responsive cells, vertical-responsive cells and corner-responsive cells). This seems to be the way that the brain operates; process local stimuli and then combine the results incrementally to perceive the global scene. Local consistency is thus more important than overall consistency. If the brain cannot make the global scene consistent, it can "fall back" a level and be content with local consistency (Frisby, 1979). If global consistency were vital, the brain could interpret the Penrose triangle the three-dimensional construction shown in Figure 17, but it does not do this.

A possible psychological explanation for why the brain "favors" the impossible object over a possible one comes from Gogel's "equidistance tendency." This states that when viewing two objects separated by some angle, the objects will appear closer in depth for small angles (see Figure 18) (Hershenson 2005).

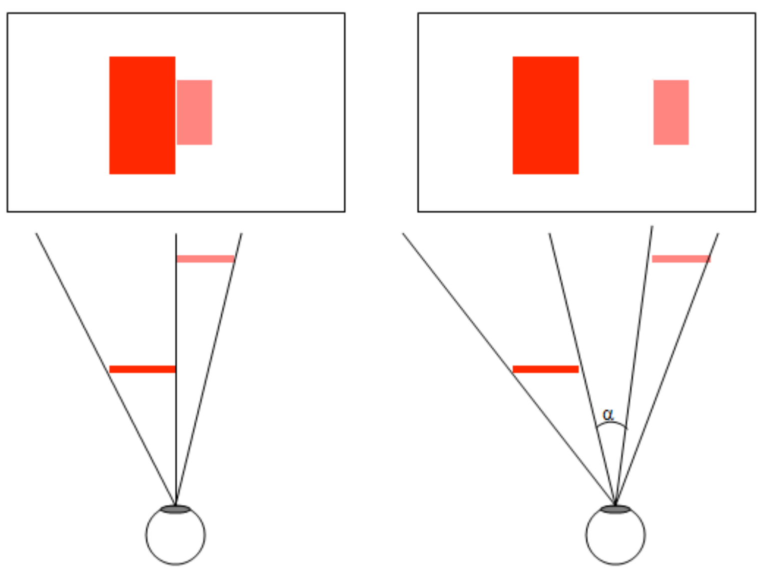

Figure 18: The smaller the separation angle of the two objects, the closer the objects appear in depth. (Hershenson, 2005)

This may shed some light on the Penrose triangle illusion. It may be that the brain is unable (or disinclined) to see the two-dimensional illusion as the three-dimensional construction in Figure 17 because this interpretation would mean that two legs of the triangle which are close to each other in the two-dimensional image are very far apart in the three-dimensional image.

In none of the sources that I've found did I see any use of the equidistance tendency to explain the Penrose triangle illusion or any other impossible figure. However, I think that it's a reasonable application of the finding, given the similarity with other published examples (Hershenson, 2000, 2005).

The two explanations offered for the Penrose triangle illusion (equidistance tendency and local vs. global consistency) seem to work pretty well independently, but they don't contradict each other so it's also possible that both explanations, taken together, are valid.

Müller-Lyer Size Illusion

The Müller-Lyer illusion is a simple size illusion consisting of two lines capped by arrowheads pointing in differing directions (see Figure 19). Most viewers perceive the line on the bottom to be longer than the line on the top, when in fact they are equal in length.

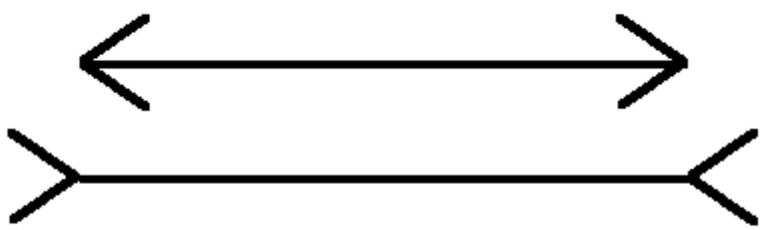

Figure 19: The Müller-Lyer illusion. Most people report that the bottom line seems longer, although the horizontal segments of each drawing are equal in length. (image source: Mueller, 2006)

The simplest explanation for this illusion is that the bottom line appears longer because the arrowheads extend past the ends of the line, making the eyes move a greater distance from end to end. Another early theory was that "the heads induced a state of empathy in the observer, making him feel as if the central line were being either stretched or compressed"

(Gregory, 1968). Currently the most popular explanation is that the lines are perceived as corners in perspective (see Figure 20) (Gregory, 1968). This explanation is based on the idea that when we see an "inside corner," it is usually further away from us, and when we see an "outside corner" it is closer to us. Using our knowledge of perspective, we subconsciously reason that the *actual* size of the more distant object must be larger.

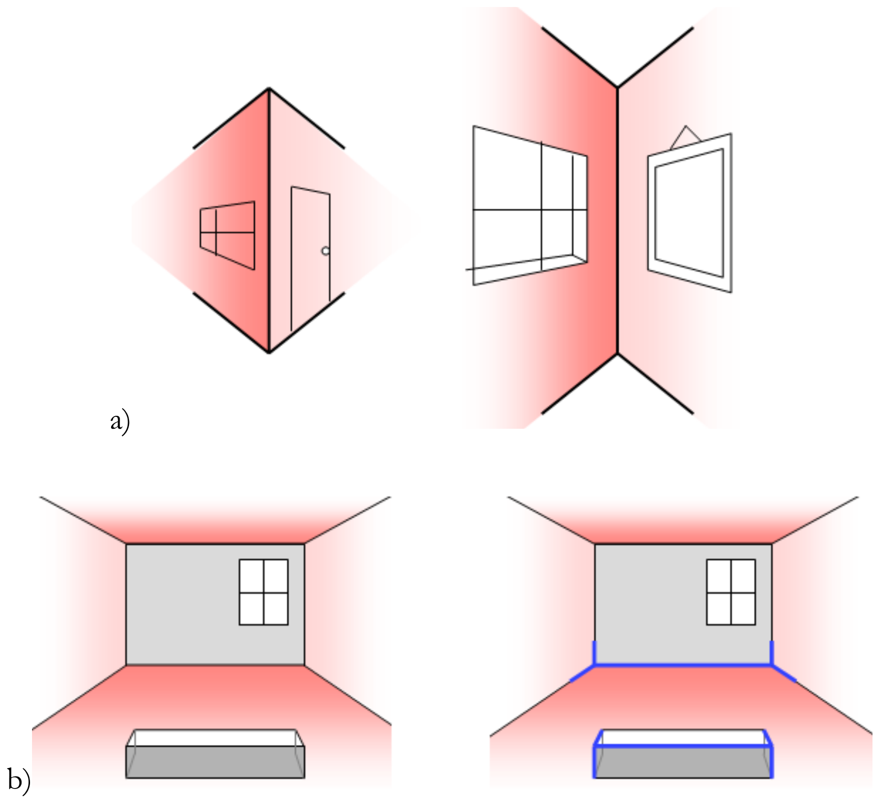

Figure 20: (a) Although the vertical "corners" of each of these images are equal in length, the vertical section in the image on the right appears significantly longer. The perspective explanation ascribes this to the fact that "inside" corners usually belong to objects that are closer to us, and "outside" corners belong to objects that are, as a whole, farther away. (b) Another way to understand the concept is to consider this image of a box sitting on the floor of a room. We know that the length of the box must be smaller than the length of the wall of the room, because of the laws of perspective.

An experimental study on this theory was conducted by Gregory and is described in (Gregory, 1968). The stimulus (one of the arrowheads) was shown to subjects, with steps taken to remove any clues about the two- or three-dimensionality of the image. The stimulus was viewed with one eye, and the lines themselves consisted of wires coated with luminous paint. Under these conditions, Gregory found that the Müller-Lyer illusion was indistinguishable to subjects from an actual three-dimensional corner. Using a clever experimental setup, the subjects were then asked to indicate the depth of various parts of the figure by positioning small points of light which were visible to both eyes. The results from this study corresponded almost exactly with the results from a parallel study in which the background had not been removed (for example, a drawing on a piece of paper). Gregory concludes that since the illusion is the same whether or not depth is *consciously* seen, perspective likely plays a role.

This theory is supported by the finding that the Müller-Lyer illusion is not universal; when psychologists showed the illusion to members of a Zulu tribe who lived in circular huts and thus had little experience with corners, they were much less likely to be affected by the illusion (Bianchi, 2003). This finding suggests that the perception of depth may be learned.

The perspective theory currently seems to be the most popular and widely reprinted explanation for the Müller-Lyer illusion. However, there are findings that would seem to contradict it. One small study involved a man who received a corneal implant after having been blind since the age of three. He seemed to be unsusceptible to depth-related illusions such as the Shepard Tables illusion (see Figure 21), but was still affected by the Müller-Lyer illusion. This would suggest that the Müller-Lyer illusion is not in fact caused by depth processing.

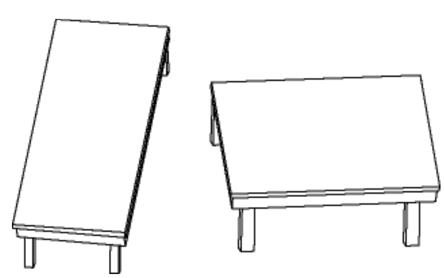

Figure 21: Tables drawn by Roger N. Shepard. The tops of the tables are exactly the same size and shape; it is our understanding of perspective that causes one table to be seen as long and narrower than the other. (image source: Bianchi, 2006)

Further evidence that the Müller-Lyer illusion is unrelated to the application of rules of perspective comes from simple alterations to the appearance of the illusion. Changing the arrowheads to semi-circles eliminates the possibility of interpreting the images as inside or outside corners but seems to preserve the size illusion (see Figure 22).

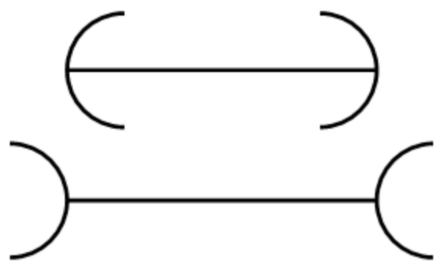

Figure 22: The Müller-Lyer illusion is preserved when the arrowheads are changed to semi-circles, providing evidence that the illusion is not caused by depth cues.

However, some psychologists argue that using semi-circles is an unfair comparison because this variation will be processed by curve-detecting cells instead of corner-detectors.

Another theory which has some credibility is the Intertip Disparity Theory (Muller). This theory states that people tend to measure the distance between the ends of the arrowheads. This would mean that the illusion should be stronger when longer arrowheads are used (see Figure 23). Research has confirmed this observation.

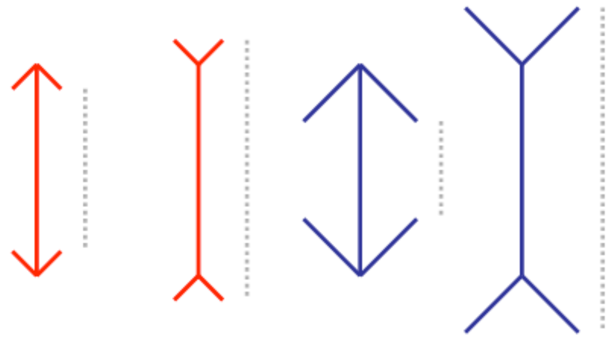

Figure 23: Longer arrowheads seem to make the Müller-Lyer illusion stronger, which makes sense if people subconsciously measure the length of the line as being the distance between the ends of the arrowheads.

Although the perspective theory remains the most popular of the proposed explanations for the Müller-Lyer illusion, there is really no consensus on the cause. As noted in one source (Famous, 2005), in the twelve years after the Müller-Lyer illusion was discovered in 1889, twelve different theories arose that attempted to explain it. How intriguing that such a simple illusion should reveal how much we have yet to learn about visual perception.

Conclusion

I began this project hoping to find lively disagreement between disciplines over what caused various optical illusions. Instead I found it to be more common for there to be disagreements within disciplines, which was not entirely unexpected. It does seem very clear that optical illusions as a broad category cannot be explained by one discipline or another; the illusions must be considered individually for meaningful analysis. Of the four illusions addressed in this paper, two of them (the Hermann grid and equiluminance) have primarily physiological explanations. One (the Müller-Lyer size illusion) has primarily psychological explanations. Only one of the illusions that I examined (the Penrose triangle) has possible explanations based on both psychology and physiology.

Another goal of this project was to determine whether, for illusions for which multiple theories exist, those theories contradict each other or can actually complement each other. In the case of the Hermann grid, there is clear evidence that the traditional explanation is wrong or incomplete, but alternate theories have not been fully developed or tested. For equiluminance, researchers do disagree on whether What cells can perceive edges, but they seem to agree that Where cells are much better suited to the task. Additional research is needed in order to resolve this issue. The Penrose triangle illusion has a physiological explanation and a psychological one. The two explanations seem to stand alone, but when considered together, they don't contradict each other. It is possible that both are right. I have not been able to find any studies that considered the effect of the equidistance tendency on the perception of the Penrose triangle, so perhaps such a study would resolve the question. The Müller-Lyer illusion has a multitude of psychological explanations, some of which contradict each other, and some of which could probably coexist. It has been studied for more than a hundred years, and still no conclusive explanation has been discovered. This simple illusion draws attention to the fact that despite all of the research that has been done on the human visual system, there is still much that is not understood.

Appendix I: Definitions of "Optical Illusion"

An optical illusion is a type of illusion characterized by visually perceived images that are deceptive or misleading. Information gathered by the eye is interpreted by the brain to give the perception that something is present when it is not. There are physiological illusions, that occur naturally, and cognitive illusions, that can be demonstrated by specific visual tricks that show particular assumptions in the human perceptual system. (Optical, 2006)

A visually perceived image that is deceptive or misleading. (American Heritage Dictionary of the English Language, Fourth Edition)

The experience of seeming to see something that is other than it appears, or (more widely) that does not exist; something having an appearance so resembling something else as to deceive the eye. Also: an illusory image or hallucination seen as a result of illness. (Oxford English Dictionary)

It is extraordinarily hard to give a satisfactory definition of an 'illusion'. It may be the departure from reality, or from truth; but how are these to be defined? As science's accounts of reality get ever more different from appearances, to say that this separation is 'illusion' would have the absurd consequence of implying that almost all perceptions are illusory. It seems better to limit 'illusion' to systematic visual and other sensed discrepancies from simple measurements with rulers, photometers, clocks and so on. (Gregory, 1997)

Illusions stem from misperceptions of depth, contrast and movement as well as from fast-moving or intermittently lit displays. (Robinson, 1972)

Sometimes, an illusion occurs when there is not enough information in the image to resolve the ambiguity. For example, important clues that would normally be present in the real world, and which would have resolved the ambiguity, are missing. Other illusions take place because an image violates a constraint based on an underlying regularity of our world. In other cases, illusions occur because two or more different constraints are in conflict. Even though the image on your retina remains constant, two interpretations may perceptually flip back and forth. Illusions are very useful tools for vision scientists, because they can reveal the hidden constraints of the perceptual system in a way that normal perception does not. (Seckel, 2000)

[We assume there is] a necessary correspondence between certain of the properties of the object (such as wavelength of reflected light, measured size, geometric shape) and those of its perceived image (color, apparent size, form). In many instances the assumed correspondence may hold and we regard the perceptions as veridical. If, however, one or more of these assumed correspondences proves incorrect, we term the perception an illusion. Accordingly, the illusions simply indicate the inadequacies of the assumed correspondences. (Held, 1974)

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