5

The Eye and the Visual Brain

> The distinctive feature of brains such as the one we own is their uncanny ability to create maps.
>
> —Antonio Damasio, from *Self Comes to Mind: Constructing the Conscious Brain*

Imagine yourself sitting on a bench in your favorite park. Your eyes are focused on a long story in the newspaper. Maybe you are reading it on your tablet computer, or maybe you are old-fashioned, as I am, and prefer the newsprint version. No matter. Either way, the world around you blurs and becomes unimportant. The storyline flows. You feel enthralled. You barely notice a group of children playing a few yards away. Your mind is off and wandering in a better place, chasing fleeting words.

Suddenly, you notice a movement in the corner of your eye: Something is flying toward you at high speed. Your hands drop the newspaper. Your heart pounds harder and faster. Your arms instinctively position themselves in front of your face in a protective shield of skin, flesh, and bone.

A soft object hits your elbow and falls to the ground. Your body relaxes. A plastic ball bounces in front of you, harmless.

To say that *a part of you* noticed a movement is a manner of speaking, for that part was not really *you*. Your conscious self didn't know what your eyes were seeing until the ball was already at your feet. The first lesson we can extract from this is that vision is fast, but reason is slow. The second lesson is that, as the famous neuroscientist Antonio Damasio wrote, "The human brain is a natural-born cartographer." In our story, in a fraction of a second and without your conscious awareness, your brain devised a map calculating the precise position of the potential flying threat—and prompted your arms to react.[1]

The third lesson of this story is that **seeing, perceiving, and knowing are different phenomena**. You can see without perceiving and without knowing that you are seeing. The eye and the visual brain are more complicated and fascinating than you may have ever thought. **Exploring their inner workings is crucial if we want to approach information graphics and visualizations as communicators, not simply as traditional graphic artists.**

The Unexplained Eye

If you are my age, the biology textbook you used during high school probably included a diagram similar to **Figure 5.1**, which shows how human visual perception works.

Light coming from a source—the sun, a light bulb—hits an object. In my diagram, that object is my friend Mike Schmidt, a talented multimedia producer who graciously agreed to be part of this teaching experience.

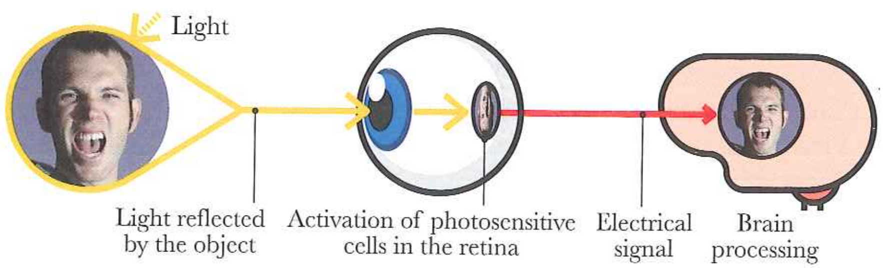

Figure 5.1 This is what I learned about the eyes and the brain when I was in high school.

Mike's skin absorbs some of the photons—the particles light is made of—and reflects some of them. The photons bouncing off his face pass through my eyes and stimulate certain photosensitive cells on my retina. Those cells transform

1 Antonio Damasio, *Self Comes to Mind: Constructing the Conscious Brain* (Toronto Pantheon Books, 2010).

the light stimulus into an electrical impulse that reaches the brain through the optic nerves.

So far, so good. Up to this point, the process is almost mechanical: a dancing game of light particles and cell activation patterns. But as a teenager, I found the last part of the diagram confusing. A photograph shows up in the middle of a pictographic brain? How mysterious. At the time, the end of the perceptual process seemed like magic to me.

The best metaphor to explain human visual perception is that of a digital video camera, where our eyes are the camera lens, our optic nerves are the cables, and our brains are the microprocessor and the hard drive. The only problem with this model is that, **while our eyes truly act as lenses, the brain is certainly not a hard drive, as we'll see.**

Let There Be Light

The next part of the perception equation is light. Understanding a bit of how it works can be useful for design and graphics, so stick with me.

Light is electromagnetic radiation. It can be described as waves that scatter in different lengths, frequencies, and energy charges. See **Figure 5.2**. The frequency of a light wave is a measure of the number of waves that cross a particular point within a given time frame. Frequency is inversely proportional to length: The shorter a wave of light is, the higher its frequency.

The energy of a ray of light is related to those two physical properties: frequency and length. The shorter the wavelength and higher its frequency, the more energy the light carries. Our mother's insistence on smearing us with sun protection cream before exposing our skin to the sun's mid-day rays has a solid scientific basis: Ultraviolet light, even after it's been filtered by the earth's atmosphere, can burn you.

As Figure 5.2 shows, our eyes can detect only a tiny fraction of the electromagnetic spectrum. The visible range for humans runs from violet (high frequency and energy, short wavelength) to red (low frequency and energy, long wavelength). Other species' visible ranges are different. Bees, for instance, can see ultraviolet light, and many predators can see infrared.

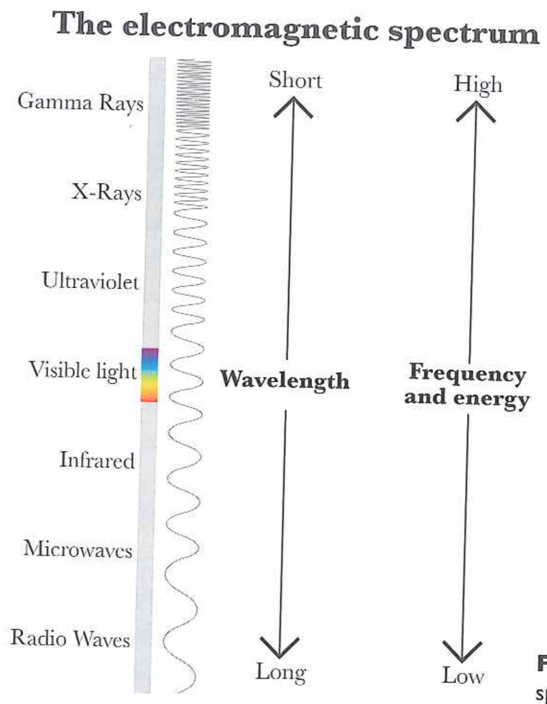

Figure 5.2 The electromagnetic spectrum.

As explained before, when light hits any object, the surface absorbs some of the light and reflects the rest. An object that appears white reflects all wavelengths of light, while a black object is one that absorbs all light visible to the eye. Between those two extremes is a vast range of possibility. We see a blue chair not because the chair oozes an intrinsic bluish quality, but because its surface swallows all frequencies of light except those that our brain identifies as belonging to blue. Without light, nothing is blue, green, yellow, black, or white.

Light and Photoreceptors

Figure 5.3 shows the main components of the human eye. Starting at the left, the pupil controls the amount of light that enters the eye. It contracts when there's too much light and opens when there is very little.

After light has entered the eye and is filtered and adjusted, it reaches the retina, a thin sheet of nerve tissue on the back side of the eye. (The retina, by the way, is not part of the eye but part of the brain—one of those factoids that proves it is not a good idea to trust your intuitions when it comes to science.) During embryonic development, the cells of the retina and optic nerve are born in the

encephalus, and, little by little, like tiny, thin tentacles, they stretch until they find the right place to attach.

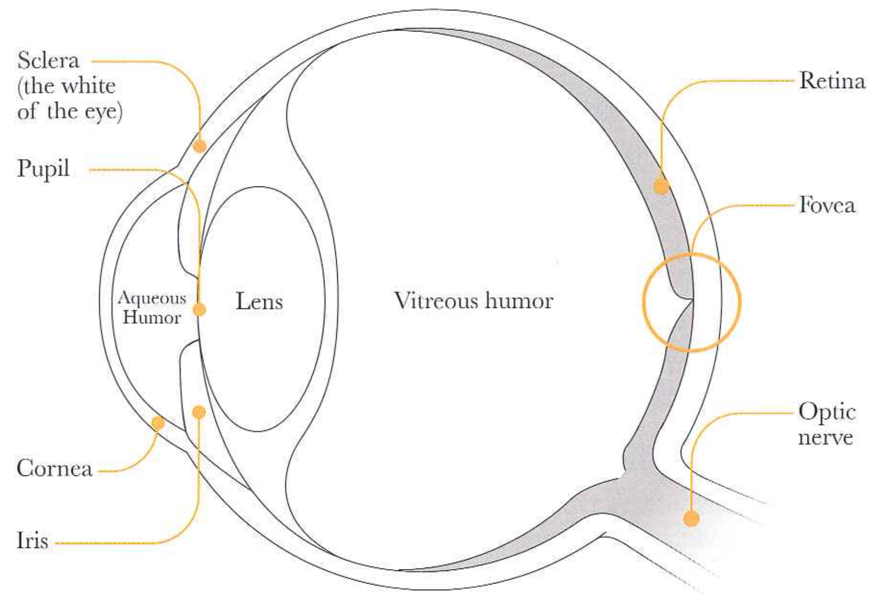

Figure 5.3 The structure of the eye.

The retina is covered with several kinds of cells. The most relevant for light detection are called **photoreceptors**. They come in two main groups: rods and cones, so called because of their shapes. Each retina has around 100 million *rods* that see in black and white and are active when light is dim. *Cones* (7 million, more or less) are in charge of color detection.

To understand how rods and cones work, wake up in the middle of the night. Open your eyes and wait until your pupils dilate enough for your surroundings to become visible. You will see the bed, the chair where you left your clothes, and the bedroom door as monochrome objects, perhaps with a very subtle blue tone. Your rods are active. Your cones are just whispering.

Now, turn on the lights. In all probability, the sudden, bright explosion of light will blind you for the second it takes for your pupils to contract. Now, what was monochrome and barely visible appears bathed in vivid hues and shades: the blue sheets on the bed, the red plastic of the chair, your green jeans and flowery shirt (I live in Miami, mind you), the white door. Cones have taken over.

Foveal, Peripheral Vision, and Animated Infographics

One of the first illusions we suffer when our eyes are open is that the acuity of our vision is the same throughout our entire visual field. You are as much a victim of this illusion as everyone else. Try this: Go for a walk. Stop on the sidewalk and close your eyes for 10 seconds. Open them and make an effort to fix them on something static in front of you: a parked car or a street sign. It is important that you keep your eyes focused on that object: Don't move them.

Now, try to identify the objects closer to the outer limits of your vision field. Remember, don't allow your eyes to move. You will not only find it is impossible to make out the surrounding objects, but also to tell *what color they are*.

The reason is that although each of our eyes is capable of taking in everything within a 180-degree angle, as shown in **Figure 5.4**, we only see with full acuity the things that lie in a very narrow field in front of us, an angle around two degrees wide. This angle is centered around the retinal region called the *fovea* (see Figure 5.3). The fovea contains only cones on a tiny surface of just one square millimeter. The cones grow sparser as we move away from the fovea to another small, surrounding region called the *parafovea*. Outside the parafovea, the retina is covered only with rods.

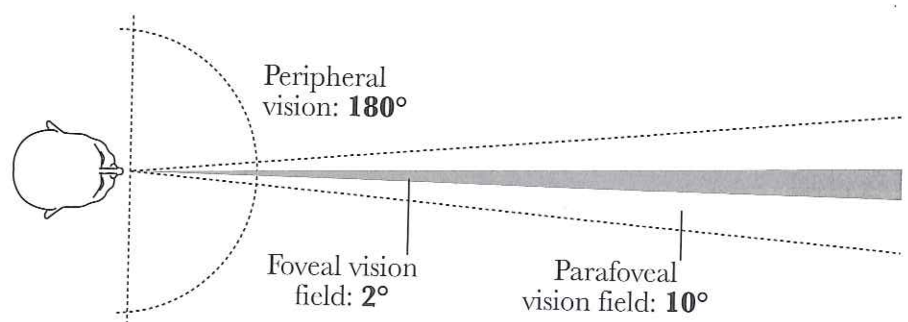

Figure 5.4 You may think that you see in a 180-degree angle in front of you with absolute acuity, but that is just a convenient illusion.

This limitation has consequences that affect perception. In order for us to identify an object, the rays of light that bounce off of it must stimulate the cones on the fovea; otherwise, we will see only a blurry mass. What is it then that creates our very convincing illusion of acuity, which leads us to believe that we see everything in our vision field with equal accuracy, as if it were a picture?

We enjoy this illusion because our eyes don't remain still, even when we are consciously forcing them to. They jerk around scenes with great speed, two or three times a second, fixing on different points of whatever is in front of them. These ocular movements are called *saccades*, and each stop your eyes make on a particular point is called a *fixation*.

Vision is the result of mapping your environment based on the aggregated information your eyes obtain from multiple fixations. But the eyes don't fix on random sections of the landscape. They are attracted first to certain features before they move to others. They *prioritize*. In several famous experiments run in the middle of the twentieth century, Russian psychologist Alfred L. Yarbus proved that, when facing a human head, our eyes fix first on those features that can better help identify the person it belongs to and his or her emotional state. **Figure 5.5** is one of the pictures included in Yarbus's papers. Notice how fixations tend to cluster around the eyes and the mouth.

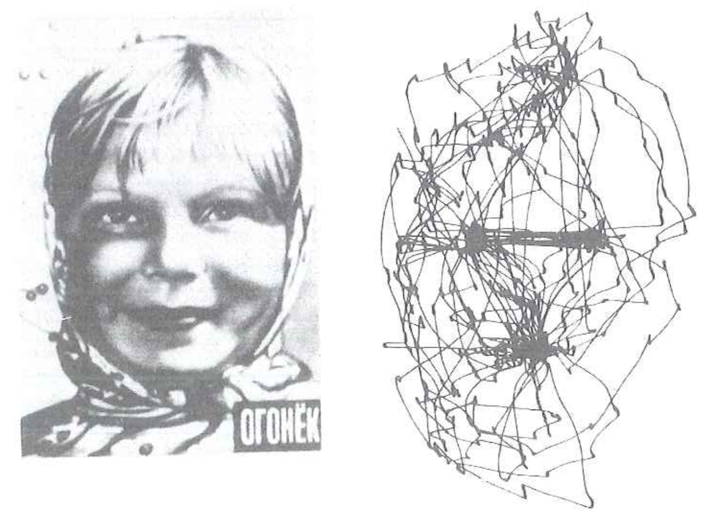

Figure 5.5 Alfred L. Yarbus studied what parts of the face attract our attention the most. This is an example of the kind of diagrams he developed. From Alfred L. Yarbus's 1967 "Eye Movements and Vision." (Reproduced with permission of Springer Publishing.)

It is the brain that merges all of the pieces of the saccadic puzzle together into an illusory, coherent mental picture. An example: Let's say I am in front of the place where I used to live when I was a professor at the University of North Carolina (**Figure 5.6**). My brain will tell me I am seeing a beautiful spring scene bathed in shades of green, brown, and blue. But what my eyes are actually sending to my brain are small snapshots from that scene within a tiny, high-resolution area—the area of my foveal vision range—set against a much blurrier surrounding.

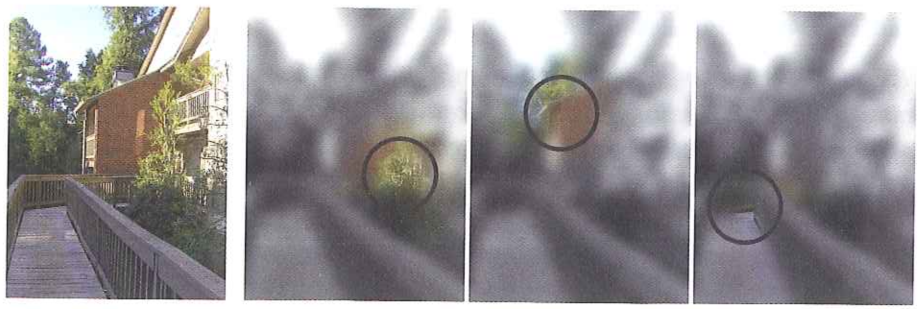

Figure 5.6 On the left, you see what your brain thinks you are seeing. On the right, you see what your eyes are really getting: tons of quick, narrow fixations, such as these views.

You've finally reached the payoff: Why is all of this relevant to information graphics and visualization? Saccadic movements and fixations are unconscious, but *they are not random*. Our species has evolved up to this day in part because it was able to efficiently identify predators, food, and receptivity in members of the opposite sex. We are designed, so to speak, to be attracted by moving creatures and objects, bright colored patches in front of us, and uncommonly shaped items, even if they are in our peripheral vision range.

Figure 5.7 represents this fact. At first, that *thing* in the corner of your eyes will not be identified because your foveas are focused elsewhere; but, as long as it is moving, it could be a potential threat, so your eyes will fix on it as soon as possible.

Here, then, is how to **translate a perceptual principle into a design principle**, (something communicators should do more often). Suppose that you are working on an animated infographic on the Mars Exploration Rovers. You are planning to include a step-by-step explanation of how the rovers get to Mars and how they unfold their wheels and solar panels.

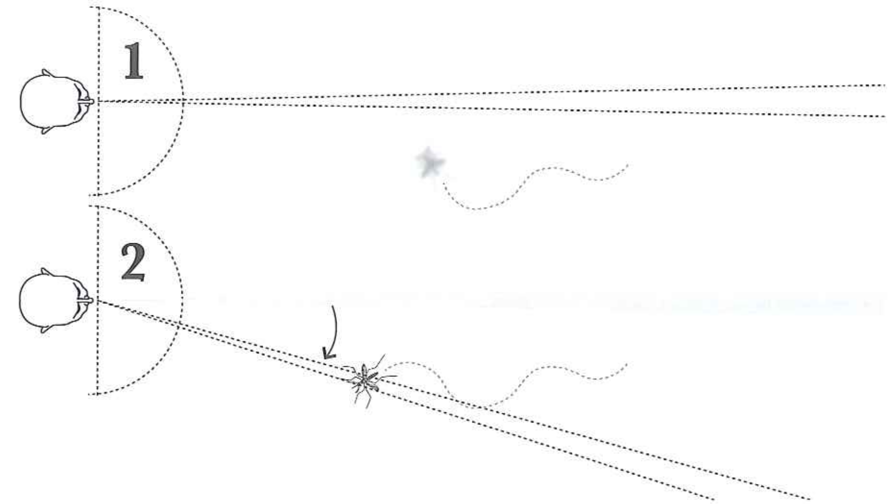

Figure 5.7 Moving objects tend to attract our eyes more than static ones.

Based on what we have just covered about the eye-brain system's attraction to moving objects and uncommon shapes, **you should never simultaneously show an animation of the robot on the right side of the screen and a text box on the left**. If you do, readers won't know what they should focus on. The text is an uncommon shape, and the robot is moving.

As shown in **Figure 5.8**, it is better to show the rover unfolding and, *only when the action has stopped*, make the text appear.

The same can be said of color. The best way to disorient your readers is to fill your graphic with objects colored in pure accent tones. Pure colors are uncommon in nature, so limit them to highlight whatever is important in your graphics, and use subdued hues—grays, light blues, and greens—for everything else. In other words: **If you know that the brain prioritizes what it pays attention to, prioritize *beforehand*.**

The Lying Brain

Your brain lies, although with good purpose. We are victims of illusions not because the brain malfunctions, but because perceiving illusions can be advantageous in some circumstances.

Quick. Go to **Figure 5.9** and tell me what you see.

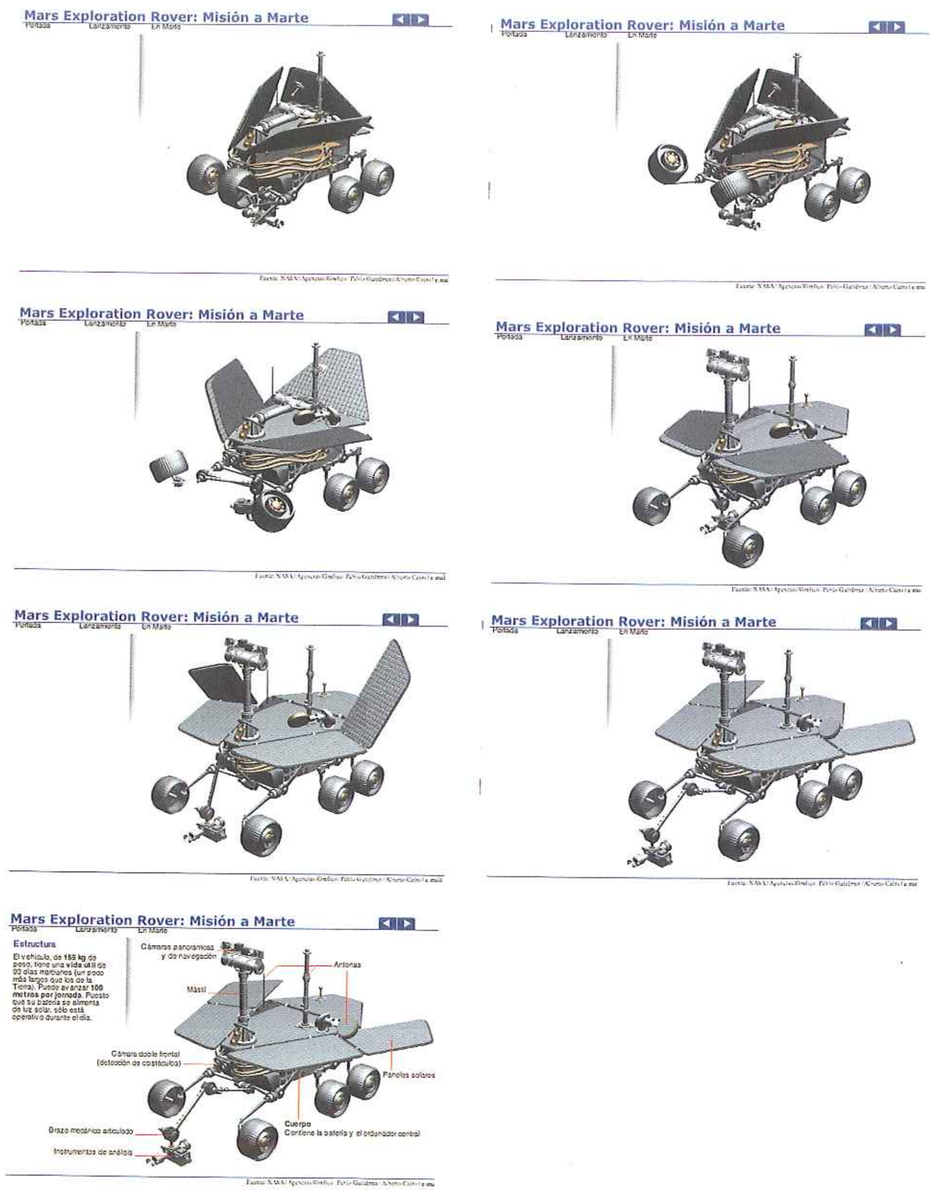

Figure 5.8 If you don't want to confuse your readers, don't show a moving object and a piece of text on opposite sides of the screen in an animated infographic. Instead, when the action stops, then let the text appear, as shown here.

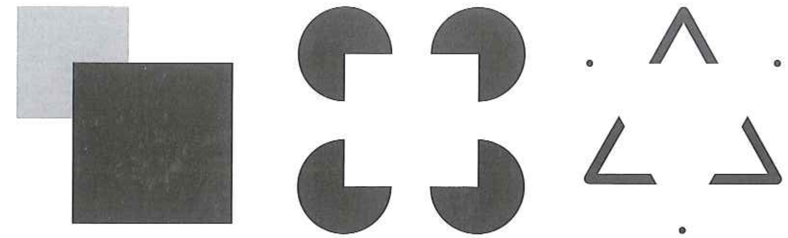

Figure 5.9 Can you see two squares, a white square over four circles, and a white triangle?

I am sure you have answered: a) two overlapping squares, b) a white square partially covering four circles, and c) a white triangle pointing down, atop a black triangle that points up.

But those shapes are not there. The gray square behind the black one is not a square at all. It is an inverted L-shape. And I didn't use any ink to paint the white square and triangle. In fact, if you erase the four little Pac-Men that define the square and triangle. In fact, if you erase the four little Pac-Men that define the white square, the square itself will vanish. And there's no white triangle there: just three black dots.

Another striking illusion—one of my favorites—is shown in **Figure 5.10**. Hold the book you are reading in front of you with your right hand. Move the book away from you, extending your arm outward as far as you can. Cover your right eye with your left hand and focus your left eye on the cross. Now, with your left eye fixed on the cross, move the book very slowly closer to your face.

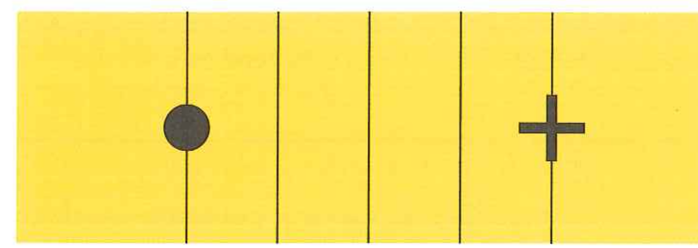

Figure 5.10 Follow the instructions in the text to view this figure, and the circle will disappear. But what shows up when it vanishes?

Tell me what happens to the circle.

Has it disappeared?

It *must* disappear. If it doesn't, try again. The circle has to vanish. Otherwise, I'd recommend you introduce yourself to the NASA SETI program—and don't forget to credit me as the discoverer of the first alien visitor to earth.

What is going on? Have your eyes stopped working? Not really, except for a small region on the retina called the *blind spot*. Go back to Figure 5.3, and notice the point where the optic nerve enters the eyeball. At that point, the retina has no photosensitive cells whatsoever. No rods, no cones.

When both your eyes are open, this is not an issue. What the brain sees is a composite image based on the information coming from the two eyes. At any time, some rays of light bouncing off of the objects in front of you may hit the blind spot of your left eye, but your right eye still notices them. That's why you still see them.

But when one of your eyes is closed or doesn't work properly, there is a small portion of the landscape that your remaining eye won't notice, because the light emanating from it is not stimulating any rod or cone. It hits your blind spot.

This is fascinating enough, but it gets better. Try the exercise again and tell me what happens when the circle vanishes. What shows up?

A line, and a surrounding patch of orange, I'll bet. But isn't that impossible? There are no light rays reflecting from the area where the circle was to stimulate your retina. You should not see anything, other than a void.

The answer to the riddle is that your brain knows that there are no voids in the world we live in. Sure, if you were to travel far enough through space and time, you might cross paths with black holes, but not on Earth. Your brain is making an assumption based on what it knows about how its environment works. It reasons: Empty areas don't exist; therefore, if my eye sees nothing, the area that I am missing is likely filled with the same colors and patterns that surround it.

The Efficient Brain

Why are we victims of visual illusions? Why doesn't the brain just see what is out there, as if it really were a video camera? **The reasons may be efficiency and response speed.**

See the three pictures in **Figure 5.11**. (I am a journalist, which explains why the image manipulation is a bit sloppy.) The picture was taken by my friend Rich Beckman. Imagine that you are a hominid walking through the savannah hundreds of thousands of years ago, and you see something that looks like random patches of brownish fur behind the grass. Would you need to stop and consciously figure out what is hiding there?

Figure 5.11 If you were out walking on the savanna, I am sure you would not stop to figure out what your eyes were seeing before you felt the urge to flee. (Photograph by Rich Beckman.)

Of course not. Your brain would immediately visualize the second picture, and suggest that you are facing something that can eat you alive. It would be *completing* what your retinas receive. And it would probably prompt the release of a plentiful shot of adrenaline through your arteries, which will be useful whether you fight or flee.

In other words, **what your retina gets is not what your brain perceives**. In fact, what we commonly call *seeing* is not a single phenomenon, but a group of at least three operations: sight, perception, and cognition. Not all of what stimulates the cells in your retina is processed with the same level of detail in the brain, and not all of what the brain perceives reaches a conscious level and becomes rational understanding. Working like this makes sense. Life would be impossible if we had to think about everything that stimulates our eyes at every instant.

Scientists have proven that seeing is not exactly the same as perceiving, as people with severe brain damage reveal. For instance, V.S. Ramachandran in his illuminating *The Tell-Tale Brain: A Neuroscientist's Quest for What Makes Us Human* (2011) describes *blindsight*, a bizarre condition that leads you to see without knowing that you see. During experiments, a supposedly blind subject was seated in front of a source of light and asked to reach it with his hand. The man complained he couldn't do that because he was blind. But when he finally agreed to try, his hand grabbed the source with no hesitation. He was seeing, although his brain was not consciously aware of that sight.

In the case of *agnosia*, a term meaning "no knowledge" coined by Sigmund Freud, damage to certain parts of the brain leaves patients incapable of identifying things. They can navigate the world, and grab and release objects with high accuracy, but they cannot tell what those objects are. Paradoxically, if you ask them to describe what a chair, a glass, or a bottle is—the very same items they cannot identify—they show no major problems.

A New Diagram For Vision

Let's recap. Remember Figure 5.1, the diagram that opens this chapter, with my friend Mike screaming at the camera. As we discussed, that is not a good representation of what really happens in the brain. **Figure 5.12** offers a more accurate alternative.

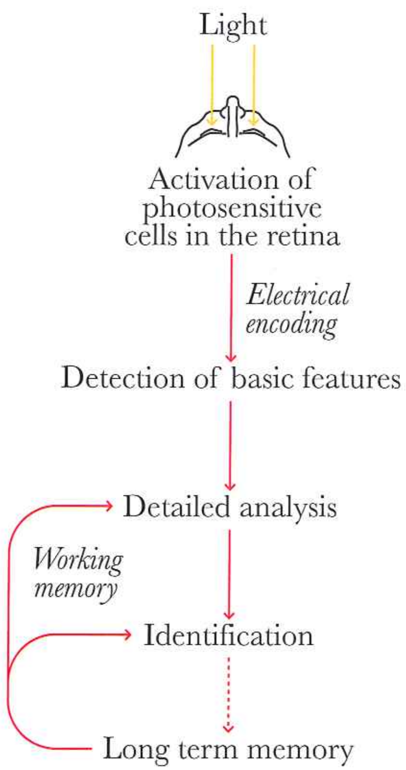

Figure 5.12 How perception really works.

Once the retina has encoded the patterns of light into electrical signals, the brain proceeds to discriminate basic object features, such as gross shapes, patches of color, and others I'll explain in the next two chapters. Only after this happens does the brain proceed to a much deeper analysis of what is being seen and to consciously identify it, based on a great deal of content that is retrieved from our memories.

But I am putting the cart in front of the horse. **Now that I've explained how the eye, the brain, light, and memory work together, I can explain how important all this is to our jobs as designers.**

6

Visualizing for the Mind

Perception is a fantasy that coincides with reality.

—Chris Firth, from *Making Up the Mind: How the Brain Creates Our Mental World*

If you know what tricks and shortcuts the brain uses to make sense of the information gathered from the senses, you can use that knowledge to your advantage. In this chapter, I will focus on the mechanisms of detecting basic features, also called **preattentive features.** The ability to anticipate what the brain wants to do can greatly improve your information graphics and visualizations.[1]

The Brain Loves a Difference

When you open your eyes to the world, one of the first things your brain does is discriminate between background and foreground. That is, it identifies the boundaries of the objects and creatures in your vision field: where the lion ends and the grass begins, and where the grass ends and the sky begins. Evolution has

1 If you want to dig deeper into the contents of this chapter, take a look at the work of Ware (2004), Malamed (2009), Few (2004), and Maceachren (2004), all listed in the bibliography at the end of this book.