

Also by David Eagleman

Sum

Why the Net Matters

Wednesday Is Indigo Blue

INCOGNITO

The Secret Lives of the Brain

David M. Eagleman



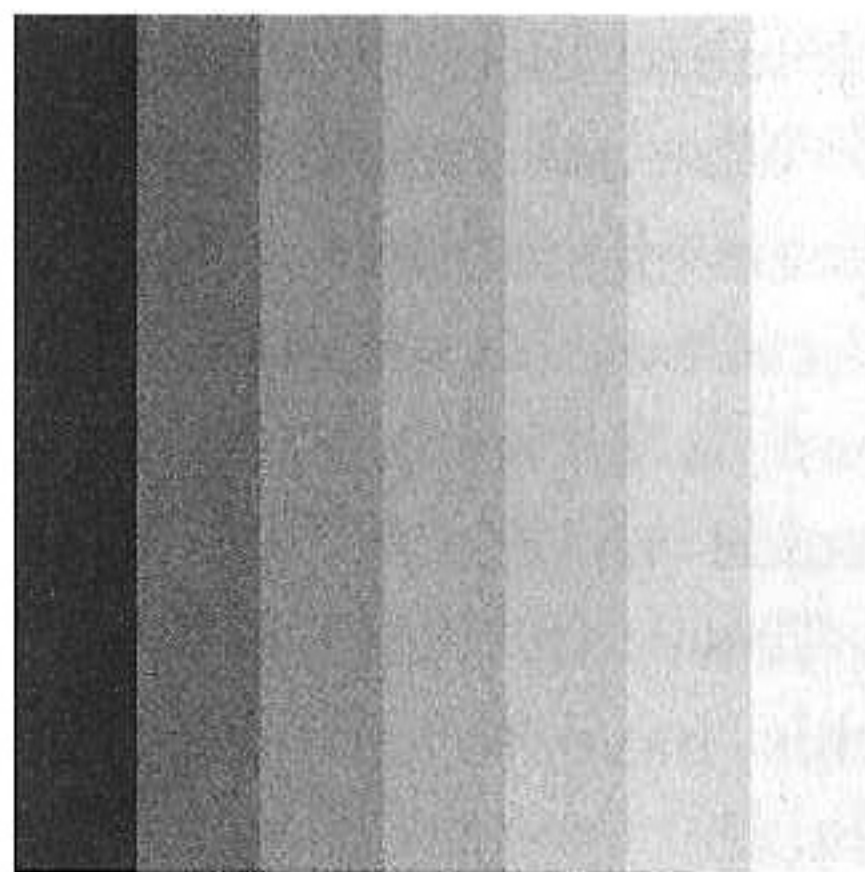
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The Testimony of the Senses: What Is Experience *Really* Like?

DECONSTRUCTING EXPERIENCE

One afternoon in the late 1800s, the physicist and philosopher Ernst Mach took a careful look at some uniformly colored strips of paper placed next to each other. Being interested in questions of perception, he was given pause by something: the strips did not look quite right. Something was amiss. He separated the strips, looked at them individually, and then put them back together. He finally realized what was going on: although each strip in isolation was uniform in color, when they were placed side by side each appeared to have a gradient of shading: slightly lighter on the left side, and slightly darker on the right. (To prove to yourself that each strip in the figure is in fact uniform in brightness, cover up all but one.)¹



Mach bands.

Now that you are aware of this illusion of “Mach bands,” you’ll notice it elsewhere—for example, at the corner where two walls meet, the lighting differences often make it appear that the paint is lighter or darker right next to the corner. Presumably, even though the perceptual fact was in front of you this entire time, you have missed it until now. In the same way, Renaissance painters noticed at some point that distant mountains appeared to be tinted a bit blue—and once this was called out, they began to paint them that way. But the entire history of art up to that point had missed it entirely, even though the data was unhidden in front of them. Why do we fail to perceive these obvious things? Are we really such poor observers of our own experiences?

Yes. We are astoundingly poor observers. And our introspection is useless on these issues: we believe we’re seeing the world just fine until it’s called to our attention that we’re not. We will go through a process of learning to observe our experience, just as Mach carefully observed the shading of the strips. What is our conscious experience *really* like, and what is it not like?

* * *

Intuition suggests that you open your eyes and voilà: there’s the world, with all its beautiful reds and golds, dogs and taxicabs, bustling cities and floriferous landscapes. Vision appears effortless and, with minor exceptions, accurate. There is little important difference, it might seem, between your eyes and a high-resolution digital video camera. For that matter, your ears seem like compact microphones that accurately record the sounds of the world, and your fingertips appear to detect the three-dimensional shape of objects in the outside world. What intuition suggests is dead wrong. So let’s see what’s really happening.

Consider what happens when you move your arm. Your brain depends on thousands of nerve fibers registering states of contraction and stretching—and yet you perceive no hint of that lightning storm of neural activity. You are simply aware that your limb

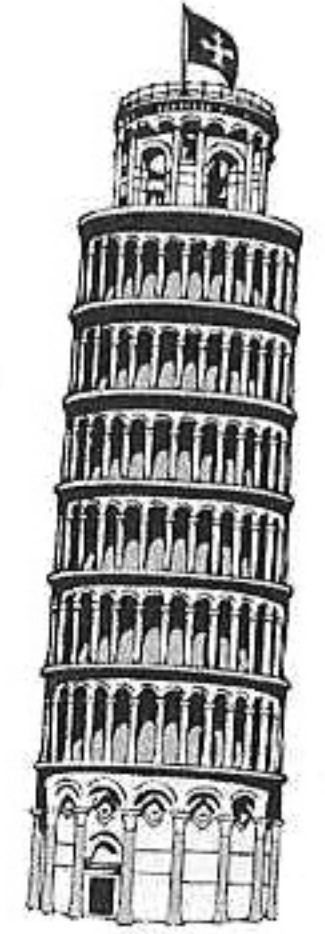
moved and that it is somewhere else now. Sir Charles Sherrington, an early neuroscience pioneer, spent some time fretting about this fact during the middle of the last century. He was awestruck by the lack of awareness about the vast mechanics under the surface. After all, despite his considerable expertise with nerves, muscles, and tendons, he noted that when he went to pick up a piece of paper, “I have no awareness of the muscles as such at all. . . . I execute the movement rightly and without difficulty.”² He reasoned that if he were not a neuroscientist it would not have occurred to him to suspect the existence of nerves, muscles, and tendons. This intrigued Sherrington, and he finally inferred that his experience of moving his arm was “a mental product. . . . derived from elements which are not experienced as such and yet . . . the mind uses them in producing the percept.” In other words, the storm of nerve and muscle activity is registered by the brain, but what is served up to your awareness is something quite different.

To understand this, let’s return to the framework of consciousness as a national newspaper. The job of a headline is to give a tightly compressed summary. In the same manner, consciousness is a way of projecting all the activity in your nervous system into a simpler form. The billions of specialized mechanisms operate below the radar—some collecting sensory data, some sending out motor programs, and the majority doing the main tasks of the neural workforce: combining information, making predictions about what is coming next, making decisions about what to do now. In the face of this complexity, consciousness gives you a summary that is useful for the larger picture, useful at the scale of apples and rivers and humans with whom you might be able to mate.

OPENING YOUR EYES

The act of “seeing” appears so natural that it is difficult to appreciate the vastly sophisticated machinery underlying the process. It may come as a surprise that about one-third of the human

brain is devoted to vision. The brain has to perform an enormous amount of work to unambiguously interpret the billions of photons streaming into the eyes. Strictly speaking, all visual scenes are ambiguous: for example, the image to the right can be caused by the Tower of Pisa at a distance of five hundred yards, or a toy model of the tower at arm’s length: both cast the identical image on your eyes. Your brain goes through a good deal of trouble to disambiguate the information hitting your eyes by taking context into account, making assumptions, and using tricks that we’ll learn about in a moment. But all this doesn’t happen effortlessly, as demonstrated by patients who surgically recover their eyesight after decades of blindness: they do not suddenly see the world, but instead must *learn* to see again.³ At first the world is a buzzing, jangling barrage of shapes and colors, and even when the optics of their eyes are perfectly functional, their brain must learn how to interpret the data coming in.



For those of us with a lifetime of sight, the best way to appreciate the fact that vision is a construction is by noticing how often our visual systems get it wrong. Visual illusions exist at the edges of what our system has evolved to handle, and as such they serve as a powerful window into the brain.⁴

There is some difficulty in rigorously defining “illusion,” as there is a sense in which all of vision is an illusion. The resolution in your peripheral vision is roughly equivalent to looking through a frosted shower door, and yet you enjoy the illusion of seeing the periphery clearly. This is because everywhere you aim your central vision appears to be in sharp focus. To drive this point home, try this demonstration: have a friend hold a handful of colored markers or highlighters out to his side. Keep your gaze fixed on his nose, and now try to name the order of the colors in his hand. The results are surprising: even if you’re able to report that there are some colors in your periphery, you won’t be able to accurately

determine their order. Your peripheral vision is far worse than you would have ever intuited, because under typical circumstances your brain leverages the eye muscles to point your high-resolution central vision directly toward the things you're interested in. Wherever you cast your eyes appears to be in sharp focus, and therefore you assume the whole visual world is in focus.*

That's just the beginning. Consider the fact that we are not aware of the *boundaries* of our visual field. Stare at a point on the wall directly in front of you, stretch your arm out, and wiggle your fingers. Now move your hand slowly back toward your ear. At some point you can no longer see your fingers. Now move it forward again and you can see them. You're crossing the edge of your visual field. Again, because you can always aim your eyes wherever you're interested, you're normally not the least bit aware that there are boundaries beyond which you have no vision. It is interesting to consider that the majority of human beings live their whole lives unaware that they are only seeing a limited cone of vision at any moment.

As we dive further into vision, it becomes clear that your brain can serve up totally convincing perceptions if you simply put the right keys in the right locks. Take the perception of depth. Your two eyes are set a few inches apart, and as a result they receive slightly different images of the world. Demonstrate this to yourself by taking two photographs from a few inches apart, and then putting them side by side. Now cross your eyes so that the two photos merge into a third, and a picture will emerge *in depth*. You will genuinely experience the depth; you can't shake the perception. The impossible notion of depth arising from a flat image divulges the mechanical, automatic nature of the computations in the visual system: feed it the right inputs and it will construct a rich world for you.

One of the most pervasive mistakes is to believe that our visual system gives a faithful representation of what is "out there" in the same way that a movie camera would. Some simple demonstrations

*Consider the analogous question of knowing whether your refrigerator light is always on. You might erroneously conclude that it is, simply because it appears that way every time you sneak up to the refrigerator door and yank it open.



Cross your eyes: the two images feed your brain the illusory signal of depth.

can quickly disabuse you of this notion. In the figure below, two pictures are shown.

What is the difference between them? Difficult to tell, isn't it? In a dynamic version of this test, the two images are alternated



Change blindness.

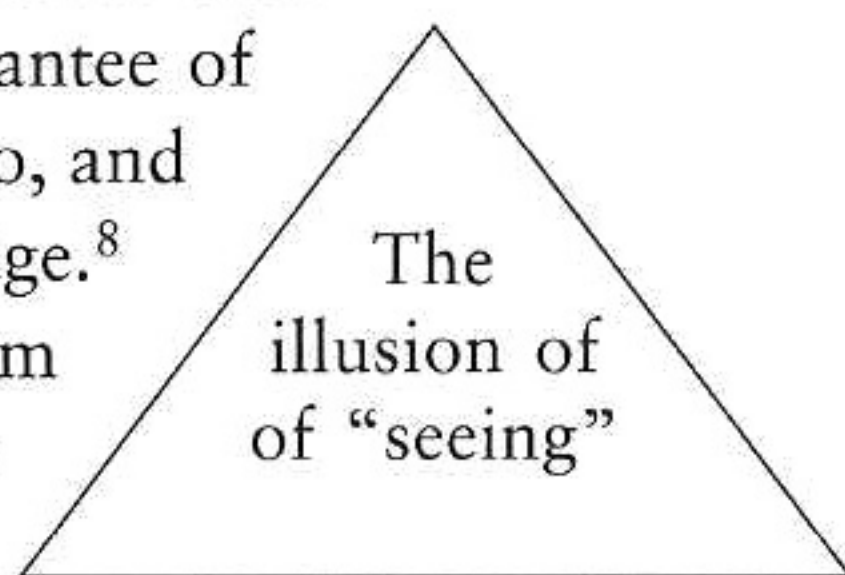
(say, each image shown for half a second, with a tenth of a second blank period in between). And it turns out we are blind to shockingly large changes in the scene. A large box might be present in

one photo and not the other, or a jeep, or an airplane engine—and the difference goes unseen. Our attention slowly crawls the scene, analyzing interesting landmarks until it finally detects what is changing.* Once the brain has latched onto the appropriate object, the change is easy to see—but this happens only after exhaustive inspection. This “change blindness” highlights the importance of attention: to see an object change, you must attend to it.⁵

You are not seeing the world in the rich detail that you implicitly believed you were; in fact, you are not aware of most of what hits your eyes. Imagine you’re watching a short film with a single actor in it. He is cooking an omelet. The camera cuts to a different angle as the actor continues his cooking. Surely you would notice if the actor changed into a different *person*, right? Two-thirds of observers don’t.⁶

In one astonishing demonstration of change blindness, random pedestrians in a courtyard were stopped by an experimenter and asked for directions. At some point, as the unsuspecting subject was in the middle of explaining the directions, workmen carrying a door walked rudely right between the two people. Unbeknownst to the subject, the experimenter was stealthily replaced by a confederate who had been hiding behind the door as it was carried: after the door passed, a new person was standing there. The majority of subjects continued giving directions without noticing that the person was not the same as the original one they were talking with.⁷ In other words, they were only encoding small amounts of the information hitting their eyes. The rest was assumption.

Neuroscientists weren’t the first to discover that placing your eyes on something is no guarantee of seeing it. Magicians figured this out long ago, and perfected ways of leveraging this knowledge.⁸ By directing your attention, magicians perform sleight of hand in full view. Their actions *should* give away the game—but they can



*If you haven’t spotted it yet, the change in the figure is the height of the wall behind the statue.

rest assured that your brain processes only small bits of the visual scene, not everything that hits your retinas.

This fact helps to explain the colossal number of traffic accidents in which drivers hit pedestrians in plain view, collide with cars directly in front of them, and even intersect unluckily with trains. In many of these cases, the eyes are in the right place, but the brain isn’t seeing the stimuli. Vision is more than looking. This also explains why you probably missed the fact that the word “of” is printed twice in the triangle on the previous page.

The lessons here are simple, but they are not obvious, even to brain scientists. For decades, vision researchers barked up the wrong tree by trying to figure out how the visual brain reconstructed a full three-dimensional representation of the outside world. Only slowly did it become clear that the brain doesn’t actually use a 3-D model—instead, it builds up something like a 2½-D *sketch* at best.⁹ The brain doesn’t need a full model of the world because it merely needs to figure out, on the fly, where to look, and when.¹⁰ For example, your brain doesn’t need to encode all the details of the coffee shop you’re in; it only needs to know how and where to search when it wants something in particular. Your internal model has some general idea that you’re in a coffee shop, that there are people to your left, a wall to your right, and that there are several items on the table. When your partner asks, “How many lumps of sugar are left?” your attentional systems interrogate the details of the bowl, assimilating new data into your internal model. Even though the sugar bowl has been in your visual field the entire time, there was no real detail there for your brain. It needed to do extra work to fill in the finer points of the picture.

Similarly, we often know one feature about a stimulus while simultaneously being unable to answer others. Say I were to ask you to look at the following and tell me what it is composed of: ||||| . You would correctly tell me it is composed of vertical lines. If I were to ask you *how many* lines, however, you would be stuck for a while. You can see *that* there are lines, but you cannot tell me *how many* without considerable effort. You can know some things about

a scene without knowing other aspects of it, and you become aware of what you're missing only when you're asked the question.

What is the position of your tongue in your mouth? Once you are asked the question you can answer it—but presumably you were not aware of the answer until you asked yourself. The brain generally does not need to know most things; it merely knows how to go out and retrieve the data. It computes on a *need-to-know basis*. You do not continuously track the position of your tongue in consciousness, because that knowledge is useful only in rare circumstances.

In fact, we are not conscious of much of anything until we ask ourselves about it. What does your left shoe feel like on your foot right now? What pitch is the hum of the air conditioner in the background? As we saw with change blindness, we are unaware of most of what should be obvious to our senses; it is only after deploying our attentional resources onto small bits of the scene that we become aware of what we were missing. Before we engage our concentration, we are typically not aware that we are not aware of those details. So not only is our perception of the world a construction that does not accurately represent the outside, but we additionally have the false impression of a full, rich picture when in fact we see only what we need to know, and no more.

The manner in which the brain interrogates the world to gather more details was investigated in 1967 by the Russian psychologist Alfred Yarbus. He measured the exact locations that people were looking at by using an eye tracker, and asked his subjects to gaze at Ilya Repin's painting *An Unexpected Visitor* (next page).¹¹ The subjects' task was simple: examine the painting. Or, in a different condition, surmise what the people in the painting had been doing just before the "unexpected visitor" came in. Or answer a question about how wealthy the people were. Or their ages. Or how long the unexpected visitor had been away.

The results were remarkable. Depending on what was being asked, the eyes moved in totally different patterns, sampling the picture in a manner that was maximally informative for the question at



Six records of eye movements from the same subject. Each record lasted three minutes. 1) Free examination. Before subsequent recordings, the subject was asked to: 2) estimate the material circumstances of the family; 3) give the ages of the people; 4) surmise what the family had been doing before the arrival of the "unexpected visitor"; 5) remember the clothes worn by the people; 6) estimate how long the "unexpected visitor" had been away from the family. From Yarbus, 1967.

hand. When asked about the ages of the people, the eyes went to the faces. When asked about their wealth, the focus danced around the clothes and material possessions.

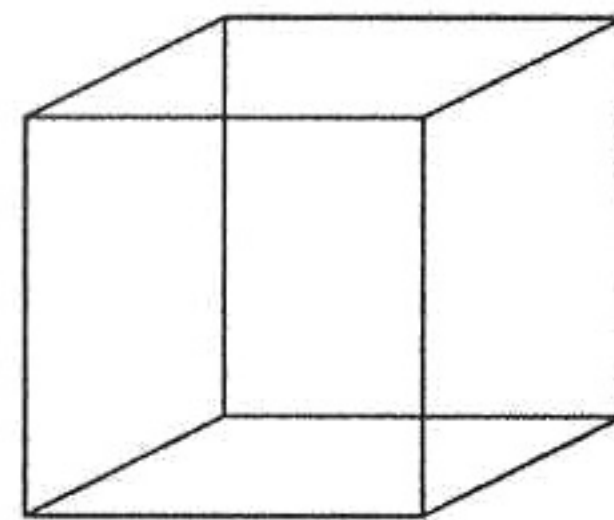
Think about what this means: brains reach out into the world and actively *extract* the type of information they need. The brain does not need to see everything at once about *An Unexpected Visitor*, and it does not need to store everything internally; it only needs to know where to go to find the information. As your eyes interrogate the world, they are like agents on a mission, optimizing their strategy for the data. Even though they are “your” eyes, you have little idea what duty they’re on. Like a black ops mission, the eyes operate below the radar, too fast for your clunky consciousness to keep up with.

For a powerful illustration of the limits of introspection, consider the eye movements you are making right now while reading this book. Your eyes are jumping from spot to spot. To appreciate how rapid, deliberate, and precise these eye movements are, just observe someone else while they read. Yet we have no awareness of this active examination of the page. Instead it seems as though ideas simply flow into the head from a stable world.

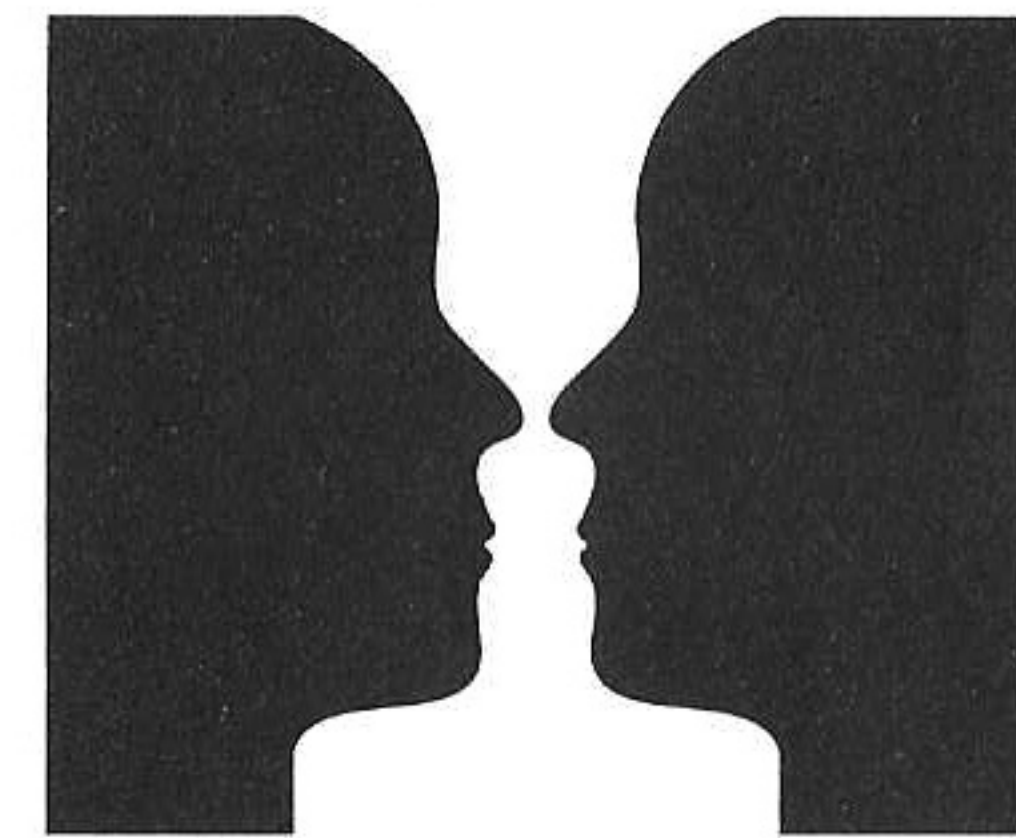
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Because vision appears so effortless, we are like fish challenged to understand water: since the fish has never experienced anything else, it is almost impossible for it to see or conceive of the water. But a bubble rising past the inquisitive fish can offer a critical clue. Like bubbles, visual illusions can call our attention to what we normally take for granted—and in this way they are critical tools for understanding the mechanisms running behind the scenes in the brain.

You’ve doubtless seen a drawing of a cube like the one to the right. This cube is an example of a “multistable” stimulus—that is, an image that flips back and forth between different perceptions. Pick what you perceive as the “front” face of the cube. Staring at the picture



for a moment, you’ll notice that sometimes the front face appears to become the back face, and the orientation of the cube changes. If you keep watching, it will switch back again, alternating between these two perceptions of the cube’s orientation. There’s a striking point here: *nothing has changed on the page, so the change has to be taking place in your brain.* Vision is active, not passive. There is more than one way for the visual system to interpret the stimulus, and so it flips back and forth between the possibilities. The same manner of reversals can be seen in the face–vase illusion below: sometimes you perceive the faces, and sometimes the vase, even though nothing has changed on the page. You simply can’t see both at once.

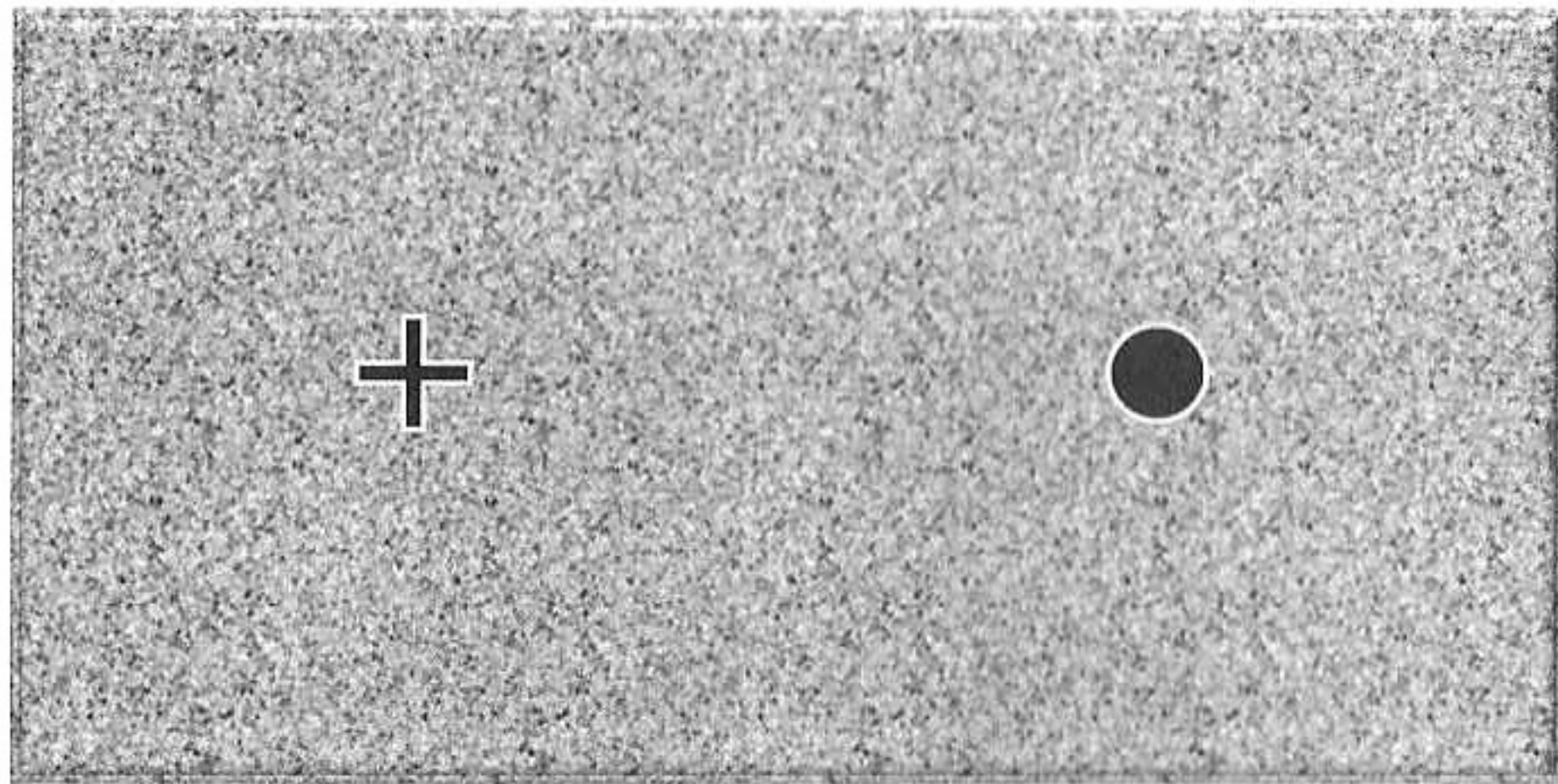


There are even more striking demonstrations of this principle of active vision. Perceptual switching happens if we present one image to your left eye (say, a cow) and a different image to your right eye (say, an airplane). You don’t see both at the same time, nor do you see a fusion of the two images—instead, you see one, then the other, then back again.¹² Your visual system is arbitrating a battle between the conflicting information, and you see not what is really out there, but instead only a moment-by-moment version of which perception is winning over the other. Even though the outside world has not changed, your brain dynamically presents different interpretations.

More than actively interpreting what is out there, the brain often goes beyond the call of duty to make things up. Consider the example

of the retina, the specialized sheet of photoreceptor cells at the back of the eye. In 1668, the French philosopher and mathematician Edme Mariotte stumbled on something quite unexpected: there is a sizable patch in the retina where the photoreceptors are missing.¹³ This missing patch surprised Mariotte because the visual field appears continuous: there is no corresponding gaping hole of vision where the photoreceptors are missing.

Or isn't there? As Mariotte delved more deeply into this issue, he



realized that there *is* a hole in our vision—what has come to be known as the “blind spot” in each eye. To demonstrate this to yourself, close your left eye and keep your right eye fixed on the plus sign.

Slowly move the page closer to and farther from your face until the black dot disappears (probably when the page is about twelve inches away). You can no longer see the dot because it is sitting in your blind spot.

Don't assume that your blind spot is small. It's huge. Imagine the diameter of the moon in the night sky. You can fit seventeen moons into your blind spot.

So why hadn't anyone noticed this hole in vision before Mariotte? How could brilliant minds like Michelangelo, Shakespeare, and Galileo have lived and died without ever detecting this basic fact of vision? One reason is because there are two eyes and the blind spots are in different, nonoverlapping

locations; this means that with both eyes open you have full coverage of the scene. But more significantly, no one had noticed because the brain “fills in” the missing information from the blind spot. Notice what you see in the location of the dot when it's in your blind spot. When the dot disappears, you do not perceive a hole of whiteness or blackness in its place; instead your brain *invents* a patch of the background pattern. Your brain, with no information from that particular spot in visual space, fills in with the patterns around it.

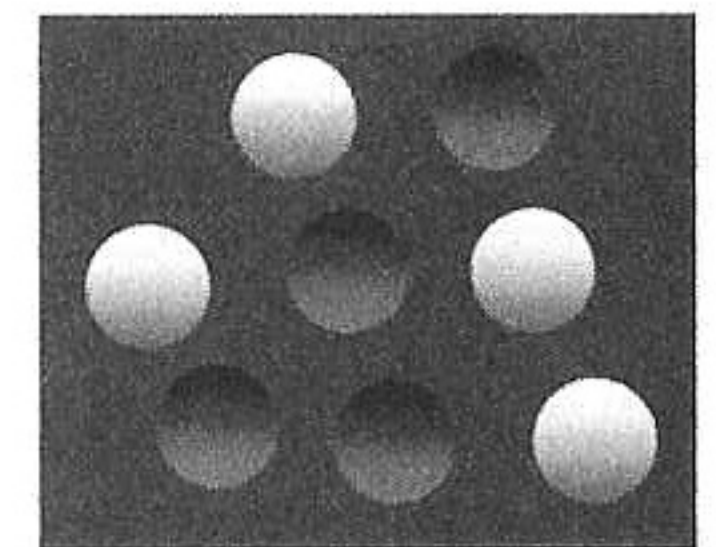
You're not perceiving what's out there. You're perceiving whatever your brain tells you.

* * *

By the mid-1800s, the German physicist and physician Hermann von Helmholtz (1821–1894) had begun to entertain the suspicion that the trickle of data moving from the eyes to the brain is too small to really account for the rich experience of vision. He concluded that the brain must make *assumptions* about the incoming data, and that these assumptions are based on our previous experience.¹⁴ In other words, given a little information, your brain uses its best guesses to turn it into something larger.

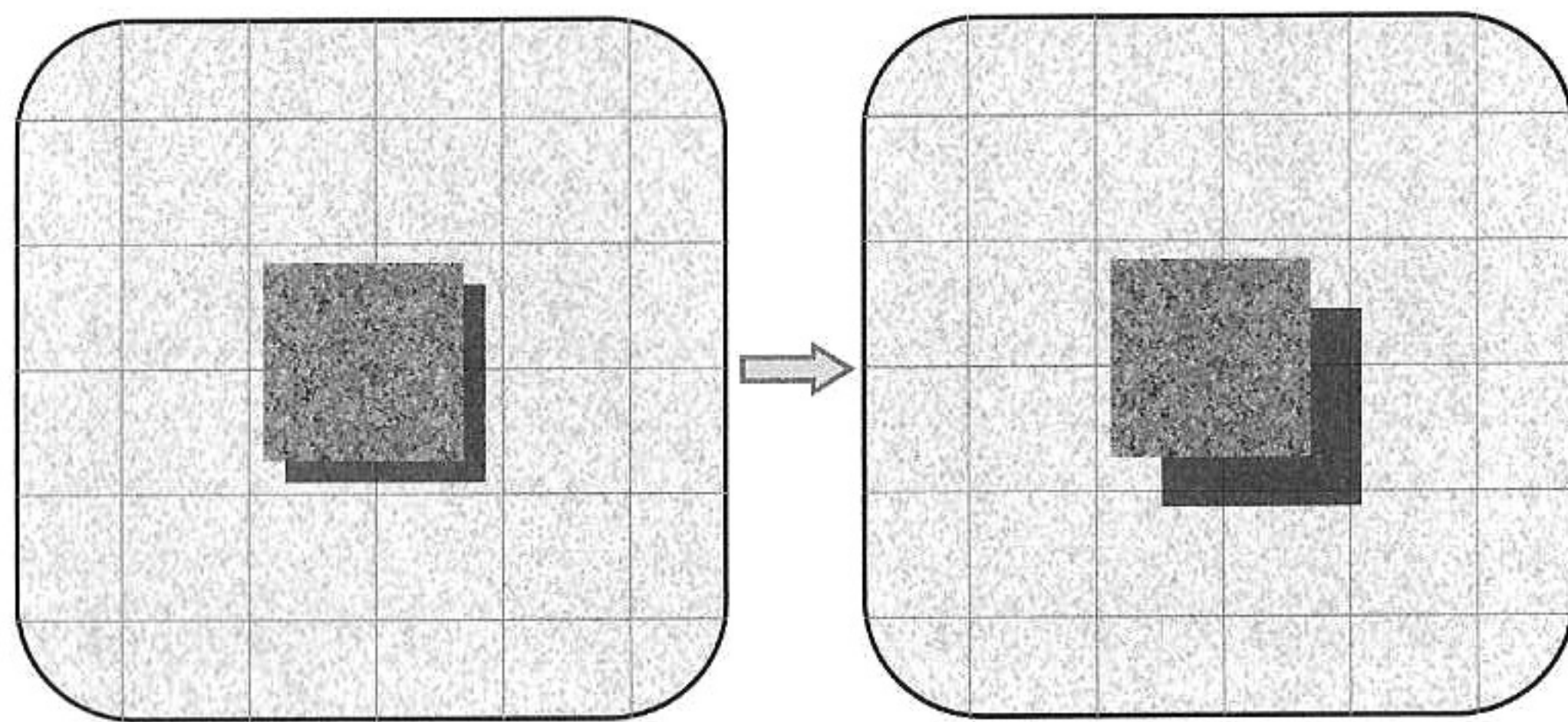
Consider this: based on your previous experience, your brain assumes that visual scenes are illuminated by a light source from above.¹⁵ So a flat circle with shading that is lighter at the top and darker at the bottom will be seen as bulging out; one with shading in the opposite direction will be perceived to be dimpling in. Rotating the figure ninety degrees will remove the illusion, making it clear that these are merely flat, shaded circles—but when the figure is turned right side up again, one cannot help but feel an illusory sense of depth.

As a result of the brain's notions about lighting sources, it makes unconscious assumptions about shadows as well: if a



square casts a shadow and the shadow suddenly moves, you will believe the square has moved in depth.¹⁶

Take a look at the figure below: the square hasn't moved at all; the dark square representing its shadow has merely been drawn in a slightly different place. This *could* have happened because the overhead lighting source suddenly shifted position—but because of your previous experience with the slow-moving sun and fixed electrical lighting, your perception automatically gives preference to the likelier explanation: the object has moved toward you.



Helmholtz called this concept of vision “unconscious inference,” where *inference* refers to the idea that the brain conjectures what might be out there, and *unconscious* reminds us that we have no awareness of the process. We have no access to the rapid and automatic machinery that gathers and estimates the statistics of the world. We’re merely the beneficiaries riding on top of the machinery, enjoying the play of light and shadows.

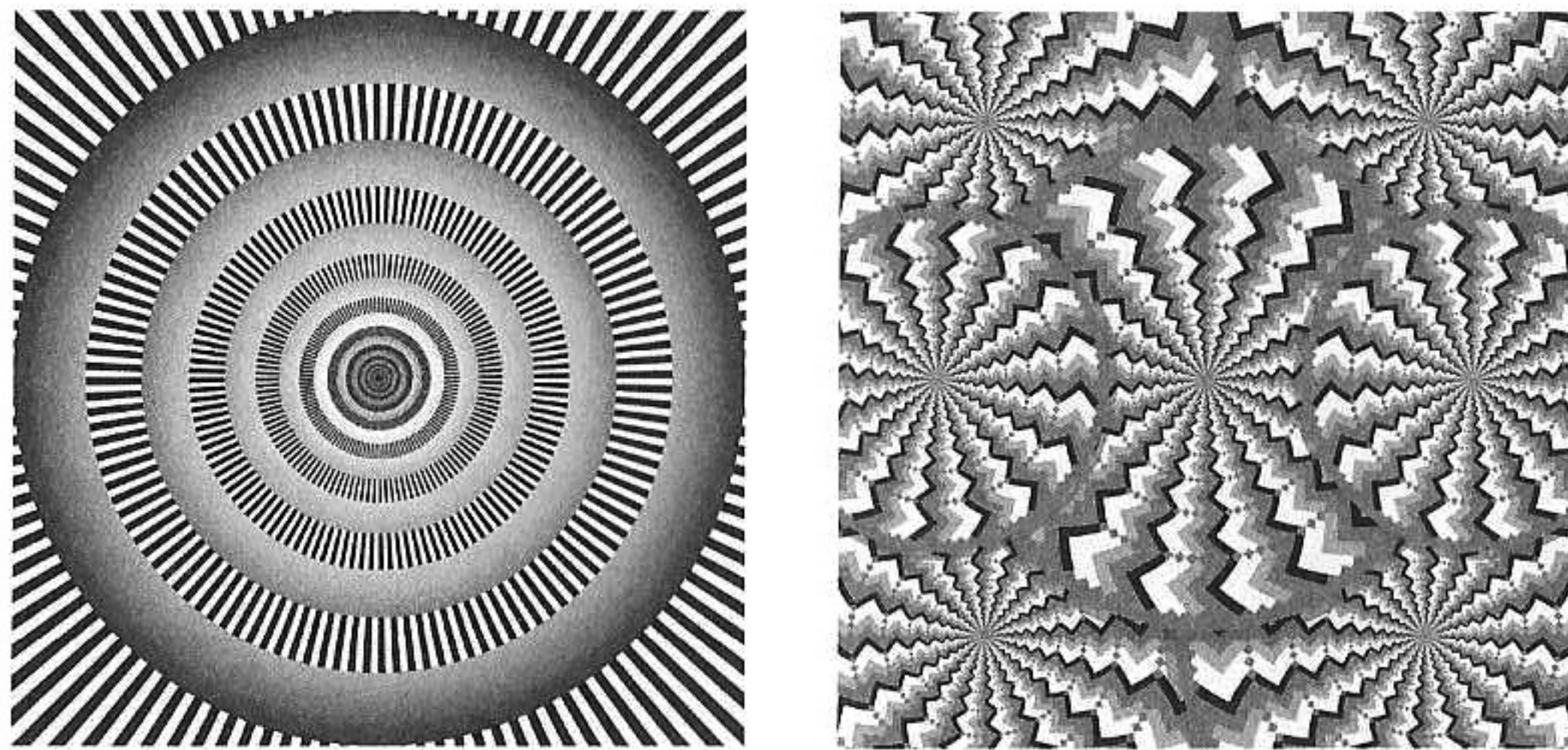
HOW CAN ROCKS DRIFT UPWARD WITHOUT CHANGING POSITION?

When we begin to look closely at that machinery, we find a complex system of specialized cells and circuits in the part of your brain called

the visual cortex. There is a division of labor among these circuits: some are specialized for color, some for motion, some for edges, and others for scores of different attributes. These circuits are densely interconnected, and they come to conclusions as a group. When necessary, they serve up a headline for what we might call the *Consciousness Post*. The headline reports only that a bus is coming or that someone has flashed a flirtatious smile—but it does not cite the varied sources. Sometimes it is tempting to think that seeing is easy *despite* the complicated neural machinery that underlies it. To the contrary, it is easy *because of* the complicated neural machinery.

When we take a close look at the machinery, we find that vision can be deconstructed into parts. Stare at a waterfall for a few minutes; after shifting your gaze, stationary objects such as the nearby rocks will briefly appear to crawl upward.¹⁷ Strangely, there is no change in their position over time, even though their movement is clear. Here the imbalanced activity of your motion detectors (usually upward-signaling neurons are balanced in a push-pull relationship with downward-signaling neurons) allows you to see what is impossible in the outside world: motion without position change. This illusion—known as the motion aftereffect or the waterfall illusion—has enjoyed a rich history of study dating back to Aristotle. The illusion illustrates that vision is the product of different modules: in this case, some parts of the visual system insist (incorrectly) that the rocks are moving, while other parts insist that the rocks are not, in fact, changing position. As the philosopher Daniel Dennett has argued, the naïve introspector usually relies on the bad metaphor of the television screen,¹⁸ where moving-while-staying-still cannot happen. But the visual world of the brain is nothing like a television screen, and motion with no change in position is a conclusion it sometimes lands upon.

There are many illusions of motion with no change of position. The figure on the next page demonstrates that static images can appear to move if they happen to tickle motion detectors in the right way. These illusions exist because the exact shading in the pictures stimulates motion detectors in the visual system—and the activity



Motion can be seen even when there is no change in position. (a) High-contrast figures like these stimulate motion detectors, giving the impression of constant movement around the rings. (b) Similarly, the zigzag wheels here appear to turn slowly.

of these receptors is *equivalent* to the perception of motion. If your motion detectors declare that something is moving out there, the conscious you believes it without question. And not merely believes it but *experiences* it.

A striking example of this principle comes from a woman who in 1978 suffered carbon monoxide poisoning.¹⁹ Fortunately, she lived; unfortunately, she suffered irreversible brain damage to parts of her visual system—specifically, the regions involved in representing motion. Because the rest of her visual system was intact, she was able to see stationary objects with no problem. She could tell you there was a ball over there and a telephone over here. But she could no longer see motion. If she stood on a sidewalk trying to cross the street, she could see the red truck over there, and then here a moment later, and finally over there, past her, another moment later—but the truck had no sense of *movement* to it. If she tried to pour water out of a pitcher, she would see a tilted pitcher, then a gleaming column of water hanging from the pitcher, and finally a puddle of water around the glass as it overflowed—but she couldn't see the liquid move. Her life was a series of snapshots. Just as with the waterfall effect, her condition of motion blindness tells us that position and motion are separable in the brain. Motion is “painted on” our views

of the world, just as it is erroneously painted on the images above.

A physicist thinks about motion as change in position through time. But the brain has its own logic, and this is why thinking about motion like a physicist rather than like a neuroscientist will lead to wrong predictions about how people operate. Consider baseball outfielders catching fly balls. How do they decide where to run to intercept the ball? Probably their brains represent where the ball is from moment to moment: now it's over there, now it's a little closer, now it's even closer. Right? Wrong.

So perhaps the outfielder's brain calculates the ball's velocity, right? Wrong.

Acceleration? Wrong.

Scientist and baseball fan Mike McBeath set out to understand the hidden neural computations behind catching fly balls.²⁰ He discovered that outfielders use an unconscious program that tells them not where to end up but simply how to keep running. They move in such a way that the parabolic path of the ball always progresses in a straight line from their point of view. If the ball's path looks like its deviating from a straight line, they modify their running path.

This simple program makes the strange prediction that the outfielders will not dash directly to the landing point of the ball but will instead take a peculiarly curved running path to get there. And that's exactly what players do, as verified by McBeath and his colleagues by aerial video.²¹ And because this running strategy gives no information about where the point of intersection will be, only how to keep moving to get there, the program explains why outfielders crash into walls while chasing uncatchable fly balls.

So we see that the system does not need to explicitly represent position, velocity, or acceleration in order for the player to succeed in catching or interception. This is probably not what a physicist would have predicted. And this drives home the point that introspection has little meaningful insight into what is happening behind the scenes. Outfielding greats such as Ryan Braun and Matt Kemp have no idea that they're running these programs; they simply enjoy the consequences and cash the resulting paychecks.

LEARNING TO SEE

When Mike May was three years old, a chemical explosion rendered him completely blind. This did not stop him from becoming the best blind downhill speed skier in the world, as well as a businessman and family man. Then, forty-three years after the explosion robbed him of his vision, he heard about a new surgical development that might be able to restore it. Although he was successful in his life as a blind man, he decided to undergo the surgery.

After the operation, the bandages were removed from around his eyes. Accompanied by a photographer, Mike sat on a chair while his two children were brought in. This was a big moment. It would be the first time he would ever gaze into their faces with his newly cleared eyes. In the resulting photograph, Mike has a pleasant but awkward smile on his face as his children beam at him.

The scene was supposed to be touching, but it wasn't. There was a problem. Mike's eyes were now working perfectly, but he stared with utter puzzlement at the objects in front of him. His brain didn't know what to make of the barrage of inputs. He wasn't experiencing his sons' faces; he was experiencing only uninterpretable sensations of edges and colors and lights. Although his eyes were functioning, he didn't have *vision*.²²

And this is because the brain has to *learn* how to see. The strange electrical storms inside the pitch-black skull get turned into conscious summaries after a long haul of figuring out how objects in the world match up across the senses. Consider the experience of walking down a hallway. Mike knew from a lifetime of moving down corridors that walls remain parallel, at arm's length, the whole way down. So when his vision was restored, the concept of converging perspective lines was beyond his capacity to understand. It made no sense to his brain.

Similarly, when I was a child I met a blind woman and was amazed at how intimately she knew the layout of her rooms and furniture. I asked her if she would be able to draw out the blueprints with higher accuracy than most sighted people. Her

response surprised me: she said she would *not* be able to draw the blueprints at all, because she didn't understand how sighted people converted three dimensions (the room) into two dimensions (a flat piece of paper). The idea simply didn't make sense to her.²³

Vision does not simply *exist* when a person confronts the world with clear eyes. Instead, an interpretation of the electrochemical signals streaming along the optic nerves has to be trained up. Mike's brain didn't understand how his own movements changed the sensory consequences. For example, when he moves his head to the left, the scene shifts to the right. The brains of sighted people have come to expect such things and know how to ignore them. But Mike's brain was flummoxed at these strange relationships. And this illustrates a key point: the conscious experience of vision occurs only when there is accurate prediction of sensory consequences,²⁴ a point to which we will return shortly. So although vision *seems* like a rendition of something that's objectively out there, it doesn't come for free. It has to be learned.

After moving around for several weeks, staring at things, kicking chairs, examining silverware, rubbing his wife's face, Mike came to have the experience of sight as we experience it. He now experiences vision the same way you do. He just appreciates it more.

* * *

Mike's story shows that the brain can take a torrent of input and learn to make sense of it. But does this imply the bizarre prediction that you can *substitute* one sense for another? In other words, if you took a data stream from a video camera and converted it into an input to a different sense—taste or touch, say—would you eventually be able to see the world that way? Incredibly, the answer is yes, and the consequences run deep, as we are about to see.

SEEING WITH THE BRAIN

In the 1960s, the neuroscientist Paul Bach-y-Rita at the University of Wisconsin began chewing on the problem of how to give vision to the blind.²⁵ His father had recently had a miraculous recovery from a stroke, and Paul found himself enchanted by the potential for dynamically reconfiguring the brain.

A question grew in his mind: could the brain substitute one sense for another? Bach-y-Rita decided to try presenting a tactile “display” to blind people.²⁶ Here’s the idea: attach a video camera to someone’s forehead and convert the incoming video information into an array of tiny vibrators attached to their back. Imagine putting this device on and walking around a room blindfolded. At first you’d feel a bizarre pattern of vibrations on the small of your back. Although the vibrations would change in strict relation to your own movements, it would be quite difficult to figure out what was going on. As you hit your shin against the coffee table, you’d think, “This really is nothing like vision.”

Or isn’t it? When blind subjects strap on these visual-tactile substitution glasses and walk around for a week, they become quite good at navigating a new environment. They can translate the feelings on their back into knowing the right way to move. But that’s not the stunning part. The stunning part is that they actually begin to perceive the tactile input—to *see* with it. After enough practice, the tactile input becomes more than a cognitive puzzle that needs translation; it becomes a direct sensation.²⁷

If it seems strange that nerve signals coming from the back can represent vision, bear in mind that your own sense of vision is carried by nothing but millions of nerve signals that just happen to travel along different cables. Your brain is encased in absolute blackness in the vault of your skull. It doesn’t *see* anything. All it knows are these little signals, and nothing else. And yet you perceive the world in all shades of brightness and colors. Your brain is in the dark but your mind constructs light.

To the brain, it doesn’t matter where those pulses come from—

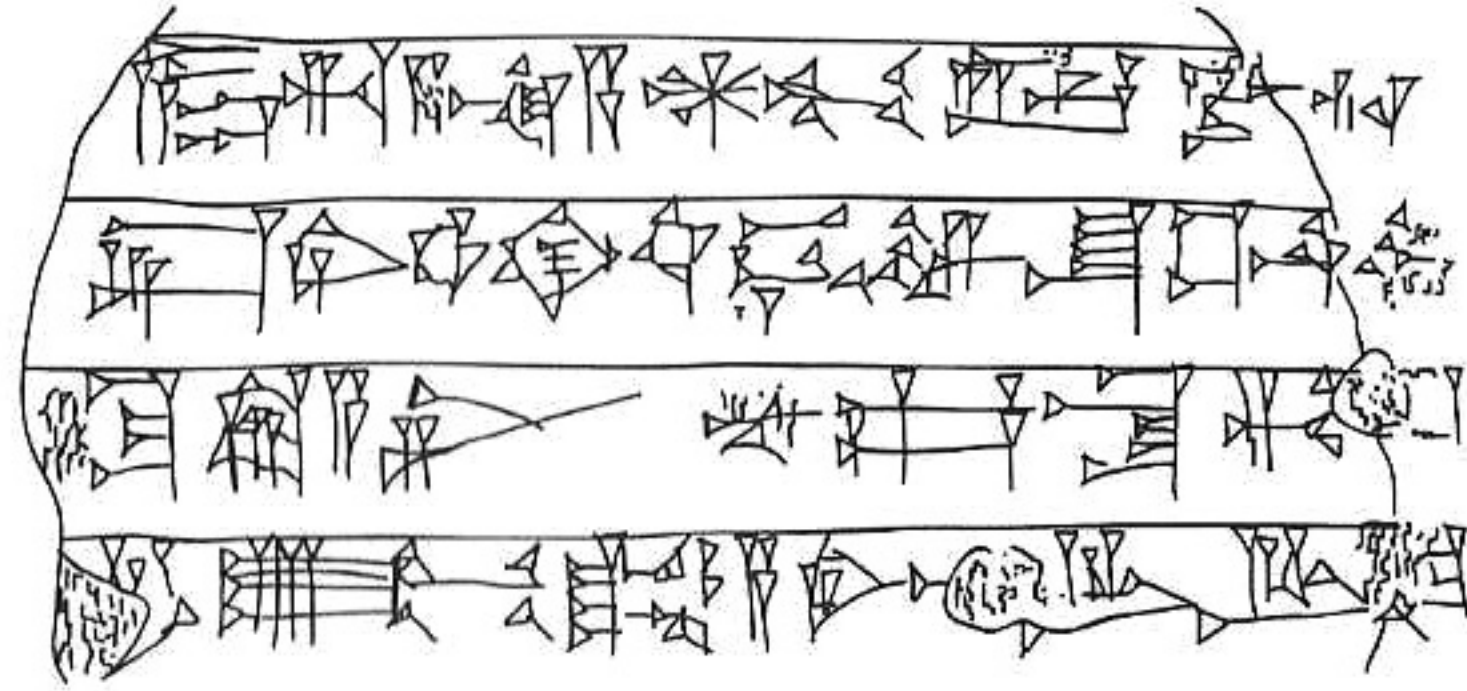
from the eyes, the ears, or somewhere else entirely. As long as they consistently correlate with your own movements as you push, thump, and kick things, your brain can construct the direct perception we call vision.²⁸

Other sensory substitutions are also under active investigation.²⁹ Consider Eric Weihenmayer, an extreme rock climber, who scales dangerously sheer rock faces by thrusting his body upward and clinging to precariously shallow foot ledges and handholds. Adding to his feats is the fact that he is blind. He was born with a rare eye disease called retinoschisis, which rendered him blind at thirteen years old. He did not, however, let that crush his dream of being a mountaineer, and in 2001 he became the first (and so far only) blind person to climb Mount Everest. Today he climbs with a grid of over six hundred tiny electrodes in his mouth, called the BrainPort.³⁰ This device allows him to *see with his tongue* while he climbs. Although the tongue is normally a taste organ, its moisture and chemical environment make it an excellent brain-machine interface when a tingling electrode grid is laid on its surface.³¹ The grid translates a video input into patterns of electrical pulses, allowing the tongue to discern qualities usually ascribed to vision, such as distance, shape, direction of movement, and size. The apparatus reminds us that we see not with our eyes but rather with our brains. The technique was originally developed to assist the blind, like Eric, but more recent applications that feed infrared or sonar input to the tongue grid allow divers to see in murky water and soldiers to have 360-degree vision in the dark.³²

Eric reports that although he first perceived the tongue stimulation as unidentifiable edges and shapes, he quickly learned to recognize the stimulation at a deeper level. He can now pick up a cup of coffee or kick a soccer ball back and forth with his daughter.³³

If seeing with your tongue sounds strange, think of the experience of a blind person learning to read Braille. At first it’s just bumps; eventually those bumps come to have meaning. And if you’re having a hard time imagining the transition from cognitive puzzle to direct perception, just consider the way you are reading

the letters on this page. Your eyes flick effortlessly over the ornate shapes without any awareness that you are translating them: the meaning of the words simply comes to you. You perceive the language, not the low-level details of the graphemes. To drive home the point, try reading this:



If you were an ancient Sumerian, the meaning would be readily apparent—it would flow off the tablet directly into meaning with no awareness of the mediating shapes. And the meaning of the next sentence is immediately apparent if you’re from Jinghong, China (but not from other Chinese regions):

မ္ဗဗ် င်းလှာလှာ ဝါမ္ဗဗ် င်တ ခွဲဒ် ဒုလှာဗ်ဗ် တွဲလော င်း င်တ င်.

This next sentence is hilariously funny if you are a reader of the northwestern Iranian language of Baluchi:

توامين انسان بنى صورتء شريدارين ء آجونين دروشمء ودى بنت اين. اشانى تها زانت، سرپدى
 ء شعور است بيت. اے وت ما وتا براتى منيل ء يکجائىء به ودين انت.

To the reader of cuneiform, New Tai Lue, or Baluchi, the rest of the English script on this page looks as foreign and uninterpretable as their script looks to you. But these letters are effortless for you, because you’ve already turned the chore of cognitive translation into direct perception.

And so it goes with the electrical signals coming into the brain: at first they are meaningless; with time they accrue meaning. In

the same way that you immediately “see” the meaning in these words, your brain “sees” a timed barrage of electrical and chemical signals as, say, a horse galloping between snow-blanketed pine trees. To Mike May’s brain, the neural letters coming in are still in need of translation. The visual signals generated by the horse are uninterpretable bursts of activity, giving little indication, if any, of what’s out there; the signals on his retina are like letters of Baluchi that struggle to be translated one by one. To Eric Weihenmayer’s brain, his tongue is sending messages in New Tai Lue—but with enough practice, his brain learns to understand the language. At that point, his understanding of the visual world is as directly apparent as the words of his native tongue.

Here’s an amazing consequence of the brain’s plasticity: in the future we may be able to plug new sorts of data streams directly into the brain, such as infrared or ultraviolet vision, or even weather data or stock market data.³⁴ The brain will struggle to absorb the data at first, but eventually it will learn to speak the language. We’ll be able to add new functionality and roll out Brain 2.0.

This idea is not science fiction; the work has already begun. Recently, researchers Gerald Jacobs and Jeremy Nathans took the gene for a human photopigment—a protein in the retina that absorbs light of a particular wavelength—and spliced it into color-blind mice.³⁵ What emerged? Color vision. These mice can now tell different colors apart. Imagine you give them a task in which they can gain a reward by hitting a blue button but they get no reward for hitting a red button. You randomize the positions of the buttons on each trial. The modified mice, it turns out, learn to choose the blue button, while to normal mice the buttons look indistinguishable—and hence they choose randomly. The brains of the new mice have figured out how to listen to the new dialect their eyes are speaking.

From the natural laboratory of evolution comes a related phenomenon in humans. At least 15 percent of human females possess a genetic mutation that gives them an extra (fourth) type of color photoreceptor—and this allows them to discriminate between colors that look identical to the majority of us with a

mere three types of color photoreceptors.³⁶ Two color swatches that look identical to the majority of people would be clearly distinguishable to these ladies. (No one has yet determined what percentage of fashion arguments is caused by this mutation.)

So plugging new data streams into the brain is not a theoretical notion; it already exists in various guises. It may seem surprising how easily new inputs can become operable—but, as Paul Bach-y-Rita simply summarized his decades of research, “Just give the brain the information and it will figure it out.”

If any of this has changed your view of how you perceive reality, strap in, because it gets stranger. We’ll next discover why seeing has very little to do with your eyes. END

ACTIVITY FROM WITHIN

In the traditionally taught view of perception, data from the sensorium pours into the brain, works its way up the sensory hierarchy, and makes itself seen, heard, smelled, tasted, felt—“perceived.” But a closer examination of the data suggests this is incorrect. The brain is properly thought of as a mostly closed system that runs on its own internally generated activity.³⁷ We already have many examples of this sort of activity: for example, breathing, digestion, and walking are controlled by autonomously running activity generators in your brain stem and spinal cord. During dream sleep the brain is isolated from its normal input, so internal activation is the only source of cortical stimulation. In the awake state, internal activity is the basis for imagination and hallucinations.

The more surprising aspect of this framework is that the internal data is not *generated* by external sensory data but merely *modulated* by it. In 1911, the Scottish mountaineer and neurophysiologist Thomas Graham Brown showed that the program for moving the muscles for walking is built into the machinery of the spinal cord.³⁸ He severed the sensory nerves from a cat’s legs and demonstrated that the cat could walk on a treadmill perfectly well. This indi-

cated that the program for walking was internally generated in the spinal cord and that sensory feedback from the legs was used only to *modulate* the program—when, say, the cat stepped on a slippery surface and needed to stay upright.

The deep secret of the brain is that not only the spinal cord but the entire central nervous system works this way: internally generated activity is modulated by sensory input. In this view, the difference between being awake and being asleep is merely that the data coming in from the eyes *anchors* the perception. Asleep vision (dreaming) is perception that is not tied down to anything in the real world; waking perception is something like dreaming with a little more commitment to what’s in front of you. Other examples of unanchored perception are found in prisoners in pitch-dark solitary confinement, or in people in sensory deprivation chambers. Both of these situations quickly lead to hallucinations.

Ten percent of people with eye disease and visual loss will experience visual hallucinations. In the bizarre disorder known as Charles Bonnet syndrome, people losing their sight will begin to see things—such as flowers, birds, other people, buildings—that they know are not real. Bonnet, a Swiss philosopher who lived in the 1700s, first described this phenomenon when he noticed that his grandfather, who was losing his vision to cataracts, tried to interact with objects and animals that were not physically there.

Although the syndrome has been in the literature for centuries, it is underdiagnosed for two reasons. The first is that many physicians do not know about it and attribute its symptoms to dementia. The second is that the people experiencing the hallucinations are discomfited by the knowledge that their visual scene is at least partially the counterfeit coinage of their brains. According to several surveys, most of them will never mention their hallucinations to their doctor out of fear of being diagnosed with mental illness.

As far as the clinicians are concerned, what matters most is whether the patient can perform a reality check and know that he is hallucinating; if so, the vision is labeled a *pseudohallucination*. Of course, sometimes it’s quite difficult to know if you’re hallucinating. You