PROBABILISTIC PERCEPTION: MORE, AND LESS, THAN MEETS THE EYE

Reading Materials

1. Biographical Information on Ruben Coen Cagli, Ph.D.

2. Visual Perception Theory

3. Misperceptions: Your Perception May Depend On Your Perspective

4. Visual Illusions (Encyclopedia of Perception)

5. Bayes’s Theorem: What’s the Big Deal?
BIBLIOGRAPHICAL INFORMATION ON RUBEN COEN CAGLI, PH.D.

I obtained my degree in theoretical physics from the University of Napoli Federico II with a thesis on quantum computing, an interdisciplinary effort to turn the fundamental properties of the microscopic world into a novel computing paradigm. In my graduate work at the same university, I combined eye-tracking experiments, Bayesian modeling and a robotic arm simulator to study eye-hand coordination. In 2008 I started a postdoc at the Albert Einstein College of Medicine in New York, studying the link between statistical structure in natural images and neuronal responses in visual cortex. In 2012 I was awarded a postdoctoral fellowship by the Swiss Society for Neuroscience and the International Brain Research Organization, to join the theoretical neuroscience lab at the University of Geneva, where I studied the origins of neuronal and perceptual variability. In summer 2016 I joined the Department of Systems and Computational Biology and Department of Neuroscience at Albert Einstein College of Medicine as Assistant Professor.
In order to receive information from the environment we are equipped with sense organs e.g. eye, ear, nose. Each sense organ is part of a sensory system which receives sensory inputs and transmits sensory information to the brain.

A particular problem for psychologists is to explain the process by which the physical energy received by sense organs forms the basis of perceptual experience. Sensory inputs are somehow converted into perceptions of desks and computers, flowers and buildings, cars and planes; into sights, sounds, smells, taste and touch experiences.

A major theoretical issue on which psychologists are divided is the extent to which perception relies directly on the information present in the stimulus. Some argue that perceptual processes are not direct, but depend on the perceiver's expectations and previous knowledge as well as the information available in the stimulus itself.

This controversy is discussed with respect to Gibson (1966) who has proposed a direct theory of perception which is a 'bottom-up' theory, and Gregory (1970) who has proposed a constructivist (indirect) theory of perception which is a 'top-down' theory.

Psychologists distinguish between two types of processes in perception: bottom-up processing and top-down processing.

**Bottom-up processing** is also known as data-driven processing, because perception begins with the stimulus itself. Processing is carried out in one direction from the retina to the visual cortex, with each successive stage in the visual pathway carrying out ever more complex analysis of the input.

**Top-down processing** refers to the use of contextual information in pattern recognition. For example, understanding difficult handwriting is easier when reading complete sentences than when reading single and isolated words. This is because the meaning of the surrounding words provide a context to aid understanding.

Gregory (1970) and Top Down
Processing Theory

Psychologist Richard Gregory (1970) argued that perception is a constructive process which relies on top-down processing.

Stimulus information from our environment is frequently ambiguous so to interpret it, we require higher cognitive information either from past experiences or stored knowledge in order to make inferences about what we perceive. Helmholtz called it the 'likelihood principle'.

For Gregory perception is a hypothesis, which is based on prior knowledge. In this way we are actively constructing our perception of reality based on our environment and stored information.

Summary

- A lot of information reaches the eye, but much is lost by the time it reaches the brain (Gregory estimates about 90% is lost).
- Therefore, the brain has to guess what a person sees based on past experiences. We actively construct our perception of reality.
- Richard Gregory proposed that perception involves a lot of hypothesis testing to make sense of the information presented to the sense organs.
- Our perceptions of the world are hypotheses based on past experiences and stored information.
- Sensory receptors receive information from the environment, which is then combined with previously stored information about the world which we have built up as a result of experience.
- The formation of incorrect hypotheses will lead to errors of perception (e.g. visual illusions like the Necker cube).

Evidence to Support Gregory's Theory

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<th>Highly unlikely objects tend to be mistaken for likely objects</th>
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<td>Gregory has demonstrated this with a hollow mask of a face (see video below). Such a mask is generally seen as normal, even when one knows and feels the real mask.</td>
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<td>There seems to be an overwhelming need to reconstruct the face, similar to Helmholtz's description of 'unconscious inference'. An assumption based on past experience.</td>
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<th>Perceptions can be ambiguous</th>
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The Necker cube is a good example of this. When you stare at the crosses on the cube the orientation can suddenly change, or 'flip'. It becomes unstable and a single physical pattern can produce two perceptions.

Gregory argued that this object appears to flip between orientations because the brain develops two equally plausible hypotheses and is unable to decide between them. When the perception changes though there is no change of the sensory input, the change of appearance cannot be due to bottom-up processing. It must be set downwards by the prevailing perceptual hypothesis of what is near and what is far.

Perception allows behavior to be generally appropriate to non-sensed object characteristics. For example, we respond to certain objects as though they are doors even though we can only see a long narrow rectangle as the door is ajar. What we have seen so far would seem to confirm that indeed we do interpret the information that we receive, in other words, perception is a top down process.

Critical Evaluation of Gregory's Theory

1. The Nature of Perceptual Hypotheses

If perceptions make use of hypothesis testing the question can be asked 'what kind of hypotheses are they?' Scientists modify a hypothesis according to the support they find for it so are we as perceivers also able to modify our hypotheses? In some cases it would seem the answer is yes. For example, look at the figure below:

This probably looks like a random arrangement of black shapes. In fact there is a hidden face in there, can you see it? The face is looking straight ahead and is in the top half of the picture in the center. Now can you see it? The figure is strongly lit from the side and has long hair and a beard.

Once the face is discovered, very rapid perceptual learning takes place and
the ambiguous picture now obviously contains a face each time we look at it. We have learned to perceive the stimulus in a different way.

Although in some cases, as in the ambiguous face picture, there is a direct relationship between modifying hypotheses and perception, in other cases this is not so evident. For example, illusions persist even when we have full knowledge of them (e.g. the inverted face, Gregory 1974). One would expect that the knowledge we have learned (from, say, touching the face and confirming that it is not 'normal') would modify our hypotheses in an adaptive manner. The current hypothesis testing theories cannot explain this lack of a relationship between learning and perception.

2. Perceptual Development

A perplexing question for the constructivists who propose perception is essentially top-down in nature is 'how can the neonate ever perceive?' If we all have to construct our own worlds based on past experiences why are our perceptions so similar, even across cultures? Relying on individual constructs for making sense of the world makes perception a very individual and chancy process.

The constructivist approach stresses the role of knowledge in perception and therefore is against the nativist approach to perceptual development. However, a substantial body of evidence has been accrued favoring the nativist approach, for example: Newborn infants show shape constancy (Slater & Morison, 1985); they prefer their mother's voice to other voices (De Casper & Fifer, 1980); and it has been established that they prefer normal features to scrambled features as early as 5 minutes after birth.

3. Sensory Evidence

Perhaps the major criticism of the constructivists is that they have underestimated the richness of sensory evidence available to perceivers in the real world (as opposed to the laboratory where much of the constructivists' evidence has come from).

Constructivists like Gregory frequently use the example of size constancy to support their explanations. That is, we correctly perceive the size of an object even though the retinal image of an object shrinks as the object recedes. They propose that sensory evidence from other sources must be available for us to be able to do this.

However, in the real world, retinal images are rarely seen in isolation (as is possible in the laboratory). There is a rich array of sensory information including other objects, background, the distant horizon and movement. This rich source of sensory information is important to the second approach to explaining perception that we will examine, namely the direct approach to perception as proposed by Gibson.

Gibson argued strongly against the idea that perception involves top-down processing and criticizes Gregory's discussion of visual illusions on the
grounds that they are artificial examples and not images found in our normal visual environments. This is crucial because Gregory accepts that misperceptions are the exception rather than the norm. Illusions may be interesting phenomena, but they might not be that informative about the debate.

Gibson (1966) and Bottom Up Processing

Gibson’s bottom up theory suggests that perception involves innate mechanisms forged by evolution and that no learning is required. This suggests that perception is necessary for survival – without perception we would live in a very dangerous environment. Our ancestors would have needed perception to escape from harmful predators, suggesting perception is evolutionary.

James Gibson (1966) argues that perception is direct, and not subject to hypotheses testing as Gregory proposed. There is enough information in our environment to make sense of the world in a direct way. His theory is sometimes known as the ‘Ecological Theory’ because of the claim that perception can be explained solely in terms of the environment.

For Gibson: sensation is perception: what you see if what you get. There is no need for processing (interpretation) as the information we receive about size, shape and distance etc. is sufficiently detailed for us to interact directly with the environment.

Gibson (1972) argued that perception is a bottom-up process, which means that sensory information is analyzed in one direction: from simple analysis of raw sensory data to ever increasing complexity of analysis through the visual system.

Features of Gibson’s Theory

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<th>The optic array</th>
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<td>The starting point for Gibson’s Theory was that the pattern of light reaching the eye, known as the optic array, containing all the visual information necessary for perception.</td>
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<td>This optic array provides unambiguous information about the layout of objects in space. Light rays reflect off of surfaces and converge into the cornea of your eye.</td>
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<td>Perception involves ‘picking up’ the rich information provided by the</td>
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optic array in a direct way with little/no processing involved.

Because of movement and different intensities of light shining in different directions it is an ever changing source of sensory information. Therefore, if you move, the structure of the optic array changes.

According to Gibson, we have the mechanisms to interpret this unstable sensory input, meaning we experience a stable and meaningful view of the world.

Changes in the flow of the optic array contain important information about what type of movement is taking place. The flow of the optic array will either move from or towards a particular point.

If the flow appears to be coming from the point, it means you are moving towards it. If the optic array is moving towards the point you are moving away from it.

Invariant Features

the optic array contains invariant information that remains constant as the observer moves. Invariants are aspects of the environment which don’t change. They supply us with crucial information.

Two good examples of invariants are texture and linear perspective.

Another invariant is the horizon-ratio relation. The ratio above and below the horizon is constant for objects of the same size standing on the same ground.

Affordances

Are, in short, cues in the environment that aid perception. Important cues in the environment include:

OPTICAL ARRAY: The patterns of light that reach the eye from the environment.

RELATIVE BRIGHTNESS: Objects with brighter, clearer images are perceived as closer.

TEXTURE GRADIENT: The grain of texture gets smaller as the object recedes. Gives the impression of surfaces receding into the distance.

Gibson's theory is a highly ecologically valid theory as it puts perception back into the real world. A large number of applications can be applied in terms of his theory e.g. training pilots, runway markings and road markings. It’s an excellent explanation for perception when viewing conditions are clear. Gibson’s theory also highlights the richness of information in optic array and provides an account of perception in animals, babies and humans.

His theory is reductionist as it seeks to explain perception solely in terms of the environment. There is strong evidence to show that the brain and long term memory can influence perception. In this case, it could be said that Gregory’s theory is far more plausible.

Gibson’s theory also only supports one side of the nature nurture debate, that being the nature side. Again, Gregory’s theory is far more plausible as it suggests that what we see with our eyes is not enough and we use knowledge already stored in our brain, supporting both sides of the debate.

Visual Illusions

Gibson's emphasis on DIRECT perception provides an explanation for the (generally) fast and accurate perception of the environment. However, his theory cannot explain why perceptions are sometimes inaccurate, e.g. in illusions. He claimed the illusions used in experimental work constituted extremely artificial perceptual situations unlikely to be encountered in the real world, however this dismissal cannot realistically be applied to all illusions.

For example, Gibson’s theory cannot account for perceptual errors like the
general tendency for people to overestimate vertical extents relative to horizontal ones.

Neither can Gibson’s theory explain naturally occurring illusions. For example if you stare for some time at a waterfall and then transfer your gaze to a stationary object, the object appears to move in the opposite direction.

Bottom-up or Top-down Processing?

Neither direct nor constructivist theories of perception seem capable of explaining all perception all of the time. Gibson’s theory appears to be based on perceivers operating under ideal viewing conditions, where stimulus information is plentiful and is available for a suitable length of time. Constructivist theories, like Gregory’s, have typically involved viewing under less than ideal conditions.

Research by Tulving et al manipulated both the clarity of the stimulus input and the impact of the perceptual context in a word identification task. As clarity of the stimulus (through exposure duration) and the amount of context increased, so did the likelihood of correct identification.

However, as the exposure duration increased, so the impact of context was reduced, suggesting that if stimulus information is high, then the need to use other sources of information is reduced. One theory that explains how top-down and bottom-up processes may be seen as interacting with each other to produce the best interpretation of the stimulus was proposed by Neisser (1976) - known as the ‘Perceptual Cycle’.

References


Misperceptions

Your perception may depend on your perspective.

By Susana Martinez-Conde and Stephen L. Macknik

Your brain creates a simulation of the world that may or may not match the real thing. The “reality” you experience is the result of your exclusive interaction with that simulation. We define “illusions” as the phenomena in which your perception differs from physical reality in a way that is readily evident. You may see something that is not there, or fail to see something that is there, or see something in a way that does not reflect its physical properties.

Some people think these illusions are simply mistakes made by the brain: erroneous computations, failures of perception that we would do well to overcome. But what if illusions are good things? Could it be that these peculiar mismatches between the inner and outer worlds are somehow desirable? Certainly, illusions are the product of evolution; we know that several illusions occur because of shortcuts that your brain takes to help you survive and thrive. Some of your misperceptions allow you to make lightning-fast assumptions that are technically wrong but helpful in practice. They can help you see the forest better—even if they make you discern the trees less precisely.

For example, you may underestimate or overestimate distances depending on various contextual cues. The psychologists Russell E. Jackson and Lawrence K. Cormack reported that when observers guessed the height of a cliff while looking down from the top, their estimates were 32 percent greater than when they were looking up from the cliff’s base. This discrepancy appears related to the way we observe the same precipice from above versus below: a cliff edge against the sky versus a cliff face sloping into open land. Given that accidents are more likely to happen while climbing down rather than up, this height overestimation, when you look down from the top, may make you descend cliffs with greater care, reducing your chances of falling.

Illusions also offer a window into how our neural circuits create our subjective experience of the world. The simulated reality your brain creates—also known as your consciousness—becomes the universe in which you live. It is the only thing you have ever perceived. Your brain uses partial and flawed information to build this mental model and relies on quirky neural algorithms to alleviate those flaws.

Because illusions enable us to see objects and events that do not match physical reality, they are critically important to understanding the neural mechanisms of perception and cognition. To encourage the discovery and study of illusions, we created the Best Illusion of the Year Contest in 2005 to honor the best new illusions from the previous year and celebrate the inventiveness of illusion creators around the world: researchers, software engineers, mathematicians, magicians, graphic designers, sculptors, and painters fascinated with mapping the boundaries of human perception. The contest is playful, but for scientists it serves a deeper purpose. All the little perceptual hiccups that the contest showcases are opportunities to peer behind the neurological curtain and learn how the brain works.

Nothing is more fundamental to our vision than how we see the brightness of an object. But even so, our visual system plays fast and loose with reality and serves up monstrously bizarre and perplexingly inaccurate interpretations of the physical world. And this raises the question that constantly cycles through the brains of vision scientists: Why doesn’t human vision faithfully represent the world we see? The answer is that illusions must help us survive (or at the very least not hinder our survival). If illusions were harmful, it is likely that they would have been weeded out of the gene pool by now.

But how can a visual illusion be useful? To illustrate,
we’ll do an experiment. Go to a dark room in your domicile with a cell phone and a book (an actual book, made of paper). Then dimly illuminate the pages of your book, using your phone, just enough to see the letters. White pages, black text—looks like a book, right? After you have completed this part of the experiment, head outside on a sunny day with the same book. Under direct sunlight, look at the same page; it looks identical, right? If you think it through, that’s impossible, because the physical reality under the two lighting conditions is very different! When you read black text on a page lit by a dim cell phone, the amount of light reflected by the white paper is around 100,000 times lower than the amount of light reflected by the black letters in direct sunlight. So why don’t the black letters seem super-white (100,000 times brighter than white) outside? The reason is that your brain doesn’t care about light levels; it cares about the contrast between the lightness of objects. It interprets the letters as black because they are darker than the rest of the page, no matter the lighting conditions.

The illusion that allows us to identify an object as being the same under different lighting conditions is a very useful one. It helps us survive. Our brain does not perceive the true brightness of an object in the world (for instance, measured with a photometer), but instead compares it with that of other nearby objects. For instance, the same gray square will look lighter when surrounded by black than when it is surrounded by white.
Cognitive scientists Kazunori Morikawa and Eri Ishii discovered a phenomenon they call the Head Size Illusion. The two faces shown here are identical except that the man on the left has a wider jaw and fuller face. The top of the head appears fatter, too, but it is not. The Head Size Illusion demonstrates that the brain does not determine the size of visual stimuli in isolation from one another; it compares objects and features with those nearby in the visual scene. The illusion occurs in everyday life, Morikawa said, and offers an opportunity for those who wish to alter their appearance. “If one part of your face or body appears wider or thinner than average, other parts appear wider or thinner, too,” he explained.

You may perceive these two side-by-side faces as female (left) and male (right). But both are versions of the same androgynous face. The two images are identical, except that the contrast between the eyes and mouth and the rest of the face is higher for the one on the left than for the one on the right. This illusion shows that contrast is an important cue for determining the gender of a face: low-contrast faces appear male, and high-contrast faces appear female. It may also explain why females in many cultures darken their eyes and mouths with cosmetics: a made-up face looks more feminine than a face without makeup.
This illusion by magician, photographer, and illusion creator Victoria Skye is an example of anamorphic perspective. By tilting her camera, she created two opposite vanishing points, producing the illusion of age progression and regression. In the case of age progression, the top of the head narrows and the bottom half of the face expands, creating a stronger chin and a more mature look. In the case of age regression, the opposite happens: the forehead expands and the chin narrows, producing a childlike appearance.

The Fat Face Thin Illusion shows two photographs that are identical, although the upside-down face appears strikingly slimmer than the right-side-up version. One possible explanation is that it is easier for the brain to recognize distinctive facial features, such as chubby cheeks, when they are viewed in the normal upright position. The neural mechanisms underlying this difference are not known, but research has shown that face-selective neurons of the human brain respond best to upright faces—probably because there has been no evolutionary pressure to recognize faces upside-down. These same neurons may encode various facial properties—like chubbiness—and be less capable of doing so accurately when faces are upside-down. If so, all upside-down faces could end up looking more similar to one another than if they were upright.
Subtle local effects can have major global consequences on how we perceive a shape, even one as simple as a circle. The circle on the left appears round only if you look directly at it. If you view it through your peripheral vision, it has corners! Visual neurons processing peripheral information have low spatial resolution, allowing them to “see” the gross details of objects only. When you see the circle on your left at the center of your vision—where your visual neurons have small, high-resolution windows on the world that scientists call “receptive fields”—you can see the curves that form the circle, and also the checkerboard pattern on the surface of the ring. In the periphery of your vision, however, visual neurons see the world through larger, low-resolution receptive fields that poorly appreciate the circle’s subtle curves while favoring its high-contrast large checks. And because the checks form diagonal lines when blurred, you see a diamond shape instead of a circle out of the corner of your eye. In contrast, when you view the ring on the right through the center of your vision, you perceive it as roughly circular with a checkerboard surface. But when you view it peripherally, it looks much more rounded. That’s because the smaller elements that form the circle smear out to gray in the larger peripheral receptive fields, and so the circular interpretation of the ring dominates your perception.

Three-Bar Cube by Italian sculptor Guido Moretti appears to be a cube, a solid structure, or an impossible triangle. This specific vantage point is known to scientists as the accidental view, but there is nothing accidental about it. If the observer is to perceive the illusion, the view must be carefully staged and choreographed; otherwise, the audience will fail to see the “impossible” sculpture.

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Visual Illusions

Visual illusions are subjective percepts that do not match the physical reality of the world. When we experience a visual illusion, we may see something that is not there, fail to see something that is there, or see something different from what is there. Visual illusions not only demonstrate the ways in which the brain fails to recreate the physical world, but they are also useful tools to identify the neural circuits and computations by which the brain constructs our visual experience.
The terms *visual illusion* and *optical illusion* are often used interchangeably. However, unlike visual illusions, optical illusions do not result from brain processes. Instead, an optical illusion is the perception of a distortion that results from the physical properties of light, such as reflection and refraction, and/or the optics of the eye. An example of an optical illusion is the phenomenon in which a pencil looks bent when it is placed upright in a glass of water, owing to the differing refraction indices of air and water. An example of a classical visual illusion is the Ebbinghaus illusion, named for its creator, Hermann Ebbinghaus. If two identical circles are placed side by side, one surrounded by large circles and the other surrounded by small circles, the first central circle will look smaller than the second one (see *Action and Vision*, Figure 2a). The Ebbinghaus illusion cannot be explained by the physical properties of the visual stimulus or by the optics of the eye. Instead, it is due to neural processes that compare a visual object with its context.

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

How to Make Visual Illusions

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

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

Categories of Visual Illusions

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

Adaptation Illusions

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

**Brightness Illusions**

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

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

**Color Illusions**

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

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

**Illusions of Size**

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

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

**Shape and Orientation Illusions**

These are illusions in which an object appears to take on shapes or orientations that are different from the actual physical ones. Distortion effects are often produced by the interaction between the
actual shape or orientation of the object, and the shapes or orientations of other nearby figures. A classical example is the Café Wall illusion, first discovered in a café in Bristol, England. The black and white tiles in the Café Wall are perfectly straight, but look tilted (see Figure 1).

Invisibility Illusions

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

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

Illusory Motion

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

Stereo-Depth Illusions

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

Susana Martinez-Conde and Stephen L. Macknik

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

Further Readings


Bayes's theorem, touted as a powerful method for generating knowledge, can also be used to promote superstition and pseudoscience.

By John Horgan on January 4, 2016

I'm not sure when I first heard of Bayes' theorem. But I only really started paying attention to it over the last decade, after a few of my wonkier students touted it as an almost magical guide for navigating through life.

My students' rants confused me, as did explanations of the theorem on Wikipedia and elsewhere, which I found either too dumbed-down or too complicated. I conveniently decided that Bayes was a passing fad, not worth deeper investigation. But now Bayes fever has become too pervasive to ignore.
Bayesian statistics “are rippling through everything from physics to cancer research, ecology to psychology,” The New York Times reports. Physicists have proposed Bayesian interpretations of quantum mechanics and Bayesian defenses of string and multiverse theories. Philosophers assert that science as a whole can be viewed as a Bayesian process, and that Bayes can distinguish science from pseudoscience more precisely than falsification, the method popularized by Karl Popper.

Artificial-intelligence researchers, including the designers of Google’s self-driving cars, employ Bayesian software to help machines recognize patterns and make decisions. Bayesian programs, according to Sharon Bertsch McGrayne, author of a popular history of Bayes' theorem, “sort spam from e-mail, assess medical and homeland security risks and decode DNA, among other things.” On the website Edge.org, physicist John Mather frets that Bayesian machines might be so intelligent that they make humans “obsolete.”

Cognitive scientists conjecture that our brains incorporate Bayesian algorithms as they perceive, deliberate, decide. In November, scientists and philosophers explored this possibility at a conference at New York University called “Is the Brain Bayesian?” (I discuss the meeting on Bloggingheads.tv and in this follow-up post, “Are Brains Bayesian?”)

Zealots insist that if more of us adopted conscious Bayesian reasoning (as opposed to the unconscious Bayesian processing our brains supposedly employ), the world would be a better place. In “An Intuitive Explanation of Bayes' Theorem,” AI theorist Eliezer Yudkowsky (with whom I once discussed the Singularity on Bloggingheads.tv) acknowledges Bayesians’ cultish fervor:

“Why does a mathematical concept generate this strange enthusiasm in its students? What is the so-called Bayesian Revolution now sweeping through the sciences, which claims to subsume even the experimental method itself as a special case? What is the secret that the adherents of Bayes know? What is the light that they have seen? Soon you will know. Soon you will be one of us.” Yudkowsky is kidding. Or is he?

Given all this hoopla, I’ve tried to get to the bottom of Bayes, once and for all. Of the countless explanations on the web, ones I’ve found especially helpful include Yudkowsky’s essay, Wikipedia’s entry and shorter pieces by philosopher Curtis Brown and computers scientists Oscar Bonilla and Kalid Azad. In this post, I’ll try to explain—primarily for my own benefit—what Bayes is all about. I trust kind readers will, as usual, point out any errors.*

*Named after its inventor, the 18th-century Presbyterian minister Thomas Bayes, Bayes' theorem is a method for calculating the validity of beliefs (hypotheses, claims, propositions) based on the best available evidence (observations, data, information). Here’s the most dumbed-down description:
Initial belief plus new evidence = new and improved belief.

Here's a fuller version: The probability that a belief is true given new evidence equals the probability that the belief is true regardless of that evidence times the probability that the evidence is true given that the belief is true divided by the probability that the evidence is true regardless of whether the belief is true. Got that?

The basic mathematical formula takes this form: \( P(B|E) = P(B) \times P(E|B) / P(E) \), with \( P \) standing for probability, \( B \) for belief and \( E \) for evidence. \( P(B) \) is the probability that \( B \) is true, and \( P(E) \) is the probability that \( E \) is true. \( P(B|E) \) means the probability of \( B \) if \( E \) is true, and \( P(E|B) \) is the probability of \( E \) if \( B \) is true.

Medical testing often serves to demonstrate the formula. Let's say you get tested for a cancer estimated to occur in one percent of people your age. If the test is 100 percent reliable, you don't need Bayes' theorem to know what a positive test means, but let's use the theorem anyway, just to see how it works.

To solve for \( P(B|E) \), you plug the data into the right side of Bayes' equation. \( P(B) \), the probability that you have cancer prior to getting tested, is one percent, or .01. So is \( P(E) \), the probability that you will test positive. Because they are in the numerator and denominator, respectively, they cancel each other out, and you are left with \( P(B|E) = P(E|B) = 1 \). If you test positive, you definitely have cancer, and vice versa.

In the real world, tests are rarely if ever totally reliable. So let's say your test is 99 percent reliable. That is, 99 out of 100 people who have cancer will test positive, and 99 out of 100 who are healthy will test negative. That's still a terrific test. If your test is positive, how probable is it that you have cancer?

Now Bayes' theorem displays its power. Most people assume the answer is 99 percent, or close to it. That's how reliable the test is, right? But the correct answer, yielded by Bayes' theorem, is only 50 percent.

Plug the data into the right side of Bayes' equation to find out why. \( P(B) \) is still .01. \( P(E|B) \), the probability of testing positive if you have cancer, is now .99. So \( P(B) \) times \( P(E|B) \) equals .01 times .99, or .0099. This is the probability that you will get a true positive test, which shows you have cancer.

What about the denominator, \( P(E) \)? Here is where things get tricky. \( P(E) \) is the probability of testing positive whether or not you have cancer. In other words, it includes false positives as well
as true positives.

To calculate the probability of a false positive, you multiply the rate of false positives, which is one percent, or .01, times the percentage of people who don’t have cancer, .99. The total comes to .0099. Yes, your terrific, 99-percent-accurate test yields as many false positives as true positives.

Let’s finish the calculation. To get P(E), add true and false positives for a total of .0198, which when divided into .0099 comes to .5. So once again, P(B|E), the probability that you have cancer if you test positive, is 50 percent.

If you get tested again, you can reduce your uncertainty enormously, because your probability of having cancer, P(B), is now 50 percent rather than one percent. If your second test also comes up positive, Bayes’ theorem tells you that your probability of having cancer is now 99 percent, or .99. As this example shows, iterating Bayes’ theorem can yield extremely precise information.

But if the reliability of your test is 90 percent, which is still pretty good, your chances of actually having cancer even if you test positive twice are still less than 50 percent. (Check my math with the handy calculator in this blog post.)

Most people, including physicians, have a hard time understanding these odds, which helps explain why we are overdiagnosed and overtreated for cancer and other disorders. This example suggests that the Bayesians are right: the world would indeed be a better place if more people—or at least more health-care consumers and providers-- adopted Bayesian reasoning.

On the other hand, Bayes’ theorem is just a codification of common sense. As Yudkowsky writes toward the end of his tutorial: “By this point, Bayes' theorem may seem blatantly obvious or even tautological, rather than exciting and new. If so, this introduction has entirely succeeded in its purpose.”

Consider the cancer-testing case: Bayes’ theorem says your probability of having cancer if you test positive is the probability of a true positive test divided by the probability of all positive tests, false and true. In short, beware of false positives.

Here is my more general statement of that principle: The plausibility of your belief depends on the degree to which your belief-- and only your belief--explains the evidence for it. The more alternative explanations there are for the evidence, the less plausible your belief is. That, to me, is the essence of Bayes’ theorem.

“Alternative explanations” can encompass many things. Your evidence might be erroneous, skewed
by a malfunctioning instrument, faulty analysis, confirmation bias, even fraud. Your evidence might be sound but explicable by many beliefs, or hypotheses, other than yours.

In other words, there’s nothing magical about Bayes’ theorem. It boils down to the truism that your belief is only as valid as its evidence. If you have good evidence, Bayes’ theorem can yield good results. If your evidence is flimsy, Bayes’ theorem won’t be of much use. Garbage in, garbage out.

The potential for Bayes abuse begins with $P(B)$, your initial estimate of the probability of your belief, often called the “prior.” In the cancer-test example above, we were given a nice, precise prior of one percent, or .01, for the prevalence of cancer. In the real world, experts disagree over how to diagnose and count cancers. Your prior will often consist of a range of probabilities rather than a single number.

In many cases, estimating the prior is just guesswork, allowing subjective factors to creep into your calculations. You might be guessing the probability of something that—unlike cancer—does not even exist, such as strings, multiverses, inflation or God. You might then cite dubious evidence to support your dubious belief. In this way, Bayes’ theorem can promote pseudoscience and superstition as well as reason.

Embedded in Bayes’ theorem is a moral message: If you aren’t scrupulous in seeking alternative explanations for your evidence, the evidence will just confirm what you already believe. Scientists often fail to heed this dictum, which helps explains why so many scientific claims turn out to be erroneous. Bayesians claim that their methods can help scientists overcome confirmation bias and produce more reliable results, but I have my doubts.

And as I mentioned above, some string and multiverse enthusiasts are embracing Bayesian analysis. Why? Because the enthusiasts are tired of hearing that string and multiverse theories are unfalsifiable and hence unscientific, and Bayes’ theorem allows them to present the theories in a more favorable light. In this case, Bayes’ theorem, far from counteracting confirmation bias, enables it.

As science writer Faye Flam put it recently in The New York Times, Bayesian statistics “can’t save us from bad science.” Bayes’ theorem is an all-purpose tool that can serve any cause. The prominent Bayesian statistician Donald Rubin of Harvard has served as a consultant for tobacco companies facing lawsuits for damages from smoking.

I’m nonetheless fascinated by Bayes’ theorem. It reminds me of the theory of evolution, another idea that seems tautologically simple or dauntingly deep, depending on how you view it, and that has inspired abundant nonsense as well as profound insights.
Maybe it’s because my brain is Bayesian, but I’ve begun detecting allusions to Bayes everywhere. While plowing through Edgar Allen Poe’s *Complete Works* on my Kindle recently, I came across this sentence in *The Narrative of Arthur Gordon Pym of Nantucket*: “In no affairs of mere prejudice, pro or con, do we deduce inferences with entire certainty, even from the most simple data.”

Keep Poe’s caveat in mind before jumping on the Bayes-wagon.

*My friends Greg, Gary and Chris scanned this post before I published it, so they should be blamed for any errors.*

**Postscript:** Andrew Gelman, a Bayesian statistician at Columbia, to whose blog I link above (in the remark on Donald Rubin), sent me this solicited comment: “I work on social and environmental science and policy, not on theoretical physics, so I can’t really comment one way or another on the use of Bayes to argue for string and multiverse theories! I actually don’t like the framing in which the outcome is the probability that a hypothesis is true. This works in some simple settings where the ‘hypotheses’ or possibilities are well defined, for example spell checking (see here: http://andrewgelman.com/2014/01/22/spell-checking-example/). But I don’t think it makes sense to think of the probability that some scientific hypothesis is true or false; see this paper: http://andrewgelman.com/2014/01/22/spell-checking-example/. In short, I think Bayesian methods are a great way to do inference within a model, but not in general a good way to assess the probability that a model or hypothesis is true (indeed, I think ‘the probability that a model or a hypothesis is true’ is generally a meaningless statement except as noted in certain narrow albeit important examples). I also noticed this paragraph of yours: ‘In many cases, estimating the prior is just guesswork, allowing subjective factors to creep into your calculations. You might be guessing the probability of something that—unlike cancer—does not even exist, such as strings, multiverses, inflation or God. You might then cite dubious evidence to support your dubious belief. In this way, Bayes’ theorem can promote pseudoscience and superstition as well as reason.’ I think this quote is somewhat misleading in that all parts of a model are subjective guesswork. Or, to put it another way, all of a statistical model needs to be understood and evaluated. I object to the attitude that the data model is assumed correct while the prior distribution is suspect. Here’s something I wrote on the topic: http://andrewgelman.com/2015/01/27/perhaps-merely-accident-history-skeptics-subjectivists-alike-strain-gnat-prior-distribution-swallowing-camel-likelihood/,”
Further Reading:

Are Brains Bayesian?

Was I Wrong about *The End of Science*?

A Dig Through Old Files Reminds Me Why I’m So Critical of Science.

Study Reveals Amazing Surge in Scientific Hype.

The views expressed are those of the author(s) and are not necessarily those of Scientific American.

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