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ABSTRACT

Science requires the acquisition and analysis of empirical (sense-derived) data. Given the same physical objects or phenomena, the sense organs of all people do not respond equally to these stimuli, nor do their minds interpret sensory signals identically. Therefore, teachers should develop lectures on human sensory systems that include some common examples of sensory limitations, variations, deficiencies, malfunctions, and diseases (as discussed herein) because they have important implications for conducting scientific investigations, science education, and introspection that are seldom included in biology textbooks. Students need to be made aware of the human tendency to self-deception in order to avoid the cognitive error of confirmation bias.

Key Words: Confirmation bias; controlled experiments; double-blind experiments; empirical data; observations; optical illusions; pheromones; repeatability; synaesthesia.

Teaching human biology usually begins with two basic subjects – anatomy (structure) and physiology (function). The function of sensation requires two processes: transduction or stimulation (at the level of sensory receptors) and perception or interpretation (in the brain). The nervous system contains structures (sensory receptors) that inform the brain about the external environment in which the body lives (exteroceptors) as well as interoceptors that inform the brain (either with or without involving a conscious response) about the status of the body's internal environment. The human body is commonly said to have five major exteroceptors: (1) eyes for seeing, (2) ears for hearing (audition) plus balance or motion, (3) nose for smelling (olfaction), (4) tongue for tasting (gustation), and (5) cutaneous exteroceptors in the skin for the sense of touch or tactition (also for pain, pressure, and heat). There are more than five sense receptors if we include interoceptors, such as proprioceptors (tension receptors) in muscles, tendons and joint capsules, or chemoreceptors for detecting blood pH, CO₂, and glucose concentrations, or receptors for

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heart rate, blood pressure, and other body conditions necessary for homeostasis.

The focus of this article is as follows. Science requires the acquisition and analysis of empirical (sense-derived) data. Given the same physical objects or phenomena, the sense organs of all people do not respond equally to these stimuli, nor do their minds interpret or perceive sensory signals identically. Therefore, along with or subsequent to discussion of basic anatomy and physiology of the human sensory systems, teachers should develop lectures that include consideration of the following general concepts.

- The unimpaired range of human senses to a given phenomenon is often quite limited, especially in comparison to the senses of some other animals.
- Sensory perception between individuals is often highly variable at any given time, as well as within an individual at various times of its life.
- The variability and limitations of human sensory perception have very important implications for conducting scientific investigations, science education, and introspection that are seldom included in biology textbooks.

○ Human vs. Animal Sensory Limits

When compared to that of other animals, the range of human senses is often severely restricted. For example, human vision is limited

to a very tiny part of the electromagnetic spectrum. The senses of some animals far exceed those of human perception (olfactory sense of dogs; ultrasonic echolocation of bats). However, some blind people have been able to develop the ability to echolocate by tapping their canes or clicking their tongues and listening for the echoes.

Some animals have one or more sensory capabilities entirely missing in humans. Sharks and related species, for example, can

detect extremely weak electric fields generated by some other animals in their environment. Specialized electroreceptor organs, termed “ampullae of Lorenzini,” are located on the snout of these predators, where they function in the detection of prey species. These electroreceptors are also sensitive to variations in water pressure, temperature, and salinity. A line of sensors along the body allows sharks (also fish and amphibians) to detect slight water-displacement movements such as those produced by fish swimming nearby (Fields, 2007). It is commonly said that sharks can “smell” blood in the water. But this would require that the term “olfaction” be defined as the sensing of specific chemicals in the animal’s external environment (airborne or aqueous) via chemoreceptors either localized or dispersed over the animal’s body surface. Some migratory birds are thought to be able to sense the Earth’s magnetic fields and may use them for navigation (Bohannon, 2007).

Humans, however, can overcome some of their sensory limitations by inventing and using scientific instruments and technologies (such as microscopes, x-ray photography, and ultrasound scans) that allow us to detect objects and phenomena far beyond the range of our unaided senses. Any occurrence or fact that is directly perceptible by the senses is termed a “phenomenon,” whereas an immaterial object of purely intellectual intuition is termed a “noumenon.” When scientists observe an object or phenomenon, they would like to employ as many of their senses as possible to produce the best description of these subjects. Sometimes the only sense that can be used is optical; for example, viewing stars, either with or without the aid of telescopes, spectrometers, or other instruments (National Research Council, 1996, p. 145). Only recently have astronomers used radio telescopes and x-ray or gamma-ray detectors to “see” aspects of the cosmos that formerly were hidden from perception.

Humans may be able to detect some sensory stimuli without the conscious brain being so informed. A pheromone is a chemical substance released by one organism that causes a behavioral or physiological response in one or more other members of the same or other species. Examples include sex attractants, alarm substances, aggregate-promotion substances, territorial markers, and trail substances of insects. The recipients of a pheromone may not even be aware that they have received an environmental signal that is causing them to respond in a directed manner. Pheromones that trigger sexual behaviors are among the best-known examples. For example, a queen bee releases a pheromone that prevents female worker bees in the same hive from producing eggs. Humans also seem to have sex pheromones. It has been reported that nasal exposure to sweat from a group of women living together has the ability to synchronize the menstrual cycles of these women, although some say that no evidence exists to support the existence of these pheromones (Doty, 2010). Pheromones are also thought to be implicated in studies reporting that daughters from homes in which the biological father is present tend to enter puberty and have their first sexual encounter at a later age than daughters whose father is absent (Ellis et al., 1999).

○ Interpersonal Variations

When a functioning sense organ (receptor) is stimulated, it sends a message to the brain, where the mind interprets the signal and decides what action or response (if any) needs to be initiated, such as causing a muscle to contract, a gland to secrete, or a memory to be made (National Research Council, 1996, p. 187). For example, whenever

I peel an onion, an airborne substance is released that burns my eyes and causes tearing. But does it affect everyone equally? Ideally, everyone observing the same phenomenon should be able to report the same sensory-derived data. Unfortunately, this is not always possible because, in part, not everyone has sense receptors or mental interpretation systems that function identically.

As a rule, the acuity of our senses diminishes with increasing age. We don’t hear, see, taste, or smell as well as we did when we were young. How many other genetic or epigenetic (developmental) differences exist in any group of people that make them unable to “sense” and/or “process” (interpret) messages from sensory receptors in the same way? Add to this the fact that different people have different life experiences (including education), and it is not surprising that even scientists may not all record the same empirical data equally or reach the same conclusions from the same material source.

Students should relate their knowledge of normal body functioning to situations, both hereditary and environmental, in which functioning is impaired. As they come across medical news in the media, students can identify new ways of detection, diagnosis, treatment, prevention, or monitoring. They should routinely try to find explanations for various disease conditions in physiological, molecular, or systems terms. (AAAS Benchmarks for Science Literacy, 2009)

Let’s look at three examples of how genetic differences in a population can cause people to perceive or fail to perceive their environment in identical ways. (1) Most people have three types of cone cells in the retina of the eye, each sensitive to one of the three additive (physiological) primary colors: red, green, and blue. However, some people have a recessive genetic mutation on the X chromosome that causes them to be totally or partially color blind to one of two primary colors (red and green). Blue color blindness is very rare and is governed by a gene on a different chromosome. In various white populations, 5–9% of men are partially color-blind. Color-blind women are expected to be much less frequent. For example, if the gene frequency in males is 0.05, then the expected frequency of color-blind females is $0.05^2 = 0.0025$, or 20 times as rare as in men. (2) Approximately 25–30% of the U.S. population has a genetic variant on a non-sex chromosome (autosome) that makes them unable to taste a substance called PTC (phenylthiocarbamide), whereas to people with the normal gene it usually tastes bitter (Smutzer et al., 2006). (3) Approximately 50% of adults cannot detect the odor of the hormone androsterone found in human perspiration, even at artificially high concentrations. Among those who can correctly identify androsterone, there is large variation from one person to another, including about 15% who misidentify it as akin to rubbing alcohol. The ability to smell androsterone is thought to be at least partly genetically determined (Keller et al., 2007).

Ideally, we should try to distinguish between malfunctioning sensory receptors and malfunctioning neural circuits in the brain. As examples, colorblindness is a defect at the receptor level, whereas motion sickness is often an undesirable neurological response in the circuitry of the brain to signals from balance organs in the inner ear.

The World Health Organization reports that 278 million people worldwide have moderate to profound hearing loss in both ears.

Some people “hear” phantom sounds that are annoying and interfere with detecting real sounds. Tinnitus is a medical condition in which the patient is plagued by a ringing or tinkling sound that is purely subjective. About 12 million Americans suffer from tinnitus. Among the possible causes for this are impacted cerumen (ear wax), labyrinthitis (inflammation of the inner ear), otosclerosis (abnormal bone growth; sometimes more frequently occurring in certain families), hysteria (emotional instability), and overdose of drugs such as quinine. Note that, among other factors, physical obstruction, disease, abnormal mental state, and drugs can interfere with some sensory functions. Even among those people of the same age who are not afflicted with tinnitus, there are wide differences in hearing acuity.

The dendrites of pain-sensing (nociceptive) nerve cells (neurons), in the skin and joints and in the mucous membranes of the nose and mouth, possess specific kinds of proteins in their cell membranes that respond to heat, cold, and mechanical pressure or stretching. Some of these protein receptors are also sensitive to plant products (phytochemicals) such as menthol (mint), cinnamon, garlic, horseradish, and chili peppers (Story & Cruz-Orengo, 2007). Most people who have tasted capsaicin (the phytochemical responsible for the “heat” in hot peppers) know that it “burns” the tongue and mouth. Once it is in the stomach and intestines, it may not be sensed by some people because the nociceptive neurons serving those organs do not possess the capsaicin receptors. Actually, there are receptors in the stomach, intestine, and (evidence suggests) the pancreas, colon, and esophagus that are activated in response to capsaicin or other stimulants, although they are not interpreted in the brain as “taste” (Rozenfurt & Sternini, 2007).

○ Implications for Conducting Scientific Investigations & Science Education

The *National Science Education Standards* (National Research Council, 1966, p. 123) begins Chapter 5 with the following major points that students should understand about scientific inquiry or investigations (bold added).

- Scientific investigations involve asking and answering a question and comparing the answer with what scientists already know about the world.
- Scientists use different kinds of investigations depending on the questions they are trying to answer. Types of investigations include **describing objects, events, and organisms**; classifying them; and doing a fair test (experimenting).
- Simple **instruments**, such as magnifiers, thermometers, and rulers, provide more information than scientists obtain using only their senses.
- Scientists develop explanations using **observations** (evidence) and what they already know about the world (scientific knowledge). Good explanations are based on evidence from investigations.
- Scientists make the results of their investigations public; they describe the investigations in ways that enable others to **repeat** the investigations.
- Scientists review and ask questions about the results of other scientists’ work.

The word “observations” here means not just seeing objects or events via the optical sense, but perceiving them via any of our sensory receptors either with or without the aid of instruments. Students should also be made aware of the role that instruments often play in making observations beyond the range of our natural senses and converting this information into forms that our senses can detect. Some instruments and techniques (e.g., microscopes and x-ray photography) present us with optical images. Sometimes the objects or phenomena being observed or measured are so continuously variable that the data themselves appear “fuzzy” or indistinct; for example, how gray is gray? (Stansfield, 2007; van Deemter, 2010). In some of these cases, instruments (thermometers or pH meters) can give us quantitative measurements (temperature, acidity/alkalinity) that can be analyzed statistically. It is important to remind students that instruments should be routinely subjected to calibration against known standards to verify that they are performing within acceptable limits of accuracy.

A single observation is seldom sufficient to convince the scientific community of its reality. Experimental data, especially, must stand the test of repeatability by other independent investigators. However, the “facts” that one gathers from nature may not always be repeatable by others because our sensory systems may not respond in the same way or our minds fail to process information from our sense organs in the same manner. Students should be taught to ask “How confident am I about the accuracy of the data?” (National Research Council, 1996, p. 174). Are there any other hypotheses or theories that can explain the same data?

Scientific experiments should be designed to avoid subconscious bias in collecting and/or analyzing data. Pain is a sensation that may vary greatly from one person to another, as well as from time to time in the same person. In addition, pain is a very subjective sensation, making it difficult to quantify the data accurately. Some people who have had an arm or a leg amputated continue to feel sensations (usually pain) in the limb that is no longer there (phantom limb syndrome). When scientifically testing a drug for its analgesic (pain-relieving) effect on humans, it is necessary to perform “double-blind” studies in which neither the experimenter nor the recipient knows whether the assigned pill contains the drug or no drug (a placebo). A third person knows these details, but they will not be revealed to the experimenter until after all the data have been collected and interpreted. The placebo group usually acts as a “control” for the treated group. However, some people may react in some way to the placebo, so it would be prudent to also include a group that received no pill in order to detect these false reactions. Scientific experiments should, if possible, include all appropriate controls. As an example of a poorly designed experiment, Shodell (2010) describes and analyzes experiments by scientists of the 1660s who were attempting to discover, by their olfactory senses, whether glass and crystal could be penetrated by pungent odors such as that of horse urine. There were no positive or negative controls, with or without glass or crystal, so it was not possible to ascertain the sensory acuity of the “sniffers.”

○ Introspection

Students need to be reminded that our minds can deceive us sometimes into believing that we see something that either does not exist or did not occur. Magicians are masters at deflecting our attention so that we fail to detect how a trick is performed. Most of us are susceptible

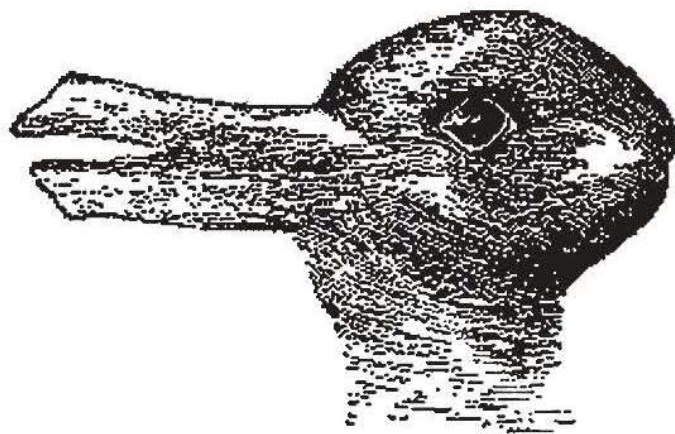


Figure 1. An optical illusion (<http://www.qualitytrading.com/illusions/images/rabbduck.gif>).

to optical illusions. They can be used in the classroom to arouse student interest while impressing on them how easily our senses can be fooled. Optical illusions can be used to investigate the property of cells in the visual system (Prud'homme-Généreux, 2010). A nice collection of visual illusions can be viewed online at <http://www.qualitytrading.com/illusions/>. One of these optical illusions looks like a duck or a rabbit, depending on how we choose to interpret it (Figure 1). Other visual, auditory, and tactile illusions are presented in Lawton (2009).

The artificial sweetener saccharin fools our sense of taste into thinking it is table sugar (sucrose). Actually, saccharin is about 300 times as sweet as sucrose (James et al., 2009). Both chemicals are odorless, so their taste is not influenced by our olfactory senses. The nose has many varieties of odor receptors; each variety is thought to recognize (bind to) a specific chemical substance or to other structurally similar substances. This principle cannot be applied to taste receptors because sucrose and saccharin are structurally unrelated. If a person is blindfolded with nostrils plugged, and then bites off a piece of either apple or onion, it is sometimes difficult to distinguish the fruit from the vegetable because so much of what we call "taste" is augmented by "smell." There used to be four primary taste sensations: salty, sour, sweet, and bitter. A fifth taste sense, called "umami," was first identified in 1908, but it has only recently been discovered to have a special receptor on the tongue. Umami is the "savoriness" response to salts of glutamic acid (such as the flavor enhancer monosodium glutamate), which are especially common in meats, cheeses, and other protein-heavy foods.

The mind doesn't always keep sensory information compartmentalized, deceiving us to perceive things that do not exist. For example, "synaesthesia" (from the Greek *syn*, "union," and *aesthesia*, "sensation") is a rare neurological condition in which two or more of the senses are interconnected in the mind (Dixon et al., 2006). In "grapheme-color synaesthesia," letters or numbers are perceived as being shaded or tinged with a specific color. In "music-color synaesthesia," susceptible individuals see colors in response to tones or other musical stimuli.

The old maxim "seeing is believing" is commonly used to support the notion that if we see something then it must be real – it must exist in a physical sense. But the way we interpret our sensory inputs can sometimes turn this maxim on its head; believing influences what we "see." Furthermore, just because a scientific theory is

supported by almost everyone, based on their uniform confirming observations, does not necessarily imply that the theory is accurately describing reality. For example, is it not an empirical (sense-derived) fact that anyone with a healthy set of eyes can see that the sun rises in the east, travels across the sky, and disappears from view in the west? The ancient astronomers Hicetas of Syracuse and Heraclides of Pontus first proposed that the Earth rotated on itself (de Santillana, 1947, p. 101). Before this, almost everyone believed that the sun moved, not the Earth. Now, of course, we "know" that this is not true. The observation of the sun's apparent motion is due to the currently accepted "truth" that the Earth rotates on its axis once every 24 hours. Just because everyone observes "something" (like the sun's apparent motion) does not necessarily make that something a fact. Our old "observation" that the sun travels across the sky was not a fact, but rather a mental concept, idea, or belief that the sun orbited the Earth. (Discussion of related epistemological or other philosophical issues such as empiricism versus rationalism has been avoided in this article as being beyond its objectives and inappropriate for K–12 students.)

Learning about the biological limitations and variations of human sensory systems and the subjective nature of many kinds of empirical data can help students be more introspective (questioning their own abilities) and more willing to critically consider different opinions before concluding whose empirical data and ideas are rationally most plausible. We all should remember how easy our senses may be fooled, and how our preconceived notions can influence how we gather and interpret empirical data.

When scientists make observations of a phenomenon from nature or laboratory, these data must be interpreted or explained as either supporting (confirming, verifying) or refuting (falsifying, disconfirming) one or more hypotheses (conjectures/inferences) or widely accepted scientific theories. Among the potential sources of error in science, some are experimental: an uncalibrated or miscalibrated instrument, missing one or more controls, or inadequate sample size. Some errors are observational: faulty sensory detection and/or perception. But the most important error for science, science education, and introspection is "confirmation bias"; the subconscious human proclivity to favor data and interpretations that support our previous ideas while minimizing or trivializing counter-evidence. "So, how does one cope with this awesome cognitive challenge? First – and this is the foremost reason for placing it squarely at the heart of a biology curriculum – one needs to be aware of how one's own brain works and its potential for mistakes" (Allchin, 2010). The sun no longer orbits the Earth!

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