Figure 1. The research facility used by Keeling on Moana Loa, Hawai'i. From the U.S. National Oceanographic and Atmospheric Administration.

Mauna Loa, Hawai'i, and Human Perception

Thomas F. Shipley[1] and Basil Tikoff[2,*]

Geology logline: *CO_2 monitoring on Moana Loa, Hawai'i, suggested significant increases of CO_2 in Earth's atmosphere with implications for global warming starting in 1965.*

Cognitive science logline: *How we talk about the human senses is not how we actually perceive with our senses. Understanding the underlying processes can help when considering the relative strengths of human collected data (self-correcting, visceral) and instrumentally collected data (quantitative, high sensitivity).*

Charles David Keeling went to Mauna Loa in the late 1950s to measure, as precisely as possible, the amount of carbon dioxide in the atmosphere. Keeling's training as a chemist allowed him to devise an instrument and a workflow that could measure carbon dioxide to within 0.2 ppm. The instrument was set up on Mauna Loa as part of the International Geophysical Year (1957–1958). Roger Revelle provided this description: "Keeling's a peculiar guy. He wants to measure CO_2 in his belly... And he wants to do it with the greatest precision and the greatest accuracy he possibly can" (Weart, 2003, p. 42). Instruments have measured CO_2 continuously from 1958 until 2022 on Mauna Loa (Fig. 1), when lava from an eruption closed the road, and the instruments were moved to Mauna Kea on the same island of Hawai'i.

The result of Keeling's measurements is widely known (Fig. 2). The rising level of atmospheric CO_2 is clear despite seasonal variability, which is large relative to a year's rise. Starting in ca. 1960 (e.g., Keeling, 1960), the overall upward trend was noticed by an increasing number of people, and its implications were publicly discussed as early as 1965 (e.g., President's Science Advisory Committee, 1965). The Keeling curve has unambiguously influenced both the geological and nongeological mind: Humans are a planetary-scale force to be reckoned with. Given the significant implications of increased CO_2 for humanity, it would be reasonable to wonder why action has been so slow. The answer is complicated and unambiguously political (e.g., Oreskes and Conway, 2010; Rich, 2018), but it is also partly a result of the nature of human perception.

In this essay, we are going to address aspects of human

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perception, which is a central topic in cognitive science. We ask the readers for their collective perseverance with the promise of a payoff in the next five essays. In cognitive science, perception is defined as the gathering of information about the world around us, including both the use of familiar human senses and instruments built to extend those senses. Effectively, perception is about understanding objects and events, but in a way that is integrated into what that understanding allows us to do and feel.

How one thinks about perception (i.e., one's mental model of how perception works) may unconsciously influence how one thinks about data in the context of an observational science. We utilize an approach to perception that focuses on the relationship between the perceiver and the environment that they are perceiving. In the cognitive science literature, this is known as an "ecological" approach because of the equal importance placed on understanding the cognitive processes of the perceiver, information in the environment, and their interaction. We contrast this approach with two alternative models, one that focuses on the perceiver and the other that focuses on the environment. The perceiver-focused model claims that all perception is learned, as was the predominant view of American psychologists until the early 1960s (e.g., Hull, 1943). In this case, one might worry that observational data are the product of a theory, with no basis in the reality of the environment. That is, a community consensus could be a hallucination. Such a view is one end member of perceptual accuracy and trust. The environment-focused model, total trust, claims that humans accurately perceive the world. In this end member, scientists simply go out and record the world the way it is. We make the case that neither end member is correct. A central theme of this essay is that perception is best conceived as a process that can correct errors, through obtaining additional information from the world when a perceptual error is made.

Three significant issues arise when one takes the approach that human perception guides observations and inferences in science. First, humans do not have conscious access to how they are perceiving the world (Idea 1). Second, perception is coupled with cognition (e.g., memory, runnable mental models, spatial or mathematical analyses) to make sense of the world (Idea 2). Third, visceral responses to perception, which motivate action, are generally coupled to cognition (Idea 3).

IDEA 1: HUMANS DO NOT HAVE CONSCIOUS ACCESS TO HOW THEY ARE PERCEIVING THE WORLD

We begin with the question: Why do humans perceive? *The answer is because human perception is needed for action.* Perception provides the ability to respond to threats or opportunities.

Because we are adapted for action, we experience the things in the world, but human perception does not provide us with the details of how our senses are stimulated. In fact, human perception is distinctly different from how we talk about it. Although we talk of feeling vibrations or seeing light, humans do neither. Rather, we feel and see **objects**; we see and hear **events**. If you pick up a pencil, close your eyes, and explore the desk in front of you, you feel the objects of the world. What you are detecting is the vibrations of the pencil against the skin of your fingers. Before conscious awareness occurs, the mind has correlated those vibrations to feeling an object.

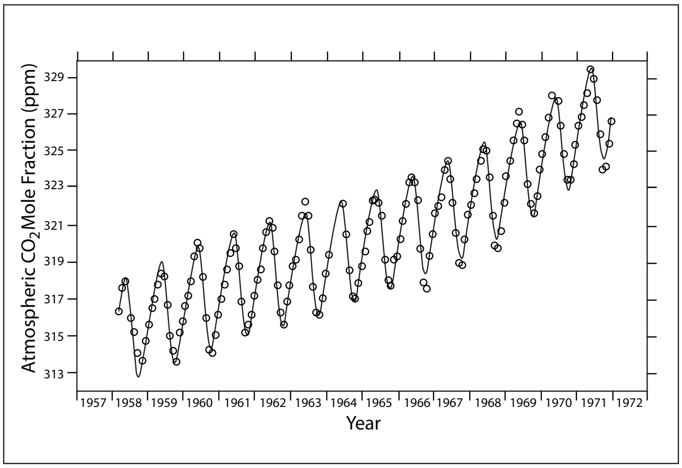

Figure 2. The Keeling curve as redrawn from Keeling et al. (1976). There is both an annual cyclicity, caused by plant growth in the Northern Hemisphere, and an upward increase, caused by human emissions of CO_2.

With vision, our brain perceives objects because photons stimulate our retina. But, the eye is not a photometer and does not report precise wavelength or luminance. We do not directly sense what is on the retina. Instead, our minds focus on the ***pattern*** of light on our retina because there is generally a consistent relationship between those patterns and what is out in the world. The important point is that we do not have access to the raw data that impinge on our senses (e.g., nasal mucosa, ear drum, or retina).

To further understand vision, it is necessary to recognize that any object "structures" the light that is reflected from it. What do we mean by this? Objects and light interact so that there are systematic patterns in the light reflected by objects; we use those patterns to see objects. For example, the light from a smoothly curving object has a continuous gradient within the visible bounds of the object. In contrast, an object with distinct sides (e.g., an object with a dihedral edge) will likely have a discontinuity in the reflected light corresponding to the discontinuity in surface orientation. Thus, an object *structures* light everywhere in the environment, so that from any perspective from which you view the object, the distinction between a smoothly curving surface and a corner will be evident.

A challenge we faced writing this essay was using *structure* as a verb, when it is a common noun in geology. The usage comes from psychologist Gibson (1979), who advocated an approach to perception that focused on detecting information relevant to a perceiver. We adopted Gibson's term to convey the important idea that an object in the world causes regularities in the patterns of smell, sound, and light (e.g., the concept of "structured light"), and that these regularities are sufficient to accurately perceive objects. Highlighting the pattern recognition process is intended to bring an awareness of a human's lack of conscious access to perceptual processes. That lack of awareness may be the source of the incorrect intuition that perceiving objects is easy and can be done directly by the senses.

It is the regularities in how light is structured—not its absolute values—that allow humans to accurately perceive the world. To see color, the mind compares the spectral distribution coming from multiple objects. Since all objects in a scene are generally illuminated by the same source, the pattern of wavelengths that is common across the scene is likely attributable to the light source. That common spectral profile can then be discounted from each object's reflectance profile to recover the object's true color. Here is how you know that it is the structure that matters, not the wavelength of a photon: A visual field that is totally uniform, and therefore unstructured, will appear gray regardless of the wavelength (Hochberg et al., 1951; Cohen, 1958). The Hochberg et al. (1951) study, for example, used ping-pong–sized half spheres that were placed over the eyes and an outside light source that produced long-wavelength light (e.g., that clearly looks red to an observer outside the experiment). That totally uniform field of long-wavelength light appeared gray to the subject. However, when the experimenter cast a shadow, from their finger, on the ping-pong half spheres, it provided some structure to the light (contrast), and the shadow was seen to be surrounded by a red field.

Although human sensors detect light, we do not perceive sensor stimulation. That is, there is no reliable relationship between individual sensor activity and what we see out in the world. Rather, a sensor's signal is only meaningful in relation to other signals.

To illustrate the need to use structure to perceive objects, consider how we see lava to be red and glowing in daylight (Fig. 3). The photons from the lava are neither red nor glowing. Rather, the photons are either reflected sunlight or emitted by the rock, but they are all just photons of predominantly long wavelength in the visible spectrum. For an illuminated scene, the returning wavelengths are influenced by both the reflective properties of the object *and* the spectrum of the light falling on the object. The mind solves the problem of disambiguating the reflective properties of an object from the wavelengths that illuminate that object by taking advantage of the regularities of the pattern of light across a scene (Gilchrist et al., 1999). How did we see the lava as glowing—appearing to give off light—if not from those emitted photons directly? The answer is by way of comparison, rather than by sensing it directly. Things appear to glow when the amount of light coming from their surface exceeds the ratio of highest (white) to least (black) reflective surfaces, so an object giving off 60 times more light than the darkest objects will appear to glow (Gilchrist et al., 1999). Because we have no conscious access to any of this processing of information, and perception is correct so much of the time, it is easy to feel that there is no underlying cognitive process associated with our senses. Consequently, we *feel* that we know exactly what is in the world; unfortunately, that is not true.

All human perception comes from sensory input that is structured by the world, not just vision. Objects and events structure the soundscape of our world; objects and events structure chemical gradients in the "smellscape" of our world. As with vision, the mind does not have conscious access to the sources that stimulate human (e.g., auditory, olfactory) sensors. Objects and events are the content of perceptual experiences because we need to know about them in order to act. The implication is that the way we talk about perception (e.g., seeing light) is not how we perceive (e.g., seeing objects).

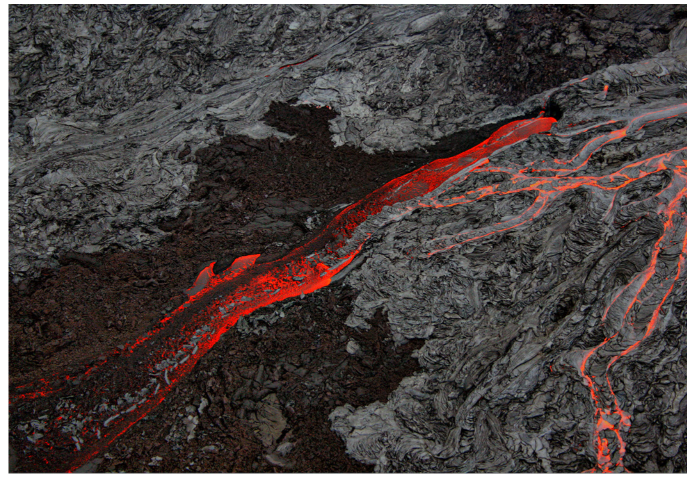

Figure 3. A glowing red lava flow from Hawai'i, taken from a helicopter. From Wikimedia Commons: Pāhoehoe and Aa flows at Hawaii.jpg. Photo by Brocken Inaglory.

IDEA 2: PERCEPTION IS COUPLED WITH COGNITION TO MAKE SENSE OF THE WORLD

The insight that perception must be coupled with cognition to make sense of the world was made by psychologist Ulrich Neisser (1976). Neisser accepted perception as a starting point and argued that optimal interactions are informed by both the information from the world and by what we already know about the world. Moreover, what humans know about the world comes from a variety of sources in one's past experiences, as recorded in memory. He advocated for a way of thinking about the mind that integrated perception and memory in a cycle in which understanding of the world changed over time.

Figure 4 illustrates the cycle of perception as proposed by Neisser. Structured information is perceived, leading to an initial interpretation of the world. That interpretation is informed by memory and necessarily leads to expectations about what else would be in the world, if one continued to move, explore, and gather further structured information. The interpretation effectively becomes a mental model of the world that could be added to with additional information or replaced when incoming information violated an expectation. Mental models—including runnable mental models—guide what one looks for in the world.

Neisser proposed this cycle to replace an approach to perception as input into a chain of processing that resulted in recognition. Such a linear system is ripe for errors resulting from expectations. In response, Neisser proposed a cycle where expectations lead to actions, such as reaching for an object or moving eyes to look at an object. The actions have expected sensory consequences, and the potential to violate those expectations gives perception the capacity to self-correct.

Note that what is meant by "recognition" is a determination of whether the object has been seen before. One can, of course, see new things. In this case, however, the part of the cycle labeled recognition would register the object or event as "unfamiliar." Because the cycle is continuous, the distinction between input and output blurs. That is, perception can lead to action, and action leads to new information to perceive.

If this cycle is a good model for how the mind works, what are the implications? We may make errors, but we correct them because perception is not static. New information may change how knowledge influences processing and recognition, and hence changes our perception. Put simply, perceptual correction comes from the world in the form of new information.

Because perception involves cognition and memory, it will necessarily differ among individuals and across cultures. As we noted in Tikoff and Shipley (2025), people lump memories into categories. Perceptual categories often reflect regularities of the world. There are many such regularities in objects and events. Different regularities may be emphasized by different cultures, which in turn influences how they lump and split object and event categories. Examples of differing categories include phonemes (the units of speech sounds, such as "ba" and "pa") and colors (Winawer et al., 2007). These categorical differences have been argued to reflect differences in communication needs among cultures (Regier et al., 2016). Thus, individual differences in memory may guide actions to pick up different aspects of objects and events. In the same way, expertise may guide the categorization of information that affords finer splitting in the area of expertise.

APPLICATION OF NEISSER'S CYCLE TO GEOLOGY

This perceptual process is a close analogy to the practice of science, a point made explicitly by Shipley and Tikoff (2016). In science, expectations may influence models, but eventually observations can correct erroneous models. The cycle of perception (Fig. 4) allows structured information in the world to be detected by a finely tuned system to allow optimal interactions with the world. Science attempts to determine and characterize patterns in the natural world and, by doing so, understand the underlying processes that resulted in those patterns. The meaning of those patterns, however, requires more than perception: It requires cog-

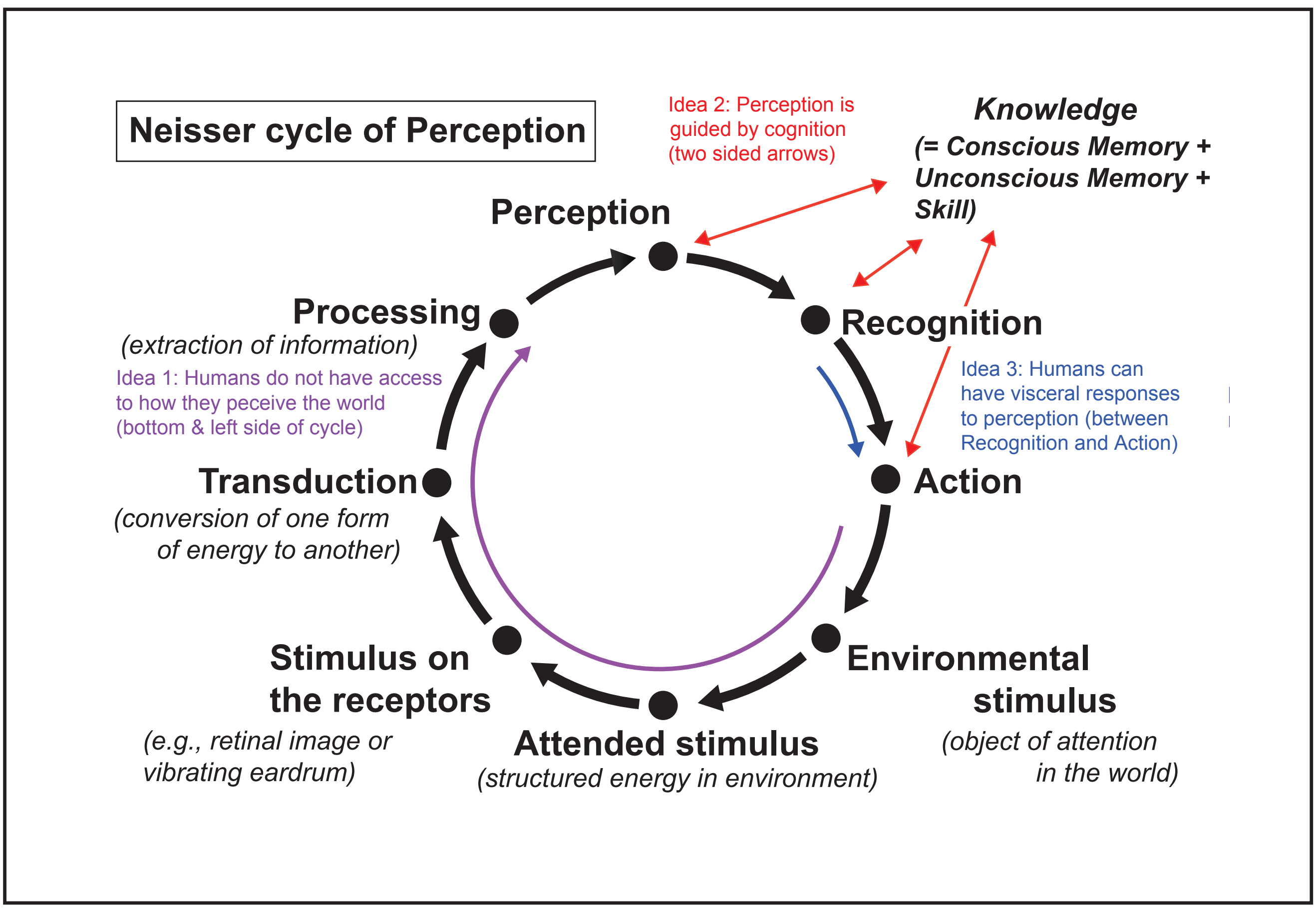

Figure 4. The ongoing cycle of perception proposed by psychologist Ulrich Neisser, as shown by the black arrows. The bottom and left-hand side of the cycle are largely unavailable to consciousness (Idea 1). Perception, Recognition, and Action are all informed by what we already know about the world (knowledge), and this relationship is shown by double-sided arrows (Idea 2). Visceral responses are a part of the perception cycle (Idea 3). Perception guides action, which allows us to explore the world and to correct perceptual errors. Figure is modified from Neisser (1976).

nition. For the purposes of practicing geology, that cognition requires some combination of: (1) memory (Shipley and Tikoff, 2025); (2) ability to utilize a runnable mental model (Tikoff and Shipley, 2025); and/or (3) ability to visualize (see upcoming essay on the Burgess shale in the June 2025 issue of *GSA Today*).

We continue the analogy between the ecological approach to perception—with its unconscious pattern processing—and a scientist making observations. The fact that a geologist can make sense of an outcrop indicates that the patterns and the processes are not arbitrary. Knowing what is out in the world and why it is important (e.g., the meaning of something in the world) can come from the regularities between geological patterns and processes. This claim may seem counterintuitive, but it arises from the nonarbitrary nature of how the world structures information. For example, imagine standing on top of a cliff. How could we know the meaning of a cliff if not by memory? The optics at the cliff's edge tell us there is no further support for a foot, and thus taking a step would be a bad idea. Thus, both mental models (from a theoretical view) and the world itself, as picked up by perception (from an empirical view), provide meaning. *Information in the world allows mental models to improve over time*

The take-home message is that scientific observations based on perception tend to be correct because the world itself acts to correct both perception and scientific inferences. Another level of uncertainty is added with using instruments, where interpretation mediates action.

THE NATURE OF PERCEPTION: REALITY DERIVED FROM INSTRUMENTS

For this essay about detecting CO_2, the relevant senses are olfactory and taste. These two combined senses are referred to as "chemosenses" in the cognitive science literature. Organisms from bacteria to humans use chemosenses to collect information about the presence and amount of a wide range of molecules, from complex polypeptide pheromones to simple CO_2. Human chemosenses are narrow and dull relative to some animals, but they do provide information about the prevalence of some molecules in our environment that matter to us. However, humans cannot detect CO_2 below lethal concentrations of ~15%

The use of instrumentally derived data provides a useful contrast to data derived from human senses. On Mauna Loa, Keeling effectively extended our chemosenses using a workflow that was both like and unlike the processes that animals use to gather information from the chemicals around us. How did Keeling and colleagues make the measurements? The air was sampled every few minutes throughout the day, interspersed with regular intervals of testing a reference standard with known levels of CO_2 to maintain calibration. Keeling recorded data only when readings over 6 hours were stable, and this procedure filtered out the small local burps of volcanic carbon dioxide.

Keeling's protocol and instrumentation provided more accurate data than could human senses. Even if humans could detect CO_2 at nonlethal levels, our capacity to maintain consistency of any perceived intensity is limited. Human perception is optimized for the breadth of stimuli, not the precision along any dimension or narrow range of stimuli. Human capacity to detect a change in any stimulus, also known as "just noticeable difference," is typically on the order 1%–5%. As an example, a good bank teller can tell when a 50-penny roll of coins is a single coin short. Keeling prioritized precision using a standard to maintain calibration to be as stable as possible over time, noting differences of ~0.025% (Harris, 2010).

Years of experimentation have shown us good methods for using instruments so that they will give continuously reliable results. Scientists know that instruments are capable of both drift (variable over time error) and bias (constant error). As a result, scientists have put in place protocols to correct and/or limit these effects. Central features of these protocols are calibration (testing the instrument against some standard) and duplication (using multiple instruments to see if the same answer is obtained).

Humans' organic detectors are no more immune to the potential for drift and bias than are inorganic detectors. Human senses have no analog to calibration, as we do not pause hourly to calibrate the retina with a referent light source. Why not? First, as noted in Idea 1, we rarely care about the absolute values of light or sound. The valuable information almost always exists at the level of relationships among properties. Thus, the mind uses relationships, such as ratios, which are less vulnerable to drift in the absolute magnitude of a sensor's output. For example, when smelling, we notice changes in odorant level and not odorants that remain constant, which explains why we generally do not smell ourselves (whew). Second, the human senses likely take advantage of statistical predictability in the world to keep the sensors tuned (Barlow, 1990). Third, as described above, the base function of perception is to support action. Calibration will occur when action errors are made. A classic psychology experiment illustrates the capacity to adapt to the introduction of a calibration error. Humans wearing prisms that shift the optical directions of objects (as if the muscles of the eye needed calibration) will recalibrate their perceptual-motor system in minutes to accurately reach for objects (Welch, 1986).

IDEA 3: VISCERAL RESPONSES TO PERCEPTION ARE GENERALLY COUPLED TO COGNITION, WHICH MOTIVATE ACTION

Up to this point in the essay, we have discussed basic perceptual processes without consideration of emotion. However, humans have emotions, and emotions affect perception, and vice versa.

There are few things humans are born with an aversion to (bitter tastes associated with toxic plants and optical cliffs make the short list). Many of our emotional responses that inform the meaning of objects and events must be learned from direct experience and community. How do humans have visceral reactions to a scene of death or destruction? Of many possible examples, consider the image of a shell-shocked Syrian boy. Famous images of suffering during conflicts captured something about the human realities of each conflict and were taken as emblematic of those conflicts. This is the power of a visceral reaction to perception, but why do specific images capture attention? They likely arrived at a time where people's mental models understood sufficient aspects of the broader conflict. This understanding, combined with that one image, allowed a viewer to infer the suffering of many people.

In a similar way, Keeling's work in Hawai'i became emblematic of worldwide atmospheric CO_2 concentrations. Why Hawai'i? The careful selection of a sampling site high on Mauna Loa was intended to minimize proximal sources and collect air that was as directly representative of the atmosphere as possible. The Hawai'ian islands are small landmasses in a large ocean. Moreover, there is a persistent atmospheric inversion in Hawai'i at ~2000 m. By sampling above the inversion layer on Mauna Loa, Keeling and collaborators could avoid picking up local influences, including carbon dioxide sources (e.g., bacteria in soil) or sinks (plants). Surrounded by basalt and nothing but a large ocean upwind, it is hard to imagine a much better place to sample and make a case that observed CO_2 levels represent a global average.

A single observation of CO_2 on Mauna Loa allows inferences to be made about the world because it was made at the right place from which to extend from the specific to the general. We are admittedly simplifying the story somewhat, as atmospheric CO_2 was measured by Keeling in a few places that gave the same result (Keeling, 1960). Aside from the placement in Hawai'i, why is a data set from a single place or a single picture so compelling? The Neisser cycle, involving observation and cognition, underlies the notion that human perception can be efficient. Humans, for instance, do not focus visual processing on all the points of the interior of objects, but rather at the edges of objects. A single observation, for example, to determine color, taken at the edge of the object can be extrapolated toward the entire interior of an object. Thus, observations over time, but at a point in space, provide the structured information that allows efficient estimation of the changes in a spatially distant world.

What Keeling's curve lacks for most viewers, however, is the visceral impact of the photograph mentioned above. The information in the Keeling curve does not speak to all humans directly. Only experts, who both can analyze the percentage change of CO_2 and have mental models that connect CO_2 to heat retention, can look at the Keeling curve and feel the danger. That is, one needs the right training to have the appropriate cognition to understand the signal. Moreover, the Keeling curve lacks the visceral nature that would apply to a threat detected by perception alone, such as a large object coming directly at you. Unlike perception of other aspects of the world, there are not multiple opportunities to learn to adapt our behavior to errors in the reading of the Keeling curve.

Thus, while there are formal similarities between directly perceiving the world and knowledge mediated by a built instrument, they will likely differ in the universality of their visceral impact. Pungent smells are universally unpleasant and result in quick action to remove them. Contrast that with the response to CO_2 data collected by Keeling. Even in the 1960s, the trend of increasing CO_2 in the atmosphere was clear (see full report by Keeling et al., 1976). By 1979, models of the role of increasing CO_2 were sufficiently clear that estimates of global warming made then are within the range of current observations. For experts, the meaning and thus implications for actions were clear. There were many options in a series of forking paths that we could have chosen (e.g., Rich, 2018); we are in our current situation because of those choices. The gift that Charles David Keeling gave humanity was an early warning and time to deal with the issue. That we did not, as a society, have the will to enact changes to counteract the trend leads to humanity's contrition and scientists' weariness.

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