Chapter 2
Perceptual, Attentional, and Cognitive Heuristics That Interact with the Nature of Science to Complicate Public Understanding of Science

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Effective communication of scientific findings is critical to sustaining an informed society that can make the best decisions from the science that it funds and that affects daily life. Yet, despite a scientist's best intentions, attempts to communicate scientific results are often fraught with difficulty. Here, we draw together disparate strands of scholarship to argue that the patterns of perception, attention, and cognition, which guide how humans take in and deal with information, are typically at odds with the demands of processing complex scientific information and with how science produces knowledge. Scientists who hope to impact public understanding will benefit from an awareness of these human patterns, how they interact with understanding the nature of science, and what this means for presenting scientific information to the public.

Gaining the Public's Attention

Gaining and maintaining the public's attention is one of the first challenges a scientist meets when trying to share research findings. In a sea of messages competing for the public's attention, what breaks through and what manages to sustain attention? A growing literature informs how people respond to perceptual stimuli, what information holds salience for them, and how they consciously and unconsciously allocate their attention. Findings based on research from visual and auditory perception and the design of our perceptual apparatus offer some useful insights. Relevant key findings are as follows: (1) We do not encode information perfectly; (2) Our attention is spotlight-like—we stitch together broader images from the pieces that we focus on; (3) We are selective in what information we take in; and (4) We privilege certain kinds of information over others. We consider research in support of each of these key findings below.

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Less-than-Perfect Encoding. Our visual perceptual apparatus is designed such that we carry out less-than-perfect encoding of information. Minor movements of our eyes, microsaccades, are necessary so that we don't habituate on objects in our visual field. Microsaccades are involuntary and they basically "refresh the picture." If the image on our computer did not refresh, we would be left with an old image. This is not the case with our eyes. If we were to habituate on the visual stimuli, the image would simply fade away. Therefore, one could argue that our eyes are able to see because at times we cannot see (Martinez-Conde, Macknik, Troncoso, & Dyar, 2006). Microsaccades occur very quickly and prevent continuous perception, even if we don't realize that we do not continuously perceive information from the outside world (e.g. Martinez-Conde, Macknik, & Hubel, 2004; Morrone & Burr, 2006).

Each time we shift our attention from one thing to another, we engage in another form of movement and resulting visual suppression called a saccade. Saccades are quick, simultaneous movements of both eyes in the same direction. They last from about 20 to 200 ms (e.g., Ibbotson, Crowder, Cloherty, Price, & Mustari, 2008). The visual image is briefly suppressed to prevent blurring of the image. Saccades are considered voluntary compared to microsaccades because we can attempt to suppress saccades by holding our focus on one thing. The combination of microsaccades and saccades results in a kind of inherent "blink" in our visual system, even though we have the impression that we are seeing everything that comes our way.

Spotlight-like Attention. Further, our visual apparatus is designed to take in small, focused parts of a broader image in a manner often likened to the image that falls in the beam of a flashlight or spotlight. These small yet high-resolution images are stitched together to form the larger image. Rather than look at a scene in a steady way, the eyes move around, locating interesting parts of the scene and building up a mental "map" corresponding to the scene (Posner, Snyder, & Davidson, 1980). By moving the eye so that small parts of a scene can be sensed with greater resolution, bodily resources can be used more efficiently. (If an entire scene were viewed in high resolution, the diameter of the optic nerve would need to be larger than the diameter of the eyeball itself.) However, this kind of focusing apparatus comes with the cost of potentially missing the bigger picture. Images in the middle of the scene are most likely to be perceived. While still the prevailing model, the spotlight analogy for visual perception has been critiqued for being too simplistic (Cave & Bichot, 1999). Recent research elaborates on this claim. It reveals, for instance, that the characteristics of stimuli towards the edges impact perception (Müller & Ebeling, 2008) and there may be some variation according to individual preferences (Kastner & McMains, 2007) as well as individual differences (Heitz & Engle, 2007). There may also be differences in how certain populations, such as those with dyslexia, process visual stimuli (personal communication, T. Rose, 2008).

A body of research referred to as "change blindness" examines our inability to detect changes even when they are happening right before our eyes and even when we are aware that *something* is changing (e.g., Grimes, 1996; McConkie & Currie, 1996; Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1998). Change blindness is a broad term and covers a range of phenomena at different levels, but at the most basic level, it appears to be a consequence of the combination of microsaccades, saccadic suppression, and this "stitching together of smaller, focused images." In order to detect change, we need to map the scene as it was and we need to compare this to a mapping of the scene after the change. However, stitching together spotlight beams of images to create a bigger picture of a scene, and then doing that again in order to make a comparison, is taxing from a cognitive perspective.

Even when we know that something is changing, it can be hard to detect the precise nature or features of the change. "Blink" is built into our visual system due to microsaccades, saccades, and stitching together beams of focus to assemble a larger scene. However, most of the time, we aren't aware that changes are taking place—we are incidentally encoding information and don't attend to the details of a scene. This results in change blindness at a much broader level. A series of experiments by Simons and Levin (1998) referred to as "the rude door changer" illustrates this phenomenon. An experimenter approached a stranger on the street to ask directions. While the stranger was giving directions to the experimenter, two "rude" movers walked in between them carrying a large door, blocking the stranger's view of the experimenter. Amidst the interruption, the experimenter was replaced by a second experimenter, in similar clothes, whose appearance was not dramatically different, though certainly not the same. Fifty percent of the strangers in this experiment thought they were talking to the same person before and after the "rude" movers walked through, completely missing the switch!

Selective Processing. Another body of research, on a phenomenon called inattentional blindness (IB), helps to illustrate that the source of attentional difficulties extends well beyond our visual system. Research shows that people often do not notice stimuli that are right in front of them if they are attending to something else (e.g., Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005). Haines (1991) gives the unnerving example of airline pilots during a simulated landing who are so focused on the control console that they miss the fact that the runway in front of them is blocked by another plane. Inattentional blindness can be so complete that after finishing their simulated landing, those test pilots said that they never realized that there was anything obstructing their way. Moreover, while much of the inattentional blindness research has focused on visual perception, there is evidence to suggest that without focused attention, other senses are also impacted. Mack and Rock (1998) have reported similar findings from their investigations into auditory stimulation (conducted with their colleague, Jack Hoppenstand) and into tactile stimulation.

How can we make sense of these events? Most of us tend to believe that we perceive something as a consequence of attending to it. However, as this research indicates, humans are selective about what information we take in and we prioritize some forms of information over others. We process only portions of the steady stream of stimulation headed our way because we can't possibly take in everything going on around us. Indeed, research (e.g. Mack & Rock, 1998) suggests that perception and attention are distinct but related phenomena, and there are different levels of perception and attention. Perception can be both unconscious and conscious. Unconscious perception refers to the early processing of perceptual stimuli prior to awareness. Sensory stimulation is being processed, but we aren't aware of it. Conscious perception, in contrast, refers to the processing of perceptual stimuli once attention is engaged.

Attention refers to our ability—intentional or unintentional, and with more or less depth—to turn our cognitive powers toward the stimuli we detect in the world. So it serves as a filter between all the stimuli in the world and our limited ability to be conscious of things around us. We direct our attention to more things than we consciously become aware of, but we cannot become aware of anything that doesn't capture our attention. As Lamme (2003) explains: "It seems that attention guards the gate towards a representation that can be consciously reported or remembered (as in IB)... Many sensory inputs reach the brain and, via the process of attentive selection, some of these reach a conscious state, which allows us to report about them" (p. 12). A steady stream of information reaches us that we are not consciously aware of and, from the viewpoint of our attention, we simply miss. Yet other information makes it "through the gate."

Research also reveals the surprising reality that sometimes things in front of us do capture our attention—that is, our eyes might briefly move toward a new object in our visual field, for instance, toward the plane blocking the runway—but we never become *aware* that the object is there. Most and his colleagues (2005) summarize this puzzling interaction between implicit and explicit perception and the fundamental paradox that it creates: "On one hand, people engaging in challenging tasks must often maintain focus, effectively ignoring irrelevant information that might distract them from their goal... On the other hand, attention must be distractible; if potentially dangerous or behaviorally relevant objects appear, they should divert cognitive resources" (p. 218).

What does this research suggest for how the public takes in scientific information? It reveals that the information that we consciously attend to is more limited than we realize. What scientists, educators, and communicators assume the public takes in may be incongruous with the actual information people are able or inclined to attend to. Indeed, we humans prioritize attending to certain kinds of information over others even *before* becoming aware that we are taking in information at all. So what makes us more or less likely to notice certain information over other?

Influences on What We Take In. Experimental psychologists have conducted a range of studies to find out what makes us more or less likely to notice something that is right before our eyes. Attentional capture is impacted by a number of variables pertaining to stimuli, for instance, size, location, familiarity, loudness, the image or sound of our own names, and certain emotional stimuli including faces (e.g., Eastwood, Smilek, & Merikle, 2001; Moray, 1959; Ohman, Flykt, & Esteves, 2001; Vuilleumier, 2005; Yamasaki, LaBar, & McCarthy, 2002). Very large and very loud stimuli are likely to break through and demand our attention. There is also clear evidence that the meaningfulness and relevance of the stimulus impact whether or not we notice it. Meaningfulness even outweighs how recently we were exposed to a stimulus: we are less likely to notice a person whom we passed by yesterday than we are to notice someone whose face has meaning for us.

One of the keys to the door between attention and awareness is expectation. Expectation is so powerful that we often find patterns and representations (and assign them meaning) even when what we see is random (Shermer, 2009). There is some evidence that expecting to see a stimulus impacts how our brains respond to it. According to Treisman (2009), "Neural changes can specify the timing of attention effects. Functional MRI activation and single-unit changes occurring in anticipation of the stimulus have proved that attention can affect the baseline activity in specialized extrastriate areas even before the stimulus is presented" (p. 196, citing Chawla, Rees, & Friston, 1999; see also Hopfinger, Buonocore, & Mangun, 2000; Kastner & Ungerleider, 2000).

Further, the more demanding the task, the more expectation matters (White & Davies, 2008). This suggests that when we're working hard to comprehend complex information, like scientific evidence and interpretations, expectation may have a pronounced effect on our ability to focus our attention on the myriad pieces of information before us. This tendency can be helpful and protective—for instance, we are neurologically and cognitively attuned to notice faces of people we recognize in the midst of teeming crowds (Buchen, 2008). However, it can also lead us to construe patterns that are not there.

Expectation is not always explicit. According to Gagnepain and colleagues, "Implicit memory has been defined as the expression of past experiences occurring beyond the boundaries of consciousness and without any intentional recollection" (Gagnepain, Lebreton, Desgranges, & Eustache, 2008, p. 276). They point to priming as one of the most well-known phenomena of implicit memory. Priming refers to "a change in the speed or accuracy with which a stimulus is processed, following prior experience of the same or related stimulus" (p. 276). Priming can occur through repeated exposure to a stimulus whether we are aware of it or not. For instance, if we pass a certain person on the street everyday, whether or not we attend to the person, we are more likely to select that person than another stranger as familiar.

Priming turns out to be a powerful psychological predictor of how we implicitly perceive and subsequently attend to stimuli. Having detected a stimulus once makes us more likely in the future to attend to it; this is a form of priming (Hinojosa, Pozo, Méndez-Bértolo, & Luna, 2009). Even our speech is unexpectedly primed—the way we form our sentences tends to mimic the syntactic structure of sentences we've just heard before crafting our own (Pickering & Branigan, 1999). Experiments have shown that we are primed by visual imagery too: for example, women smokers on a diet tended to associate smoking with weight control if, before being questioned, they viewed pictures of models rather than neutral photos of nature (McKee, Nhean, Hinson, & Mase, 2006). According to Mack and Rock (1998), "There is now ample evidence in the literature that sensitive, direct methods of testing often reveal that perceptions not consciously experienced seem to be encoded, and facilitate or inhibit subsequent perception when that same or a related stimulus object is subsequently presented to the observer" (p. 173).

Expectation not only shapes what we become aware of, but what meaning we make of that which we consciously consider and also how we behave. For example, researchers suggest that being primed with ideas of hostility can make us more likely to judge someone we don't know as being hostile (Garcia, Weaver, Moskowitz,

& Darley, 2002). Negative terms tend to prime us for negative judgment, and positive to positive. Yet the expectations we develop through association can be quite specific—we distinguish guilt from sadness, for instance, suggesting that we're sensitive to the particular meaning of an idea and not simply its valence (Zemack-Rugar, Bettman, & Fitzsimmons, 2007).

Priming has also been shown to impact behavior. Unconscious cues that are related to meanings or beliefs we already hold can shape our subsequent action. For instance, people primed with words associated with the elderly (like "old" or "Florida") left a psychology study by walking more slowly than people who weren't primed that way (Berger, 2008, referencing Bargh, Chen, & Burrows, 1996). Researchers suggest that priming was at work when sales of the Mars candy bar rose unexpectedly and anomalously after the U.S. space program landed an exploratory craft on the red planet (Berger, 2008).

In light of this copious research on perception, attention, and awareness, what insights can we glean about how we present scientific information to the public? While there are many, we propose a few salient lessons. Perhaps most importantly, we should recognize that human attention is imperfect. Presentations that require constant focused attention to glean their meaning, such as those that follow a carefully crafted, linear narrative, may fail to connect. Yet this is the format of most scientific papers: researchers trace the logic of the research project through a parsimonious and lean account that minimizes repetition. This same logical structure, which demands "perfect attention," often governs class lectures and public presentations. Scholars may have developed coping strategies, for instance, by investing effort into monitoring their own attention and rereading passages of text. But we ask too much of the public if we require audiences to revisit scientific information multiple times in order to attend to it. Instead, we might mirror the design of successful educational television programs that account for attentional blink by revisiting the main storyline at multiple points and in varied ways.

The process of "stitching together images" given our "beam of focus" to glean the bigger picture has clear implications for the layout of published reports and the visual display of important messages. Attentional capture is unlikely to happen unless information in one of those initial "beams" breaks through. Images in the center of a scene are the most likely to be detected by the most people. In addition, we are more likely to shift our attention between different parts of one object than between different objects (e.g., Egly, Driver, & Rafal, 1994; Tipper & Behrmann, 1996). Finding ways in scientific presentations to bind together important images may help readers attend to multiple key points. We might also heed the finding that certain emotional stimuli—faces, guns, or our own names—have privileged access to human attention (Blanchette, 2006; Mack & Rock, 1998). Further, we have all felt the impact of an emotionally charged image that endures, that continually creeps back into our consciousness. Given their aspiration to objectivity, scientists may feel that it is manipulative to gain the public's attention by using such stimuli, but in the steady stream of stimuli, familiar and sentimental images do have the advantage of garnering public attention over other stimuli.

Finally, being open to new information is not as easy as we think. We can implicitly take in information that primes what we later notice, how we react to it, and how willing we are to take in subsequent information that does not seem to fit. This suggests the importance of priming readers or viewers for salient points in a presentation. Research by Teige-Mocigemba and Klauer (2008) suggests that it may be possible to control priming and to strategically contradict its effects, for example, by intentionally thinking of something positive in negative priming instances and negative in positive priming instances. So, for instance, if an audience is likely to bring a set of implicit assumptions to their interpretation of scientific research, one might prime them at the outset with examples designed to contradict these assumptions.

Patterns of Engagement with Causal Complexity, Salience, and Risk

Even in cases where we gain the public's attention, how can we sustain this attention and encourage the public to view scientific findings as salient and, when prudent, to be willing to change their behaviors and opinions based on those findings? Research on how people attend to risk in situations that involve causal complexity introduces further challenges in sustaining public attention and impacting people's choices and behavior.

Risk perception is a broad-ranging and complex topic that can be studied from a number of academic angles, including the fields of psychology, sociology, cultural theory, cognitive psychology, decision theory, economics, medicine, and public health. Research on causal complexity analyzes the biases and mental shortcuts, or heuristics, that people tend to use when considering phenomena or explanations that have complicating features such as non-linearity, distributed causality, or time delays and spatial gaps (e.g., Feltovich, Spiro, & Coulson, 1993; Grotzer, 2003, 2004; Perkins & Grotzer, 2005; Wilensky & Resnick, 1999). Together, these bodies of scholarship suggest some interesting patterns in how people attach salience to research findings.

Often making sense of research findings involves the analysis of risk. Consider the factors at play when one decides whether it is safe to eat eggs during a salmonella outbreak, when one weighs the pros and cons of undergoing a new medical treatment, or when one evaluates legislation prompted by warnings about climate change. A person's analysis of risk perception and behavior is not entirely rational—it entails complex interactions between affect, cognition, and behavior that can result in seemingly puzzling behavior choices (Sunstein, 2002). For instance, people's actions suggest that the calculated, mathematical level of risk often differs from a person's perception of risk, and people are often unwilling to modify their behavior in instances where mathematics suggest that they should, and willing when the mathematics suggests otherwise (e.g., Slovic, Fischhoff, & Lichtenstein, 1982a, 1982b). For instance, Sunstein (2002) explains that, amidst the sniper attacks in the Metropolitan Washington D.C. area in the fall of 2002, people made significant changes in their behaviors, yet they did not make changes in dietary or driving habits that were, probabilistically, much more likely to cause them harm. Kahneman, Slovic, and Tversky (1982) and colleagues have carried out extensive research to demonstrate the difficulties people have in reasoning about probability (see also Slovic, Monahan, & MacGregor, 2000) as well as how people misjudge samples, make errors of prediction, and confuse correlation with causality, to name a few common difficulties.

Analyzing these difficulties reveals heuristics that people tend to engage in and how these can lead to certain risk assessments. These mental shortcuts have been extensively studied (e.g., Kahneman et al., 1982; Slovic, 2000; Tversky & Kahneman, 1973) and have been written about widely by scholars who study risk and the public's reaction to it (Gardner, 2008; Gilovich, 1991; Sunstein, 2002; Thaler & Sunstein, 2008). What are some of these heuristics and biases and how might they influence human behavior? We review some of the most well-known heuristics below and refer the interested reader to the many sources that explain these heuristics in detail (e.g. Kahneman et al., 1982; Sunstein, 2002).

The *availability heuristic* (Tversky & Kahneman, 1973) refers to people's tendency to make predictions based on the information that is most available to them, rather than on more systematic assessments. According to Slovic, Fischhoff and Lichtenstein (2000), it is defined as "judging the probability or frequency of an event by the ease with which relevant instances are imagined or by the number of such instances that are readily retrieved from memory" (p. 37). It is often the case that something we can recall easily also seems to us to occur frequently. For example, we might think that crime is a common occurrence in our hometown if crimes are frequently reported on the local news, or if a neighbor was a victim of crime. We tend to turn to narratives about events that have happened to us or to those around us rather than rely on statistical data.

The tendency to rely on affect as a shortcut (Slovic, 2000) is another common response pattern. *Affect heuristic* refers to the tendency to use emotion as a mental shortcut in judging risks and benefits (Slovic, 2000; Finucane, Alhakami, Slovic, & Johnson, 2000). So, for instance, if a person adores skydiving and loathes scuba diving, that person may underestimate the risk associated with jumping from planes and overestimate the risk of underwater exploration. Likewise, we tend to overestimate the benefits of activities we like. Another mental shortcut, *the proportionality effect*, refers to our tendency to place greater importance on reducing the proportion of a risk than the raw number of those affected by risk (Tversky & Kahneman, 1982). For example, as Cass Sunstein (2002) explains, people more often favor a hypothetical governmental intervention that would save one in 100 people out of a population of 1000 (10 lives) over an alternative intervention that would save one in a million out of a population of 200 million (200 lives). Though sometimes people consider proportions as well as raw numbers in assessing risk, and though factors such as morals, values, and affect are also at play, we generally prefer the greater proportional impact over the greater numerical one.

Such mental shortcuts have benefits when we have little information available to us or if we have to make a quick decision based upon whatever information we have.

Yet, they can be costly in those instances when we are tasked with reasoning about research data or other information of significant complexity. Drawing conclusions based on our prior personal experience tends to cause errors because we are basing those conclusions on a biased sample. For instance, dramatic images or events with shock value—like the example of crime above—that we can easily recall can lead us to overestimate the likelihood of certain kinds of events (Morgan et al., 1985). It can also lead us to focus less on everyday, mundane risks that are statistically more prevalent (Slovic, 2000). To continue the above example, when choosing an apartment and considering how safe a certain neighborhood is, we might scan our memory for cases of anything bad that happened there. If we can't think of any, we might conclude without any systematic data that the neighborhood must be safe. However, one dramatic crime event, even if it is a rare occurrence, might shift our entire sense of the neighborhood. At the same time, our attention to crime rates might cause us to miss or overlook information about higher cancer rates that might otherwise affect our view of the safety of that neighborhood.

As Sunstein (2002) has argued, it is likely that the key role of emotion in facilitating these heuristics is a consequence of the way our brains and bodies process information. LeDoux (1996, 2000, 2007) differentiates between emotional memories (implicit or unconscious memories), in which sensory information takes a direct path to and is processed in the amygdala, and memories of emotion (emplicit or conscious memories), which are processed at the level of the hippocampus and neocortex. Emotional memories help prompt our immediate reactions to a situation. Processing at the level of the hippocampus comes into play after this initial reaction, but at this point the body has already begun to respond to the emotional memory and we may already feel the impact of that first response, such as the feeling of a rush of adrenaline. LeDoux's research suggests that while the amygdala influences the information processing in the hippocampus and neocortex, the hippocampus and neocortex appear to have very little effect on the amygdala. This makes it difficult to consciously override what our bodies tell us or to change our unconscious responses in the future.

This distinction between levels of emotional response has important consequences for understanding how people normally reason. We tend to think that reasoning should be cool, rational, and emotionless. One might assume that our immediate responses are always problematic and that we need our secondary, reasoned response to prevail. But neuroscience research suggests that this separation is not necessarily possible except for people with certain brain impairments who reason passionlessly (Damasio, 1994). Further, it's not clear that such rationality is preferable: those with dispassion-producing brain impairments tend to be ill-equipped for real-world reasoning. The distinction itself may not be meaningful in people without impairments. According to Damasio, "Nature appears to have built the apparatus of rationality not just on top of the apparatus of biological regulation, but also *from* it and *with* it" (p. 128). Rather than view mind and body as separate—what Damasio calls "Descartes' error"—we should view our bodily reactions as part of a system prepared to respond to environmental dangers. However, as we consider below, it is possible that our immediate emotional responses may not always serve us well in a complex causal world.

Our emotions interact with how we handle the complex causality inherent in most risk situations. Our emotional responses can lead us to reactions that help us to face certain kinds of causal features but to ignore others. Immediate and innate fear reactions, which evolutionary biologists postulate may persist in humans because they helped protect our ancestors from danger, are generated in the amygdala and bypass the reasoning region of the neocortex (LeDoux, n.d.). For instance, if you are eating lunch and a wasp descends upon you, you are likely to spring into action to escape assault. For most people, wasp stings are not life threatening, but one can readily connect the wasp (cause) with the stings it can inflict (effect) through a simple and spatially proximate chain of causal reasoning. The amygdala mobilizes action and one does not have to engage higher order reasoning to respond. However, you might be willing to sit next to a colleague who is smoking cigarettes and not give it a second thought. Your colleague's cigarette is unlikely to trigger an immediate emotional response and/or concern about the risk posed by it because, in contrast to the wasp, thinking about the risk of cigarette smoke requires grappling with temporally distant causes and effects, non-obvious causes, and compounded probabilities.

When reasoning about complex phenomena, people tend to make assumptions about the nature of the causality involved. These assumptions are often at odds with the forms of causality inherent in those phenomena. Feltovich et al. (1993) identified characteristics of concepts or situations that cause difficulty for most people and found that people tend to simplify phenomena, exercising a reductive bias. The authors explain that people often reduce dynamic phenomena to static "snapshots" and continuous processes into discrete steps. For example, one might inappropriately interpret the weather on a given day as evidence for or against climate change without reasoning about longer term changes over time. Subsequent research found that people rely on an array of similar tendencies in situations involving complex causality (e.g., Grotzer, 2004; Perkins & Grotzer, 2005; Resnick, 1996). According to Grotzer (2009), people in these situations typically assume the following:

> 1) linearity as opposed to nonlinearity in the relation of cause(s) and effect; 2) direct connections between causes and effects without intervening steps or indirect connections; 3) unidirectionality as opposed to bidirectionality; 4) sequentiality as opposed to simultaneity; 5) obvious and perceptible as opposed to non-obvious and imperceptible causes and effects; 6) active or intentional agents as opposed to non-intentional ones; 7) determinism—wherein effects must consistently follow "causes" or the "cause" is not considered to be the cause—as opposed to probabilistic causation; 8) spatial and temporal contiguity between causes and effects as opposed to spatial gaps or temporal delays; and 9) centralized causes with few agents—missing more complex interactions or emergent effects—as opposed to decentralized causes or distributed agency. (pp. 57–58)

There is substantial support for these tendencies in the research literature (e.g., Chi, 2000; Feltovich et al., 1993; Ferrari & Chi, 1998; Grotzer, 2000; Grotzer & Basca, 2003; Hmelo-Silver, Pfeffer, & Malhotra, 2003; Houghton, Record, Bell, & Grotzer, 2000; Perkins & Grotzer, 2005; Wilensky & Resnick, 1999).

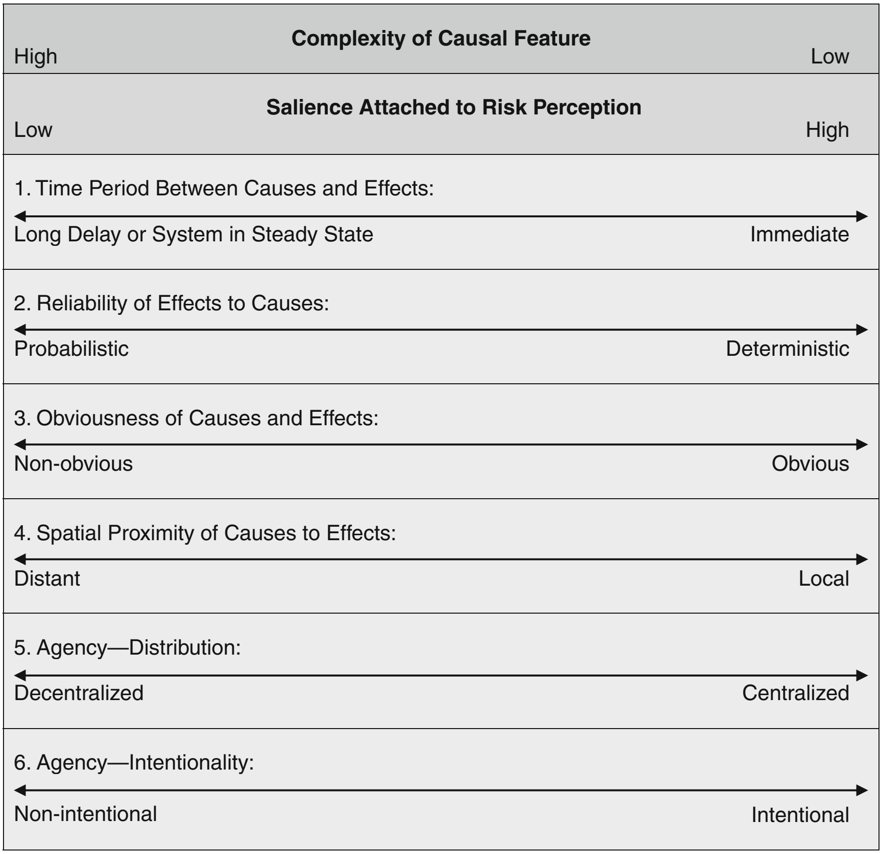

Fig. 2.1 Complex causal dimensions and perceptions of risk

The inherent causal complexity and the particular features of this complexity can interact with how we attend to and attach salience to particular risk situations and to related scientific information (Grotzer & Lincoln, 2007). Figure 2.1 illustrates the relationship between causal features and our tendency to attend to and attach salience to risk. Factors on the left side of the table are less likely to garner our perceptual, attentional, and cognitive resources than those on the right. By failing to process these left-side features, which tend to characterize causally complex situations, we may misconstrue the nature of a given phenomenon and thus ignore certain forms of risk. For example, people have difficulty reasoning about time delays. Time delays are a feature of a number of causally complex phenomena (recall the potential risk associated with sitting near your cigarette-smoking colleague). Since we have difficulty reasoning about time delays, we struggle to perceive causal relationships that are temporally distant; ultimately, we are less likely to perceive a particular time-delayed cause as related to later risk.

While one can roughly think about each of the features in Fig. 2.1 as existing along a continuum, there is more nuance to each than is set out in the diagram. For instance, complex causality along the temporal dimension can take a number of forms: delay between cause and effect, slow accumulation of effects such that the effects are increasingly perceptible, trigger effects, immediate effects, and so on. It is also the case that these dimensions interact with one another. Slowly accumulating effects may be initially non-obvious and become increasingly perceptible as the effects aggregate.

Particular risks can be assessed according to these dimensions. The development of AIDS (Acquired Immune Deficiency Syndrome) is characterized by a long latency period and extreme uncertainty from the point of HIV exposure to the onset of disease (Becker & Joseph, 1988; Prohanska, Albrecht, Levy, Sugrue, & Kim, 1990). It involves a non-obvious causal mechanism, temporal delays between causes and effects, and patterns of spread that involve decentralized causality. Assessing risk of contracting AIDS involves probabilistic causation about various risk-related behaviors and, indeed, about the behavior of the underlying mechanism itself (since HIV, as we currently understand it, does not lead to disease in all infected individuals). Causal features such as these are much harder to hold salient than those that trigger our innate fear mechanisms, such as immediacy, intentionality, and obvious causes and outcomes. The lack of these fear-triggering features means that we also find it difficult to attend to the research on global warming, which involves many forms of complexity: the effect is cumulative, there is a larger temporal and spatial gap between the cause and the effect, and the causes are distributed and non-intentional, to name a few.

Research on how people handle particular risks offers support for this interpretation of how complex causality and risk interact. For instance, people are more likely to go off of their statin heart medicine than their arthritis medicine because of the difference in the immediacy of the effects (Jackson, 2000; Pepine, 2003). The result of stopping arthritis medication is immediate pain, whereas the result of stopping statin medication is a higher risk of heart problems in the long term, but not necessarily any immediate effects.

The situation in Picher, Oklahoma, vividly illustrates the interrelationship between these dimensions. For approximately 100 years, Picher was a prosperous mining town where many kinds of metals were extracted, mostly zinc and lead, but also cadmium and other metals (Keheley, 2006). The leftover material from the mining process, called "chat," was left in mountain-sized piles all around the town. Generations of children from Picher played on the chat piles and even had their birthday parties on them. In the early 1970s, the mining operations shut down, but the piles continued to loom over the town's playing fields and schoolyard.

In 1980, Picher was designated part of one of the largest Superfund sites in the United States (Tar Creek). The legacy of the mining that occurred in previous years became the subject of intense study and concern. Research from the 1980s and 1990s on the health of those living in or near the Superfund Site found elevated rates of stroke, kidney disease, high blood pressure, heart disease, skin cancer, and anemia (Neuberger, Mulhall, Pomatto, Sheverbush, & Hassanein, 1990). In the mid-1990s, 31% of children living in the 5 towns within the Superfund site were estimated to have lead poisoning, while 45% of children living in the most contaminated towns of Picher and neighboring Cardin were estimated to have lead poisoning (Osborn, 2006). These levels were much higher than the average rate of about 2% for both the state of Oklahoma and the entire United States (Agency for Toxic Substances and Disease Registry, 2004)—although they have declined in recent years, a likely result of remediation and education efforts. According to local educators, children in Picher experienced learning difficulties at a much higher rate than children in other towns of similar socio-economic status.

Yet families were reluctant to leave. After all, Picher was their home, the center of their lives and a source of great hometown pride. Many of the adults had lived in Picher for years, had themselves played on the chat piles as children, and had grown accustomed to the many scientists taking samples from their homes and yards. One of the authors of this chapter, Rebecca Lincoln, was also one of the researchers working in Picher. Some of her work involved collecting samples of dust, air, and water in people's homes to test for lead and other metals, but she found that, among the people whose homes she studied, opinions on whether the chat was a risk or not varied greatly. Many people to whom she talked felt that because they had grown up in Picher and had turned out fine, it was probably safe for their kids, too.

In terms of complex causal features, the cause of the problem in Picher was non-obvious. While one could see the chat piles, the dangers that they posed were invisible. Quotes from a documentary entitled, "The Creek Runs Red" illustrate the townspeople's reactions (Beesley, Brannum, & Payne, 2006). As one teenager from Picher framed it, "I like Picher, Picher wouldn't be Picher without the chat piles." People couldn't see lead in the air or in the soil around their playgrounds and yards. It wasn't until the effects became visible that people could more easily attend to what was in the chat. As one town resident put it, "When the red water started to flow into the creek, that's when the trouble started." Further, the effects on the children were slow and accumulative. Staying one more day wasn't likely to result in a noticeable difference in one's health outcomes. Indeed, slowly developing effects are perhaps the hardest to detect and respond to—they require sustained effort and attention. Those effects also had a probabilistic aspect since not everyone was visibly affected or sick. When a home buy-out plan was offered to families with children under 6 years old, some but not all moved away. As one town resident expressed, "It's still a good town, and there's nothing wrong with it. There's absolutely nothing wrong with it."

The tendency to ignore non-obvious, slowly accumulating causes is perhaps most powerful in a case like this, where risks are pitted against a strongly ingrained way of life and a deeply held, emotion-laden conception of home. As one resident put it, "I'm the fourth generation to live here and my kids are the fifth, and that means something" (Beesley, Brannum, & Payne, 2006). Further, the economic challenges of leaving were acute because most families had all of their resources invested in their homes. However, even smaller changes in behavior were hard to achieve. One mother talked about coming back to Picher following her divorce so that she would have the support of her family. During the videotaped interview, she watches as her preschool child rolls down the chat pile to play. It makes the viewer wonder how differently she might have responded if she spotted a piece of glass in the chat or if a wasp landed on her child.

In 2006, a new problem came to light in Picher when results of a subsidence study were made public (U.S. Army Corps of Engineers, 2006). While the original mining was conducted such that support structures were left in place to prevent cave-ins, later "rogue mining" had resulted in the removal of many of these structures and studies showed that town structures were now vulnerable to caving in. In fact, a number of cave-ins related to the abandoned mines had occurred over the years, some of them within the Picher city limits and encompassing roads and houses (Luza, 1986). Whereas lead accumulation had non-obvious effects, the large sink holes that threatened to swallow Picher homes were startlingly obvious and dramatic, and the 2006 report brought this problem to the forefront of area residents' minds. The comments of Senator Jim Inhofe, who represented the area, made clear the differential impact of the two kinds of effects when he said, "an elementary school could fall in and kids could be killed. That's much more of a threat than some lead would be to someone's health" (Myers & Gillham, 2006). Plans were made to move all residents from Picher; however, some were still unwilling to go. The possibility of structures falling into sink holes entails probabilistic causality, since some homes fall and others do not. However, if one looks at the problem another way, the question of whether or not one managed to leave town before losing a house to a sink hole was a simple either/or proposition. Unlike the impacts of a slowly accumulating toxin, if people managed to escape before their homes fell in, they would suffer no ill effects. The obvious and dramatic effects compelled action when the non-obvious, accumulative ones did not. In reality, it is possible that the additional risk posed by the sink holes simply tipped the already tilting balance, though that was not how many, including the senator, framed the situation.

On May 10, 2008, Picher was dealt another blow, this one with causal features and effects that were impossible to ignore. Picher was struck by one of the deadliest tornadoes in Oklahoma history. The city suffered extensive damage, with eight people killed and 150 injured (Kimball, Stogsdill, & Palmer, 2008). The government offered no funds for rebuilding, focusing instead on relocation. Picher started the process of moving people out, dissolving its various town structures, and closing its schools and post office. The town ceased its existence as a municipality in September of 2009.

The events in Picher help illustrate how obvious, immediate causes with discernible effects garner our attention and precipitate action. What are the implications of these tendencies for communicating the results and implications of scientific research? Analyzing the inherent causal features in a given body of research results is an important first step in figuring out why some research does not garner the attention that scientists believe it warrants, and how to help make abstract and complex phenomena more understandable. Scientists may also need to find ways to make non-obvious causes obvious to the public, for instance, by showing simulated time lapse videos to suggest the outcomes of slowly accumulating causes, or by representing causes and effects that span large spatial scales in ways that fall within our attentional boundaries.

The Nature of Science

To this point, we have illustrated the challenges of gaining and sustaining public attention and in helping the public to reason about complexity. However, the difficulties that people have in grasping the results of scientific research are not solely attributable to the processes of human cognition. The nature of science—namely, what constitutes scientific knowledge and how such knowledge is generated—further complicates the enterprise. The unique epistemology of science is such that deep understanding of research results requires sustained attention—and we have seen what an elusive and complicated commodity that can be.

What is it about the nature of science that necessitates this sustained attention? It is the very processes by which scientists generate knowledge. For starters, there is no one way to "do" science. Methods and practices vary widely across fields, institutions, and individuals. Even the U.S. National Science Teachers Association (NSTA) asserts, contrary to decades-old school lore, that "no single universal step-by-step scientific method captures the complexity of doing science" (National Science Teachers Association, 2000). Amidst this array of approaches to doing science, there exists considerable debate amongst the general public and academics from a range of disciplines about how to characterize scientific inquiry. The lack of agreement about what constitutes "science," while intellectually exciting, can become particularly volatile in the public realm—as when people are trying to make decisions about everyday life such as how often mammograms should be given or whether intelligent design should be taught in schools.

What counts as "science," then, is not always straightforward. Nonetheless, many scholars who specialize in scientific epistemology agree that most scientific knowledge has some features in common (see Guisasola, Almudí, & Furió, 2005 for discussion and additional sources on the characteristics of scientific knowledge). The NSTA (2000) offers a rare succinct portrayal, highlighting "the systematic gathering of information through various forms of direct and indirect observations and the testing of this information by methods including, but not limited to, experimentation" and "…a demand for naturalistic explanations supported by empirical evidence that are, at least in principle, testable against the natural world." They also agree that scientific knowledge is necessarily *tentative*. Our understanding of the world is elaborated, refined, revised, and even replaced as new evidence and more promising theories emerge. Whether the process is one of evolution or revolution, scientists routinely seek to "trade up" their existing concepts for more fruitful and parsimonious models of phenomena (e.g., Bauer, 1992; Chalmers, 1999; Guisasola et al., 2005; Kuhn, 1962).

The generally agreed-upon models that prevail in a given field at a given time function as frameworks that structure scientific work. Whether called theories or paradigms, and whether considered influences on or determinants of scientific programs, these models shape the questions that it makes sense to ask, what kind of evidence to seek, what constitutes a "fact" or a reliable observation, and what a set of findings could mean (Bauer, 1992).

Although these features might read like a set of constraints, they enable scientists to produce a wealth of reliable and useful knowledge. But they can present challenges to public understanding. Consider the example of autism research. In the 1960s, the prevailing scientific theories attributed childhood autism to the influence of "Refrigerator Parents," particularly mothers (Bettelheim, 1967). Autism was considered to be the child's response to cold, unloving environments—a retreat from a harsh family life. The findings supporting these theories may have been artifacts of the population studied—typically upper-, middle-class families which tended to have more formal households than others did and that researchers judged as cold (whether substantiated or not) based upon their formality. Further, if autism has a genetic component, what the researchers interpreted as "coldness" may have been behaviors related to autism in parents. In the 1970s, the "Refrigerator Parent" theory was debunked and now researchers are focusing on the interaction of genetic and environmental factors in autism, though much uncertainty remains. One can only imagine the emotional toll those earlier theories took on parents who were told that their child's autism was a result of inadequate love.

Scholars' view that scientific knowledge progresses through revising or replacing models is different from the view most people hold. The public tends to think of science as an accumulation of facts (Bauer, 1992; Chalmers, 1999)—the "brick-like" building up or accumulation of knowledge. According to Bauer (1992), a fable about science is that it "is commonly taken to connote fact or certainty" (p. 63). Thus, when scientists amend their knowledge they might appear to the public as waffling, uncertain, or unreliable.

All of this is complicated by the fact that the scientific enterprise involves a great deal of uncertainty. If scientists fail to explain the meaning of uncertainty in scientific research, that uncertainty may undermine public acceptance of widely accepted scientific results (Zehr, 1999). According to Koslowski (1996), uncertainty pervades scientific work—for instance, scientists may temporarily ignore disconfirming data until they formulate a solid theory. They then return to those data to try to develop a unifying theory. They also may use "working hypotheses" that don't fit all available data to reduce information-processing demands and to enable patterns to emerge. Scientists may prefer a particular theory because it is the best theory for now and because rival theories are deficient. Any one of these aspects of scientific work makes it complicated to simply "bring the public along for the ride."

Given the patterns of uncertainty and certainty, vision and revision that are central to scientific pursuits, one can imagine frustrated members of the public doubting the value of scientific knowledge, or placing their confidence in other, more unvarying knowledge claimants. According to Bauer (1992), science tends to yield better predictions than folklore or mysticism, even though we cannot assert that it deals in "facts." Scientific knowledge, he explains, might be better conceived of as a map—not facts or reality itself. Instead, scientific knowledge is a representation that helps us understand and make predictions. This is quite a different conception from the brick-like accumulation of facts that many people envision.

This disjuncture between scientists' and the public's assumptions about the nature of science, combined with the challenges we have attending to complex scientific information, can lead to alarming instances of miscommunication. Peter Doran, a polar scientist at the University of Illinois at Chicago, wrote a 2002 article in *Nature* attempting to share the results of his findings pertaining to the hole in the ozone layer over Antarctica. Doran and colleagues (2002) wrote that between 1966 and 2000, 58% of Antarctica had cooled due to bans on ozone destroying chemicals, but that the rest of the continent was warming with the rest of the world. In subsequent press reports, Doran's findings were misinterpreted as evidence of overall cooling in Antarctica. It appeared to the public that Doran was offering evidence against climate change—that scientists were changing their minds. Instead, Doran was contributing a piece of evidence to a complex puzzle that, as a whole, agreed with climate change findings. Doran (2006) found himself in a protracted effort to clarify the points.

This particular example involves considerable cognitive complexity. Reasoning about two causes working in opposite directions with different local effects is quite demanding. Further, research shows that many people believe that climate change is caused by changes in the ozone (Sterman & Booth-Sweeney, 2002). Therefore, the public was likely to conflate the causes, not to put them in juxtaposition. To many, saying that the ban on ozone resulted in cooling was equivalent to saying that global warming was not actually happening. *Confirmation bias*, the tendency to selectively sample information that is consistent with a hypothesis and to ignore contradictory information (e.g., not searching for disconfirming evidence), is a well-studied and common phenomenon (e.g., Nickerson, Perkins, & Smith, 1985). Those looking for evidence against warming of the atmosphere jumped on one piece of Doran's evidence and excluded the rest, either intentionally or, quite possibly, because they missed the complexity in the argument. Despite numerous attempts to set the record straight, Doran found that his research continued to be misinterpreted in the public arena, and was even held up as an example of scientists' inconsistency rather than as part of a larger effort to develop a robust and reliable knowledge base.

Shapin (1992) has argued that science has become more isolated from the public than it was in early modern society. He offers the example that one could walk into a mill but cannot just walk into CERN, The European Organization for Nuclear Research. This, he argues, has contributed to fundamental problems of the place of science in society. He calls for the importance of finding ways to communicate the workings of science to the general public—not only what scientists know, but how they know and to what levels of certainty.

The challenges that we have discussed make it clear that there are many factors working against public understanding of science and that the public's response to scientific research is often highly reasonable considering what is being asked of them. It puts an incredible burden on scientists in terms of helping the public achieve understanding of scientific work. However, it is possible that the challenges will be less pronounced in the future because later generations may understand the processes of science to a greater extent than most of us do today. The science education community has called for helping students understand the epistemological commitments that scientists make—the "processes scientists value for generating and validating knowledge" (Sandoval & Reiser, 2004, p. 345). The U.S. national science standards ask educators to help students understand the epistemology of science, particularly the ways of knowing and finding out in the discipline. The standards emphasize the role of theories, evidence, uncertainty, and change in how scientists conduct their work, noting that "scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge). Good explanations are based on evidence from investigations" (National Research Council, 1995). The standards also emphasize the importance of "trading up" for more powerful models, asserting that "scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories. The scientific community accepts and uses such explanations until displaced by better scientific ones. When such displacement occurs, science advances" (NRC, 1995).

Research shows that students can learn to think about epistemological issues (Smith, Maclin, Houghton, & Hennessey, 2000) and that explicit discussion of epistemology encourages more informed views of the nature of science (Khishfe & Abd-El-Khalick, 2002). Research also reveals the value of infusing learning about the nature of science in science education. One line of study suggests that a limiting factor in how people reason about evidence is related to their epistemological development (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Sandoval, 2003, 2005) and that those with greater epistemological knowledge perform better in science (e.g., Linn & Songer, 1993). This type of knowledge puts students in a better position to interpret research findings and to take part in the dialogue within and around scientific communities. And, eventually, it will help people think about and debate scientific concepts and evidence in the public arena.

We believe that understanding the nature of science is as important for an informed public as it is for scientists. Further, in positioning their research results, scientists will need to adopt a reflective stance on the differences between how they view science as an enterprise and how the public views it. Given the patterns of perception, attention, and cognition that guide how humans take in and deal with information, and the extent to which these patterns complicate the processing of complex information, communicating scientific results well necessarily engages scientists in thinking like cognitive scientists, philosophers, and sociologists of science. Awareness of these human patterns, how they interact with understanding the nature of science, and what that means for presenting scientific information to the public are critical pieces to the puzzle of helping promote public understanding of science.

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