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How Lay Cognition Constrains Scientific Cognition

Andrew Shtulman*
Occidental College

Abstract

Scientific cognition is a hard-won achievement, both from a historical point of view and a developmental point of view. Here, I review seven facets of lay cognition that run counter to, and often impede, scientific cognition: incompatible folk theories, missing ontologies, tolerance for shallow explanations, tolerance for contradictory explanations, privileging explanation over empirical data, privileging testimony over empirical data, and misconceiving the nature of science itself. Most of these facets have been investigated independent of the others, and I propose directions for future research that might integrate them so as to explore potential commonalities among seemingly disparate obstacles to science learning, as well as potential strategies for bridging lay cognition and scientific cognition in the context of science education.

1. *Introduction*

Science is hard. It took humans, as a species, thousands of years to discover some of the most fundamental scientific truths – e.g., that the earth revolves around the sun, that objects in motion remain in motion unless acted upon by an external force, that all organisms are related through common ancestry. And it takes individual humans years, if not decades, to learn those truths from others (Carey, 2009; Shtulman, 2009). Indeed, many adults never learn them, clinging instead to folk beliefs that have been thoroughly refuted by both logic and data. In a recent survey of American adults, the Pew Research Center (2015) found that only 65% of Americans believe that humans have evolved over time (compared with 98% of American Association for the Advancement of Science (AAAS) members), only 50% believe that climate change is due mostly to human activity (compared with 87% of AAAS members), and only 37% believe that genetically modified foods are safe to eat (compared with 88% of AAAS members).

Resistance to science in an age flush with scientific information and science instruction requires explanation. Here, I attempt to provide such an explanation by describing seven facets of lay cognition that run counter to, and often impede, scientific cognition. Lay cognition can support scientific cognition as well, particularly in the realms of analogical inference (Dunbar & Blanchette, 2001), probabilistic inference (Kemp, Tenenbaum, Niyogi, & Griffiths, 2010), and causal inference (Gopnik, 2012), but discontinuities between the two are what shed most light on why acquiring scientific knowledge is so difficult, both historically and developmentally.

To date, much of the research on scientific cognition has focused on the skills needed to undertake empirical inquiry (Lorch et al., 2010; Strand-Cary & Klahr, 2008; Tschirgi, 1980), the skills needed to evaluate raw empirical data (Fugelsang & Thomas, 2003; Morris & Masnick, 2014; Wright & Murphy, 1986), or both (Klahr, Fay, & Dunbar, 1993; Okada & Simon, 1997; Schauble, 1996). The present paper, however, will focus less on the cognitive underpinnings of *doing* science and more on the cognitive underpinnings of *understanding* science: its findings, its methods, its theories. While the two are certainly related (see Minner, Levy, & Century, 2010; Zimmerman, 2000), understanding science is of broader concern than doing science given that few people will ever produce science (as a vocation) yet all people are required, by the demands of our scientifically entrenched world, to consume science. Thus, my focus will be on how lay cognition constrains our understanding of science as a body of knowledge generated by, and responsive to, empirical data. Research germane to this topic has been conducted by developmental psychologists, cognitive psychologists, and science educators, and I will review those findings as they pertain to (a) constraints on our understanding of scientific explanations and (b) constraints on our understanding of scientific evidence. I will then outline directions for future research that may help integrate those findings across fields by highlighting questions that arise at their intersection.

2. Constraints on Understanding Scientific Explanations

To understand a scientific explanation, one must encode that explanation as applying to the right set of entities or processes (e.g., encoding selection-based explanations of biological adaptation as applying to populations rather than individuals). One must also be able to distinguish that explanation from alternative, non-scientific explanations (e.g., creationist explanations of biological adaptation) and recognize differences in the breadth and depth of their inferential power. Our ability to meet these criteria is discussed below.

2.1. INCOMPATIBLE FOLK THEORIES

One reason we resist scientific explanations of natural phenomena is that we already hold folk theories of the same phenomena. Folk theories are causal-explanatory structures derived from a combination of innate conceptions, first-hand experience, and second-hand testimony that posit commonsense explanations of everyday situations (Vosniadou, 1994; Wiser & Amin, 2001). Folk theories come in at least two flavors: natural and supernatural. Those of a natural flavor, typically referred to as ‘naïve theories’ or ‘intuitive theories’, posit mechanisms of change that are empirically plausible, and even empirically testable (e.g., Bonawitz, Schijndel, Friel, & Schulz, 2012), but false. For instance, many people explain biological adaptation in terms of an intuitive theory of evolution that is inconsistent with natural selection. On this theory, evolution is construed as a holistic transformation of all members of a species; each organism is thought to produce offspring more adapted to the environment than it was itself at birth (Shtulman, 2006). Natural selection plays no role in this theory, as species are construed not as populations of varied individuals but as discrete types – types that evolve as homogenous units. These folk theories of evolution, although false, provide explanations that are both internally consistent and empirically broad (Shtulman & Calabi, 2012). They are also highly resistant to instruction (Shtulman & Calabi, 2013).

Intuitive theories are evident in many other domains as well. In the domain of mechanics, many adults hold intuitive theories of motion predicated on the belief that objects in motion possess an internal force, or ‘impetus’, that will maintain their motion until dissipated or transferred to another object (Halloun & Hestenes, 1985; McCloskey, 1983). In the domain of thermodynamics, many adults hold intuitive theories of heat predicated on the belief that heat is a kind of substance that flows in and out of objects and can be trapped or contained (Reiner, Slotta, Chi, & Resnick, 2000; Chiou & Anderson, 2010). In the domain of astronomy, many adults hold intuitive theories of the seasons predicated on the belief that the Earth is closer to the sun during summer than it is during winter (Lee, 2010; Tsai & Chang, 2005). And in the domain of biology, many adults hold intuitive theories of innateness predicated on the belief that genetically encoded traits are fixed at birth and shared by all members of a species (Griffiths, Machery, & Linquist, 2009; Knobe & Samuels, 2013; Linquist, Machery, Griffiths, & Stotz, 2011).

Folk theories of a supernatural flavor are similar to those of a natural flavor except that they evoke supernatural forms of causation. In the domain of biology, for instance, many people prefer creationist explanations of adaptation to evolutionary ones (Blancke, De Smedt, De Cruz, Boudry, & Braeckman, 2012), particularly in the USA (Miller, Scott, & Okamoto, 2006). Creationist beliefs have been documented not only among religious fundamentalists, who explicitly avow such beliefs, but also among secular children and adults who implicitly appeal to creation when asked to explain where living creatures came from (Evans, 2001) or how living creatures acquired complex traits (Lombrozo, Shtulman, & Weisberg, 2006). Likewise, many people prefer to explain consciousness in terms of souls rather than brains (Bering, 2006; Richert & Harris, 2008), explain illness in terms of witchcraft or karma rather than germs (Legare & Gelman, 2008; Raman & Gelman, 2004), and explain death in terms of a spiritual transformation rather than physiology (Harris & Gimenez, 2005; Rosengren et al., 2014). Supernatural theories are, in many ways, more pernicious than intuitive theories because they entail no commitment to naturalism and thus no commitment to revision or refutation (Shtulman, 2013).

2.2. MISSING ONTOLOGIES

One reason that folk theories are preferred to scientific theories is that many scientific theories rely on ontologies missing from the learner's mental repertoire of known ontologies (Chi, 2005; Thagard, 1992). An ontology, as psychologists use the term, is a framework for organizing and interpreting a domain of phenomena. It is a theory that specifies a unique category of existence – an ontological category – that differs from other known categories in its properties and its role in causal operations. Some examples of ontological categories, as studied by psychologists, are *physical object*, *material substance*, *intentional agent*, *living creature*, *artifact*, *event*, and *number* (Carey, 2009). Each category is psychologically distinct from the others. Physical objects, for instance, are psychologically distinct from numbers in the types of properties they are attributed (e.g., weight and location vs. sign and magnitude) and the types of operations they are thought to enter into (e.g., mechanical operations vs. arithmetic operations).

Research on the ontological foundations of everyday knowledge suggests that we are conservative in how many ontological categories we represent (Chi, 2005; Slotta & Chi, 2006). When confronted with information that does not conform to any known category, we tend to distort that information so that it does. Evolution by natural selection, for instance, is a process that operates over populations, yet, in the absence of a population-based ontology of biological kinds, we assimilate information about evolution into an organism-based ontology, construing evolution as the directed mutation of individual organisms (Shtulman, 2006). Germ transmission is a process that operates at the microbial level, yet, in the absence of a microbe-based ontology of infectious disease, we assimilate information about germs into a substance-based ontology, construing germs as non-biological toxins rather than as biological organisms (Solomon & Cassimatis, 1999). And heat is a process of energy transfer at the molecular level, yet, in the absence of an energy-based ontology of physical change, we assimilate information about heat into a substance-based ontology, construing heat as an invisible substance that flows in and out of objects and can be trapped or contained (Reiner et al., 2000).

Naïve conceptions of heat are a prime example of how scientific information may be assimilated into non-scientific ontologies (Chiou & Anderson, 2010; Slotta, Chi, & Joram, 1995; Wiser & Amin, 2001). In one study, Slotta et al. (1995) gave physics experts and physics novices two sets of questions: questions about heat and isomorphic questions about material substances. Physics experts provided qualitatively different responses across the two sets of questions, but physics novices did not. Rather, physics novices reasoned about heat transfer similarly to how they reasoned about the flow of a material substance, claiming, for example, that coffee would stay hotter in a ceramic mug than in a styrofoam mug because ceramic is less porous than styrofoam just as helium would stay longer in a rubber balloon than in a paper balloon because rubber is less porous than paper. Moreover, the language they used to justify their judgments was the same in both cases, appealing to material properties like containment ('keeps', 'traps', 'blocks'), absorption ('soaks up', 'takes in', 'absorbs'), and macroscopic motion ('leaves', 'flows through', 'escapes'). These effects are ameliorated if novices are taught to think of heat as a process rather than as a substance (Slotta & Chi, 2006), but devising strategies for teaching new ontologies is far from trivial (Ohlsson, 2009).

2.3. TOLERANCE FOR SHALLOW EXPLANATIONS

If you ask most adults to rate their understanding of natural phenomena like why tides occur or how rainbows are formed, they typically rate their understanding as moderate – e.g., as a 4 on a scale from 1 to 7. If you then ask adults to explain those phenomena, their confidence in their understanding drops from a 4 to a 3. And if you then ask a diagnostic question about their understanding (e.g., 'If tides are caused by the earth's rotation relative to the moon, why do they change twice per day and not just once?'), their confidence drops from a 3 to a 2. Our tendency to overrate our understanding of natural phenomena has been labeled the 'illusion of explanatory depth' (Rozenblit & Keil, 2002). This illusion has been documented in both children and adults (Mills & Keil, 2004), in both physical domains and social domains (Alter, Oppenheimer, & Zemla, 2010), and in both domain novices and domain experts (Lawson, 2006).

The illusion is not merely a byproduct of general overconfidence (e.g., Fischhoff, Slovic, & Lichtenstein, 1977). Rather, it appears to be specific to complex causal systems – systems with multiple causal pathways, multiple levels of analysis, non-perceptible mechanisms, and indeterminate end states. The better a phenomenon exemplifies these properties, the greater the illusion that we understand it (Rozenblit & Keil, 2002). Moreover, the illusion does not exist for forms of knowledge that lack these properties, such as facts (e.g., the capital of Ukraine), procedures (e.g., how to bake chocolate chip cookies), or narratives (e.g., the plot of *Star Wars*). Because the illusion is specific to *explanatory* information, it has at least two implications for our understanding of scientific claims. First, the illusion likely bolsters the perceived adequacy of our folk theories, as we are unaware of the shallowness of the explanations provided by such theories. Second, the illusion likely limits the degree to which we engage with scientific theories, as we feel we have acquired a deep understanding of the phenomena covered by those theories after only passing exposure to them. Both implications are potentially problematic for science education, although the relation between science education and the illusion of explanatory depth has yet to be investigated directly.

2.4. TOLERANCE FOR CONTRADICTORY EXPLANATIONS

Just as we tend to be tolerant of the shallowness of our folk theories, we tend to be tolerant of inconsistencies between our folk theories and our scientific theories. Folk theories block the acquisition of scientific theories, as noted above, but they also interfere with the operation of those theories once acquired (Dunbar, Fugelsang, & Stein, 2007; Evans & Lane, 2011; Knobe & Samuels, 2013; Potvin, 2013). For instance, our first folk theory of biology, acquired in early childhood, identifies life with motion. Animals are thought to be alive because they move, but so are non-living entities like the sun and the clouds, which move as well. And plants are thought *not* to be alive because they do not appear to move. By early adolescence, we abandon this 'animistic' theory of biology for a more scientific, 'vitalist' theory on which life is identified not with motion but with metabolic processes, like eating, breathing, and growing (Hatano & Inagaki, 1994). Nevertheless, when adults asked to classify various entities as 'alive' or 'not alive' as quickly as possible, they classify plants as alive more slowly and less accurately than they classify animals as alive (Babai, Sekal, & Stavy, 2010; Goldberg & Thompson-Schill, 2009). And when classifying non-living entities as 'not alive', they classify animate entities (e.g., comets, rivers) as not alive slower and less accurately than they classify inanimate entities (e.g., brooms, towels) as not alive (Goldberg & Thompson-Schill, 2009). These response patterns have been documented not only among college undergraduate but also among college biology professors, who have spent multiple decades studying the properties of life.

Similar response patterns have been documented in many other domains as well (Masson, Potvin, Riopel, & Foisy, 2014; Potvin, Masson, Lafortune, & Cyr, 2015; Shtulman & Valcarcel, 2012) and among both science novices and science experts (Kelemen, Rottman, & Seston, 2013; Shtulman & Harrington, 2015). They have also been documented in Alzheimer's patients, whose folk theories and scientific theories conflict openly and blatantly (Lombrozo, Kelemen, & Zaitchik, 2007; Zaitchik & Solmon, 2008, 2009). When Alzheimer's patients are asked what it means for something to be alive, they are more likely to cite motion than metabolism, similar to young children. When asked to provide examples of things that are alive, they always mention animals but rarely mention plants. And when asked to judge the life status of entities presented to them, they tend to judge mammals, birds, and reptiles as alive but judge flowers and trees as not alive, even without time restrictions (Zaitchik & Solomon, 2008). Healthy elderly adults, on the other hand, continue to provide a scientifically informed pattern of judgments, implying that Alzheimer's disease impairs one's ability to monitor conflicts between scientific theories and folk theories and to repress responses consistent only with the latter.

Speeded-response studies have revealed competition not just between scientific theories and intuitive theories but also between scientific theories and supernatural theories. Evolutionary accounts of the origin of species actively compete with creationist accounts in the minds of scientifically literate adults (Preston & Epley, 2009; Tracy, Hart, & Martens, 2011), neurological accounts of cognition and behavior actively compete with dualist accounts (Forstmann & Burgmer, 2015; Preston, Ritter, & Hepler, 2013), and physiological accounts of death actively compete with spiritual accounts (Bering, 2002). While some people have devised explicit means of reconciling scientific and supernatural explanations – e.g., positing evolution as a proximate cause of biological adaptation and God as a distal cause or positing the brain as a proximate cause of behavior and the soul as a distal cause – most have not (Legare, Evans, Rosengren, & Harris, 2012). Rather, most people vacillate between scientific and supernatural explanations depending on the events being explained or the context in which an explanation is provided. For instance, we are more likely to cite the brain than the soul as an explanation for thinking but more likely to cite the soul than the brain as an explanation for feeling (Richert & Harris, 2008). And we are more likely to explain death in physiological terms than in spiritual terms when at a hospital but more likely to do the opposite when at a church (Harris & Gimenez, 2005).

Taken together, these findings imply that, even if we understand scientific theories in the abstract, we are inconsistent and inefficient at applying them to specific situations. Competing theories of the same domain interfere with their application across the lifespan.

3. *Constraints on Understanding Scientific Evidence*

Thus far, I have argued that scientific explanations are difficult to understand because most people lack the ontologies required to represent those explanations and we rely instead on folk theories of the relevant phenomena. Folk theories provide shallower explanations than do scientific theories, but most people tend to be unaware of how shallow those explanations are. Moreover, as we learn science, we tend to be tolerant of inconsistencies between our scientific theories and our folk theories, vacillating between the two across topics and contexts. In the following section, I argue that misconceptions about scientific claims are further complicated by misconceptions about the evidence in support of those claims. In particular, our everyday affinity for explanatory information and our everyday reliance on testimony cause us to privilege explanation and testimony over empirical data in the justification of scientific claims. We also fail to appreciate, at a more fundamental level, the role of empirical data in generating scientific knowledge.

3.1. PRIVILEGING EXPLANATION OVER EMPIRICAL DATA

Explanations are fundamental to how we think and how we learn (Lombrozo, 2006). We seek explanations as means of integrating new information into existing knowledge (Chi, Leeuw, Chiu, & LaVancher, 1994), interpreting unexpected observations (Koslowski, Marasia, Chelenza, & Dublin, 2008), and discovering hidden causal structure (Walker, Lombrozo, Legare, & Gopnik, 2014). With respect to the latter function, explanations provide us with an answer as to how one event (e.g., carbon emission) is related to another (e.g., climate change). Empirical data, on the other hand, provide us with reason to believe that the two events are, in fact, related, by virtue of their covariation across multiple observations or experimental interventions. Both explanation and empirical data play a role in scientific argumentation, but non-scientists tend to focus exclusively on the former, actively seeking explanations while ignoring the available data (Ahn, Kalish, Medin, & Gelman, 1995), especially when those data conflict with the explanations we find most convincing (Chinn & Brewer, 2001).

In one pioneering study, Kuhn (1991) asked people of varying ages and educational backgrounds to justify their positions on everyday issues like the causes of poverty and the causes of student underachievement. She found that most people do not cite evidence in support of their positions, nor do they recognize what sources of evidence might be relevant to those positions. Rather, most people support their positions with explanations. For instance, a person asked to justify her belief that students underachieve when their parents are not involved in their education is more likely to provide an explanation for how those two factors are related (‘parents need to make sure that their children do their homework’) than to identify a relevant source of empirical data (‘children whose parents are involved in their education probably get better grades than children whose parents are not’). Even when participants were explicitly prompted for evidence (e.g., ‘If you were trying to convince someone else that your view is right, what *evidence* would you give to try to show this?’), they continued to provide explanations. Findings of this nature have been replicated in a variety of tasks (Koslowski, 1996; Kuhn & Udell, 2003), including tasks focused specifically on the justification of scientific claims (Hogan & Maglienti, 2001; Iordanou & Constantinou, 2014; Sandoval & Millwood, 2005).

Our preference for explanation over empirical data is not absolute. Most people recognize the relative value of empirical data when those data are identified for them (Brem & Rips, 2000), and even children will rank data over explanation in a forced-choice decision as to which provides the strongest support for an empirical claim (Sandoval & Cam, 2011). But our first inclination when evaluating empirical claims is to identify explanations consistent with those claims, not data (Ahn et al., 1995), and when we encounter data that defy explanation, we tend to ignore those data altogether (Chinn & Brewer, 2001; Koslowski et al., 2008).

3.2. PRIVILEGING TESTIMONY OVER EMPIRICAL DATA

Our affinity for explanations is matched by an affinity for testimony (Harris & Koenig, 2006). We seek out explanations to clarify our experience, and we seek out testimony to *transcend* that experience – i.e., to transcend the limitations of firsthand observation. Learning from testimony requires trust and deference: trust that others are telling the truth and deference to others' judgment on matters beyond our expertise. Recent research by developmental psychologists suggests that we appreciate both requirements from an early age. Children as young as four seem to know whom they can trust (Mills, 2013; Landrum, Eaves, & Shafto, 2015) and to whom they should defer (Danovitch & Keil, 2004; Lutz & Keil, 2003) when faced with questions they cannot personally answer.

Our willingness to accept others' testimony, while critical for learning science, can be problematic if not applied judiciously. In theory, we should extend deference only on the basis of epistemic considerations (e.g., expertise within the relevant domain, access to the relevant information), yet, in practice, we extend deference on the basis of many superficial considerations as well, including whether an informant is attractive (Bascandziev & Harris, 2014), whether an informant is nice (Landrum, Mills, & Johnston, 2013), and whether an informant speaks with a native accent (Kinzler, Courriveau, & Harris, 2011). We are particularly swayed by whether multiple informants are in agreement. Studies have shown that consensus information trumps most other forms of information, including statistical information about the reliability of the consensus opinion (Harries, Yaniv, & Harvey, 2004; Yaniv, Choshen-Hillel & Milyavsky, 2009), social information about those providing the consensus opinion (Chen, Corriveau, & Harris, 2013; Cialdini & Goldstein, 2004), and even perceptual information that contradicts the consensus opinion (Asch, 1956; Bond & Smith, 1996).

Consensus information sways our acceptance of scientific information as well (Lewandowsky, Gignac, & Vaughan, 2013), regardless of whether we understand the basis of that consensus. Young children are highly confident in the existence of unobservable scientific entities like oxygen, germs, and vitamins, even though they are unaware of what those entities are or why they are believed to exist. Their confidence appears to stem directly from their perception of public consensus surrounding the entities' existence (Guerrero, Enesco, & Harris, 2010; Harris, Pasquini, Duke, Asscher, & Pons, 2006). Even adults' confidence in the existence of unobservable entities appears to stem directly from their perceptions of public consensus. In one study (Shtulman, 2013), adults with multiple years of college-level science education were asked (a) why they believe in the existence of unobservable scientific entities (e.g., electrons, genes, black holes), (b) how confident they are in the existence of those entities, and (c) how many other people, in their estimation, believe in the existence of those entities. Most participants were unable to cite empirical considerations in support of their scientific beliefs, but they were still highly confident in those beliefs, particularly beliefs they perceived to be widespread among the general public.

Furthermore, participants' modal response as to why they believe in the existence of unobservable entities was to defer to the testimony of trusted authorities – e.g., 'I've learned about electrons in most of the science classes I've taken' or 'I believe in black holes because I trust my physics teacher Mr. Murray'. While deference to authority is a justifiable practice in science, given that scientific authorities have earned that status on the basis of their empirical expertise, participants' patterns of deference extended beyond the domain of science and into the domain of the supernatural as well. That is, participants deferred to authority not only as a means of justifying their scientific beliefs but also as a means of justifying their supernatural beliefs (e.g., 'It's what I was taught in church', 'I accept the authority of religious sources', 'The Bible says we have souls'), which suggests that both types of belief rest on similar epistemic grounds. Indeed, participants' tendency to privilege deference over data was most pronounced among those with high levels of supernatural belief and low levels of understanding of the nature of science (discussed below). Lay appeals to scientific testimony thus appear largely uninformed.

3.3. MISCONCEIVING THE NATURE OF SCIENCE

Science is a body of knowledge, but it is also a method of inquiry. It is a way of discerning the world's causal structure by testing hypotheses about that structure against controlled observations. Most people do not, however, conceive of science in these terms. They conceive of science in more concrete, less epistemic terms: 'making a discovery', 'solving a problem', 'developing a technology', 'trying something new'. They hold what Schauble and colleagues call an 'engineering model' of experimentation in which experiments are construed as vehicles for generating material outcomes rather than as tests of ideas (Schauble, Klopfer, & Raghavan, 1991; see also Carey, Evans, Honda, Jay, & Unger, 1989; Smith, Maclin, Houghton, & Hennessey, 2000). Likewise, most people think that scientists are in the business of 'proving their ideas true' and have little appreciation for the inferential nature of hypothesis testing (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002) or the tentative nature of scientific claims (Lederman & O'Malley, 1990). Misconceptions about the 'nature of science', or NOS, have been documented among people of various ages, cultures, and educational backgrounds (Deng, Chen, Tsai, & Chai, 2011). Even those who have obtained graduate-level education in non-scientific fields tend to believe (a) that scientists abide by a single, deterministic set of procedures, (b) that scientists develop their ideas solely through observation and not also through inference, and (c) that scientists who study the same data will inevitably arrive at the same conclusions (Lederman et al., 2002).

Understanding the nature of science is important not only because science is a fundamental tool for advancing human knowledge but also because many scientifically important skills and dispositions depend upon it. Studies have shown that individuals with higher levels of NOS understanding are better able to integrate formal scientific principles into their everyday understanding of domain-specific phenomena (Songer & Linn, 1991) and are better able to identify the roots of scientific controversy and means for resolving them (Smith & Wenk, 2006). They are also more likely to understand difficult scientific topics in astronomy, geology, mechanics, and thermodynamics (Shtulman & McCallum, 2014) and to accept counterintuitive scientific ideas, such as evolution and common descent (Lombrozo, Thanukos, & Weisberg, 2008). That said, science is a multi-faceted enterprise, and instruments designed to measure NOS understanding cover topics that cohere only at an abstract level, e.g., the relation between theory and data, the relation between theory and method, the requirements for drawing causal inferences, the nonlinear trajectory of scientific investigation, the role of creativity and imagination in designing scientific experiments, and the socio-cultural context within which science is practiced. There is little agreement among science education researchers on which topics are most critical to teach or assess (Deng et al., 2011), let alone which topics best predict the skills and dispositions noted above.

4. Future Directions

The findings reviewed above indicate that scientific cognition runs counter to several facets of lay cognition. Many of those facets are likely to be interrelated, yet they have traditionally been studied in isolation, often by researchers adopting different methodologies and different theoretical perspectives. In particular, the four facets of lay cognition reviewed in the first half of the paper (regarding our understanding of scientific explanations) have typically been studied by cognitive and developmental psychologists, whereas the three facets reviewed in the second half of the paper (regarding our understanding of scientific evidence) have typically been studied by education researchers. Below, I propose three questions in need of further research that might help to bridge these lines of inquiry.

First, how does our understanding of scientific theories influence our evaluation of the evidence relevant to those theories? Are we less inclined to privilege explanation and testimony over empirical data the better we understand the theory? It seems plausible that those who hold an accurate understanding of scientific claims (e.g., evolution by natural selection) are more likely to understand the data that bear on those claims (e.g., the distribution of fossils across different eras, the distribution of genes across different genomes) and the methods that yield those data (e.g., carbon dating, comparative genetics). Yet it also seems plausible, given the complicated dynamics of conceptual change (Carey, 2009; Vosniadou, 1994), that developing an understanding of the content of scientific theories requires different cognitive resources from those required to understand the relation between scientific theories and scientific data.

Second, how do we coordinate conflicting sources of scientific (or pseudoscientific) information? Developmental psychologists have recently turned their attention to testimony-based learning, as noted above, and the emerging consensus is that we do not accept testimony uncritically. Rather, from an early age, we scrutinize informants on the basis of their past accuracy, their past reliability, their agreement with other informants, and their access to the information they are reporting (Mills, 2013; Landrum, Eaves, & Shafto, 2015). Applied to science learning, this research suggests that we should be good discriminators of valid claims and invalid claims, yet we clearly are not (Lewandowsky, Ecker, Seifert, Schwarz, & Cook, 2012). We readily endorse claims that are empirically false, explanatorily shallow, or mutually contradictory, as discussed above. Our precocious ability to evaluate the validity of others' testimony may fail us in the domain of science because scientific testimony is more complex and more nuanced than the kinds of testimony studied to date (e.g., object labels, object functions), but further research is needed to verify this speculation.

Third, how does NOS understanding affect our tolerance for shallow and contradictory explanations? Improving NOS understanding is touted as one of the most important goals of science education (by, for instance, the National Research Council, 2013), and there is evidence that doing so has widespread consequences for scientific cognition. Still, it remains unclear whether the relation between NOS understanding and other forms of scientific competency – e.g., applying scientific principles to everyday problems, identifying the sources of scientific disagreement, accepting counterintuitive scientific ideas – is causal or coincidental. It also remains unclear whether NOS understanding is related in any way to the endorsement of folk theories. Folk theories are perhaps the largest impediment to acquiring (and using) scientific theories, and it would behoove science educators to know how much of their instructional time should be spent explaining domain-general scientific principles and how much should be spent challenging domain-specific scientific misconceptions.

In sum, studying the relations between constraints on the understanding of scientific explanations and constraints on the understanding of scientific evidence promises to shed light not only on the conceptual prerequisites for scientific cognition but also on strategies for bridging lay cognition and scientific cognition in the science classroom. While many psychologists and education researchers have trumpeted the strengths of lay cognition for supporting scientific reasoning (Gopnik, 2012; Sandoval, Sodian, Koerber, & Wong, 2014; Schulz & Bonawitz, 2007), its shortcomings are equally noteworthy, and those shortcomings must be addressed if we hope to improve public understanding of scientific explanations and public acceptance of scientific evidence in a world increasing dominated by science.

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Short Biography

Andrew Shtulman is an Associate Professor in the Departments of Psychology and Cognitive Science at Occidental College. He holds an A.B. in Psychology from Princeton University and a Ph.D. in Psychology from Harvard University. His research explores conceptual development and conceptual change, particularly as they relate to science education, and he is a recipient of an Early Career Development Award from the National Science Foundation and an Understanding Human Cognition Scholar Award from the James S. McDonnell Foundation.

Notes

* Correspondence: Occidental College, 1600 Campus Road, Los Angeles, CA, 90041, USA. E-mail: shtulman@oxy.edu.

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