Developing an Understanding of Science

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Abstract

Young children are adept at several types of scientific reasoning, yet older children and adults have difficulty mastering formal scientific ideas and practices. Why do “little scientists” often become scientifically illiterate adults? Here, we address that question by examining the role of intuition in learning science, both as a body of knowledge and as a method of inquiry. Intuition supports children’s understanding of everyday phenomena but conflicts with their ability to learn physical and biological concepts that defy firsthand observation, such as molecules, forces, genes, and germs. Likewise, intuition supports children’s causal learning but provides little guidance on how to navigate higher-order constraints on scientific induction, such as the control of variables or the coordination of theory and data. We characterize the foundations of children’s intuitive understanding of the natural world, as well as the conceptual scaffolds needed to bridge these intuitions with formal science.

Keywords: conceptual development, conceptual change, intuitive theories, causal learning, inquiry skills, science education
Developing an Understanding of Science

Children are often described as “little scientists,” and for good reason. They construct rich, coherent theories of the world around them (Shtulman, 2017). They use these theories to guide exploration and intervention, and they can use the evidence generated through such activities to revise their theories (Gopnik & Wellman, 2012). They can recognize when evidence is confounded (Schulz & Bonawitz, 2007) or inconclusive (Gweon et al., 2010) or when it points to an unknown causal variable (Schulz & Sommerville, 2006). They gather evidence not just from inquiry but also from testimony, querying the people around them for explanations (Chouinard et al., 2007) while also monitoring what they hear for unsubstantiated claims (Mills, 2013). And they are fundamentally curious about how things work and why things happen (Jirout & Klahr, 2012).

Despite the notable abilities of children, adults are not particularly fond of science, nor do they tend to understand it. National polls indicate that millions of people believe that dinosaurs coexisted with humans, that the earth’s continents are fixed in place, that atoms are smaller than electrons, and that the sun revolves around the earth. And millions deny that humans evolved from nonhuman ancestors, that humans are changing the climate, that genetically modified foods are safe to eat, and that vaccines are safe to receive (National Science Board, 2018; Pew Research Center, 2015). Studies of adults’ scientific reasoning skills have documented similar deficits. Adults have difficulty discerning correlations from contingency data (Fugelsang & Thompson, 2003), coordinating the influence of multiple variables (Kuhn et al., 2015), and interpreting evidence that runs counter to their beliefs (Chinn & Brewer, 1998). Many adults are also woefully uninformed about the nature of science, misinterpreting the purpose of experiments (Lederman et al., 2014), conflating explanation and evidence (Smith & Wenk, 2006), and mistaking empirical support for definite proof (Shtulman, 2013).
These two literatures, in juxtaposition, raise the question of why little scientists become science illiterates and science deniers. Skills and dispositions documented in young children seem to disappear with age, and the scientific knowledge that children seem poised to acquire—genetics, mechanics, thermodynamics, and so forth—is actually acquired rarely or poorly. In this review, we focus on the role of early intuitions in shaping the development of scientific knowledge and scientific inquiry. We argue that these intuitions are generally misaligned with formal science, though for different reasons when considering why learners fail to understand science (a) as a body of knowledge and (b) as a method of inquiry.

Learning domain-specific scientific ideas requires concepts that are absent from early knowledge of the natural world and, in many cases, inconsistent with that knowledge. Learning domain-general inquiry skills, on the other hand, requires contextual support that is missing from how science is typically taught and how scientific reasoning is typically measured. While early intuitions are often an unappreciated obstacle for learning scientific content, they are also an underutilized resource for learning scientific processes. Increasing science literacy and science acceptance among the general public requires neither the wholesale rejection of intuitive ideas nor their wholesale acceptance, but rather a more nuanced approach, in which particular intuitions about natural phenomena are challenged, while particular intuitions about empirical inquiry are leveraged.

**Domain-Specific Concepts: Understanding Science as a Body Knowledge**

Children do not wait until they enter the science classroom to learn how the world works. They form their own homespun ideas, informed by perceptual biases, personal experiences, and cultural input (Carey, 2009; Shtulman, 2017). These explanations, known as “folk theories” or “intuitive theories,” tend to be coherent, early-emerging, and widespread. They are termed *theories* because they serve the same function as scientific theories: helping us explain past
events, predict future events, contemplate counterfactuals, and intervene on present circumstances to bring about desired outcomes (Gopnik & Wellman, 2012). They are termed *intuitive* because they lack the precision and accuracy of scientific theories. While they allow us to predict and explain everyday phenomena—freezing, floating, falling, breathing, growing, dying—they can interfere with learning scientific theories of those same phenomena (Shtulman, 2017; Vosniadou, 2009). Below we consider several fundamental concepts in the physical and biological sciences and how intuitive theories constructed in early childhood interfere with learning those concepts.

**Physical Concepts**

Humans come equipped to track many aspects of the physical world: how heavy something feels, how big it appears, whether it is hot, whether it moves, how fast it moves, and where it has gone. These perceptual abilities allow us to interact with physical objects in ways that further our goals and minimize our chances of injury, but they do not necessarily align with objects’ true properties, as revealed by science. We perceive whether an object can be lifted or thrown but not its weight; whether an object will burn us or freeze us but not its temperature; how quickly an object moves but not the forces acting on it; and where an object has fallen but not how it fell. Misalignment of perception and reality leads children to develop intuitive theories that suffice in everyday situations but interfere with learning scientific theories of the domain. Below we provide four examples of this misalignment, along with the conceptual insights needed to align them.

**Matter.** From infancy, humans appreciate several properties of physical objects: that they cohere across changes in location, that they cannot pass through one another, that they trace continuous paths through space, and that they move on contact with other objects (Spelke, 1994). Knowledge of these properties allows us to track objects and predict their trajectories (Scholl &
Pylyshyn, 1999), but it complicates our understanding of matter more generally. Substances that do not possess the properties of solid objects, such as liquids and gases, are not initially viewed as matter, and matter itself is initially viewed as holistic and homogenous, like solids appear to be (Smith, 2007; Samarapungavan et al., 2017; Chiang & Wynn, 2000).

If preschoolers asked to imagine what would happen to an object repeatedly divided in half, they claim it would eventually disappear, taking up no space and having no weight (Smith et al., 2005). Preschoolers’ conception of weight is how heavy something feels (heft) and their conception of volume is how big something appears (bulk), and they expect heavy objects to be big and big objects to be heavy. The idea that two objects could have the same weight but different sizes or the same size but different weights is hard for them to grasp (Smith, 2007). Understanding matter as divisible (not holistic) and dense (not homogenous) requires thinking of it as composed of tiny particles (Samarapungavan et al., 2017). Only on a particulate theory of matter does it make sense that matter too small to be felt would still have weight or that small objects can weigh more than large objects if their particles are more tightly packed. A particulate theory is also needed to understand why objects as heavy as a boat can float, why solids expand and contract, or why substances can change from solid to liquid to gas.

Acquiring a particulate understanding of matter involves collapsing the distinction between solids and non-solids and creating distinctions between heft and weight and between bulk and volume. These insights can be fostered by providing counterexamples to children’s holistic misconceptions (Hardy et al., 2006; Smith, 2007), such as the discovery that objects too small to feel still have weight (on an analytic scale), that objects too small to see still have volume (under a microscope), that heavy objects sometimes float, that light objects sometimes sink, and that substances maintain their mass across phase changes. Such input helps children recognize the inadequacies of a holistic theory and begin constructing a particulate theory.
Particulate theories remain counterintuitive, though. Many adults fail to recognize that gases are a form of matter but heat and sound are not (Shtulman & Legare, 2020), and they tend to conflate weight and density when judging an object’s buoyancy (Potvin et al., 2015).

**Heat.** Humans have heat receptors in their skin, but these receptors do not detect heat *per se*; they detect heat transfer, which we perceive as warmth. Objects at the same temperature can have dramatically different warmths, such as the difference between a seatbelt’s cloth strap and metal clasp in a hot car, and warmth can change independent of temperature, such as when the air feels colder on a windy day or hotter on a humid day. Because insulators like wool and wood are associated with warmth, children think of them as producing or trapping heat rather than slowing the dissipation of heat (Lewis & Linn, 2003). And because heat transfer to the body (warming) is perceived as distinct from heat transfer from the body (cooling), children think of heat and cold as separate entities (Clough & Driver, 1985). Indeed, both heat and cold are viewed as substances, like an invisible fluid that flows in and out of physical objects (Reiner et al., 2000). Statements like “heat escapes from your head” or “scarves keep out the cold” are conceived of as literal, not metaphoric.

Substance-based views of heat originate in childhood but linger into adulthood. When adults reason about thermal transformations, most deploy the same logic as when reasoning about material transformations (Slotta et al., 1995). Asked whether coffee would stay hotter in a ceramic cup or a styrofoam cup, adults tend to focus on the porousness of the material, similar to when they are asked whether helium would stay longer in a paper balloon or a plastic balloon. Porousness is relevant to the dispersion of matter but not the transfer of heat, yet many adults claim that coffee would stay hotter in a ceramic cup just as helium would stay longer in a plastic balloon. Only adults with extensive physics education reliably distinguish thermal and material transformations (Slotta et al., 1995).
The knowledge needed to reconceptualize heat as a form of energy is knowledge of emergent processes (Chi et al., 2012). Heat is not a substance but a process—a process that emerges from the collective interaction of independent molecules. These interactions occur across the entire system, simultaneously and indefinitely. Many phenomena are emergent processes—traffic, weather, cities, economies—but this framework is absent from early cognition and thus absent from children’s reasoning about heat. Teaching children how systematic patterns at one level of a system can arise from random interactions at a lower level allows them to think of heat as emerging from matter rather than as a special type of matter (Chang & Linn, 2013; Slotta & Chi, 2006).

**Motion.** Humans are adept at tracking moving objects. As infants, we can accurately predict where objects are going and how quickly, even when they collide with other objects or move out of view (Baillargeon, 2004; Rosander & von Hofsten, 2004). Our visual system is designed for detecting motion (Borst & Egelhaaf, 1989) and, by extension, distinguishing objects in motion from objects at rest. But from a Newtonian point of view, motion and rest are equivalent states, differing only by the observer’s frame of reference. It’s changes in motion (acceleration) that requires explanation, not motion itself.

Our focus on motion, rather than acceleration, leads us to posit a cause: an internal force, or “impetus,” transferred from one object to another (McCloskey, 1983). Belief in impetus leads people to make incorrect, yet coherent, predictions about freefall (Howe et al., 2012; Kaiser et al., 1985; Venkadasalam & Ganea, 2018). Objects with horizontal velocity fall to the ground in a parabolic path, but many people—children and adults alike—believe they move parallel to the ground at the beginning of their fall, until some of their impetus has dissipated, and perpendicular to the ground at the end of their fall, once all their impetus has dissipated. Heavy objects are thought to fall faster than light ones, owing to their extra impetus. Objects released by
a carrier, like a bomb dropped from a plane, are not attributed any impetus and predicted to fall straight down, whereas objects accelerated centripetally, like a ball swung on a string, are attributed a curved impetus and predicted to fall in a curve.

One way to convince learners that acceleration implies a force but motion does not is to help them differentiate their intuitive notion of force (impetus) from a scientific notion (an interaction between objects) (Alonzo & Steedle, 2009; Vosniadou et al., 2001). For instance, an object at rest on a surface does not appear to have any forces acting on it, but it actually has two: the downward pull of gravity and the upward push of the surface, known as the “normal force.” Students typically deny the normal force is real, but they can be persuaded otherwise if the normal force is likened to forces they can perceptually observe, like a spring pushing against our hand or a cushion pushing against our back (Clement, 1993). The perceptual biases that lead us to posit impetus can be countered with perceptual experiences at odds with those biases, if harnessed appropriately.

Earth. Children’s early experiences navigating the local environment betray no sign of the earth’s global shape. When children are told the earth is round and shown depictions of the earth as a sphere, they interpret this input in ways that preserve their belief that the ground is flat and that people live only on top of the earth, because otherwise they would fall off (Vosniadou & Brewer, 1992). Some children think the earth is mostly round but has a flat top, where people live. Others think the earth is spherical but hollow, with people living inside the hollow part. And yet others think the earth is spherical but deny that people live there; they claim instead that people live on the ground and that the earth is just another planet in outer space.

These nonscientific models are typically constructed at the beginning of elementary school, and they support a variety of inferences: why the earth looks flat even though people say it is round; whether you could fall off the earth; where the sun, moon, and stars are located; and
what causes the alternation of day and night. This last inference remains challenging throughout childhood (Harlow et al., 2011; Plummer & Krajcik, 2010). Young children typically explain day and night in terms of occlusion; the moon is occluded by clouds or mountains during the day, and the sun is occluded by these objects at night. Older children extend the notion of occlusion to the horizon, claiming the sun and the moon exchange places above and below the horizon. Once children think of the earth as a sphere, they begin to posit explanations that involve the motion of the earth, but they typically think it’s the earth’s orbit that causes day and night rather than its rotation (Samarapungavan et al., 1996).

Because children are led astray by their visual perspective, challenging these perspectives can be an effective teaching tool. Children taught to think of the earth as a giant magnet, pulling tiny objects to its surface, are more likely to accept that the earth is sphere (Hayes et al., 2003). Children taught to think of sunrise and sunset as consequences of viewing the sun from a rotating earth are more likely to understand the day-night cycle (Jee & Anggoro, 2019). Children can also become motivated to correct these misconceptions on their own if the discrepancy between what they see and what they are taught is made salient, as it is for Australian children. These children are told they live in the “land down under,” and their home is depicted on the underside of a standard globe. Such peculiarities lead Australian children to develop spherical models of the earth years before their peers in the northern hemisphere (Siegal et al., 2004). Children everywhere are awash in evidence that the earth is a sphere, but that evidence becomes meaningful only when children reinterpret their perceptual knowledge of the earth’s surface.

**Biological Concepts**

While perception leads us astray when contemplating the physical world, it often provides no help when contemplating the biological world. Many biological phenomena operate outside the scope of everyday observation. We cannot see the organs that support life, the genes
that facilitate inheritance, the germs that cause illness, or the selective pressures that shape evolution. In the absence of such input, we rely on generic inference strategies: animism, vitalism, essentialism, contamination, and teleology. These strategies provide a broad but shallow understanding, as they lack the mechanistic details needed to identify the true processes at work. Animism conflates motion with life; vitalism conflates activity with metabolism; essentialism conflates innate potential with genes; contamination conflates disgust with germs; and teleology conflates a trait’s function with its origin. Below we discuss how these conceptual biases lead to systematic misconceptions, along with the mechanistic knowledge needed to overcome them.

Life. When children hear terms like living and alive, they first understand them as referring to things that can move on their own, a disposition known as “animism” (Piaget, 1929). Preschoolers classify animals as alive, but they also classify many moving but nonliving things as alive, like the sun and the clouds. They also make the converse mistake of classifying non-moving organisms, like flowers and trees, as not alive. Children know that plants grow and need nourishment several years before they recognize that they are living things (Stavy & Wax, 1989; Hickling & Gelman, 1995). Animals form the core of children’s early understanding of life, particularly humans (Carey, 1985; though see Herrmann et al., 2010). Children’s initial interpretation of biological processes, like eating and sleeping, comes from firsthand experience, and they are disinclined to extend these processes to other organisms. The less human-like the organism, the less children will extend biological properties to it (Gutheil et al., 1998). This pattern can be forestalled, though, if children have ample exposure to nonhuman organisms (Geerds et al., 2015) or grow up in cultures that emphasize the interconnectedness of living things (Medin et al., 2010).
To develop a genuinely biological understanding of life, children must first develop a vitalistic one (Inagaki & Hatano, 2014). Vitalism is the idea that organisms acquire energy from food, water, and sleep and use that energy to move, grow, and develop. Vitalism is an improvement over animism, in that biological processes are related to health and vitality, but it falls short of a mechanistic understanding, in that children have yet to learn how biological processes are instantiated in the body (Slaughter & Lyons, 2003). Information about the body is required to unify and explain several disparate ideas: that all entities with bodies are alive, that only entities with bodies are alive, that death results from the breakdown of the body, that bodies can break down in different ways, and that all bodies eventually break down.

Death, like life, is difficult to understand within an animistic or vitalistic framework. Teaching children about the body—the organs inside and how they function—allows children to grasp the physicality of life and, hence, the finality of death (Slaughter & Lyons, 2003). But notions of life and death remain elusive across the lifespan, as adults continue to exhibit misconceptions about what is alive and what is not, sometimes judging natural phenomena, like wind and fire, as alive and sometimes failing to judge plants and microorganisms as such (Shtulman & Legare, 2020). These effects are particularly strong for adults with dementia (Zaitchik & Solomon, 2008) implying that animistic conceptions of life reemerge when mechanistic conceptions can no longer be accessed.

**Inheritance.** The mechanisms of inheritance eluded scientists until the 20th century, but now even young children know the words “gene,” “genetic,” and “DNA.” Lay understanding of these terms is grounded in essentialism, or the idea that an organism’s outward appearance and behavior is determined by its inner nature or “essence” (Gelman, 2003). Essences are thought to be transmitted from parents to offspring, conferring offspring with the innate potential to develop the parents’ traits. A baby pig is expected to grow a curly tail and say “oink” even if raised by
cows, and a baby cow is expected to grow to a straight tail and say “moo” even if raised by pigs (Sousa et al., 2002). While essentialism may support an understanding of species-typical development, essences are a far cry from genes (Dar-Nimrod & Heine, 2011). Essences are immutable, but genes mutate regularly. Essences are discrete, but genes work in conjunction with other genes. Essences are homogenous, but genes contribute to the expression of multiple traits. Our lay understanding of inheritance is not genetic, despite our use of the word.

Children’s earliest understanding of inheritance is not mechanistic either. Children recognize that offspring are likely to resemble their parents but not because of the transmission of physical information prior to birth. Preschoolers correctly predict that an adopted baby will develop the physical traits of his birth parents, but many predict he will develop their beliefs and opinions as well (Solomon et al., 1996). Many preschoolers also think that similar-looking strangers share more traits than dissimilar-looking kin, that traits acquired during a parent’s lifetime can be passed to their offspring, and that parents can choose which traits their offspring will possess (Springer, 1995; Weissman & Kalish, 1999). These misconceptions can be corrected by teaching children basic facts about reproduction, namely, that babies are conceived internally and that they grow from an embryo into a baby in their mother’s womb (Springer, 1995). These facts constrain their essentialist intuitions, helping them distinguish heritable traits from non-heritable ones.

Understanding trait transmission as a physical process is still not sufficient for understanding genetics. The latter requires more detailed, biochemical knowledge. Many adolescents believe that genes circulate in the blood, like hormones, or that different parts of the body contain different genes (Venville et al., 2005). More problematically, they view the mapping between genes and traits as one-to-one, with no appreciation of the fact that genes code for proteins and proteins interact to create traits (Duncan & Reiser, 2007). These details are
necessary for understanding genetic technologies, like genetic screening and genetically modified foods (McPhetres et al., 2019). They are also needed to avoid genetic fatalism, or the idea that some traits, like body weight or mathematical ability, are determined mainly by genetics and cannot be changed (Dar-Nimrod & Heine, 2011). The actual contribution of particular genes to particular traits is often miniscule, but an essentialist construal of genes, as vehicles of innate potential, can lead people to conform to their misguided interpretations.

**Illness.** Evolution prepared humans to avoid illness by endowing us with disgust. We are universally disgusted by contagion-laden substances like rotting food and bodily waste (Curtis et al., 2004). But there are many things devoid of contagion that disgust us, and many contagions that fail to elicit disgust. Diseases like cholera and smallpox spread because humans are not inherently disgusted by cholera-infected water or smallpox-infested blankets, and clean substances that resemble contagion-laden ones, like sterile bedpans or feces-shaped fudge, regularly elicit a disgust response (Rozin et al., 2008). The disconnect between contagion and disgust arises because we have no means of perceiving germs and must rely on sights and smells merely associated with them.

Microbes were discovered in the 17th century, with the advent of the microscope, but were not linked to disease for another 180 years (Thagard, 2000). The link was slow in coming because the idea that living things survive and reproduce inside other living things requires a broader notion of life than that afforded by animism or vitalism. Children are introduced to the concept of germs early in life, through admonishments to avoid them and wash them from their bodies, but they do not view germs as living things, similar to their forebearers. Young children know that rotting food has germs, that sick people have germs, that germs can be passed from contaminated objects to uncontaminated ones, and that the process of contamination is undetectable (Blacker & LoBue, 2016; Kalish, 1996). Yet, despite this knowledge, they think of
germs more as toxins than microbes. When asked whether a person with a cough could give that cough to someone else, young children agree they could regardless of whether the cough was caused by germs or by poison (Solomon & Cassimatis, 1999). Young children also deny that germs engage in biological processes, like consuming nutrients and reproducing (Solomon & Cassimatis, 1999), as do many adults (Shtulman & Legare, 2020).

Failing to think of germs as living things has consequences for health behavior. Young children avoid substances that elicit disgust, like bodily fluids or waste, but they do not avoid substances contaminated through incidental contact. They are willing to consume juice contaminated by a grasshopper, milk contaminated by dog poo, or cereal contaminated by a sneeze (DeJesus et al., 2015; Fallon et al., 1984). Such behaviors are curtailed by social norms, but they are more effectively addressed by teaching children about the biological properties of germs and the biological pathways of infection. Adolescents who receive such instruction are better at explaining infection than those instructed on the “do’s and don’ts” of disease prevention. They also are more likely to exhibit healthy behaviors, such as sanitizing their hands before touching food (Au et al., 2008).

**Evolution.** Casual observation of plants and animals reveals that they are well adapted to their environment but not how they became so. Nor does it reveal where organisms came from or how they are related to one another. These questions have traditionally been answered in the language of intentional design: a divine being created living creatures in their current form, perfectly adapted to their environment (Mayr, 1982). This answer continues to resonate with laypeople, including children. When asked to explain where the first bear came from or the first lizard, children typically appeal to a creator, even if their parents appeal to evolution (Evans, 2001). Many children retain creationist views throughout their lives, especially those who attend schools where evolution is excluded from the curriculum (Mead & Mates, 2001). Children who
do learn about evolution typically misunderstand the process. They view it as a species-wide 
metamorphosis rather than the selective propagation of within-species variation (Shtulman, 
2006). Adaptation is thought to be directly evoked by the environment, with offspring born more 
adapted to the environment than their parents were at birth (Ware & Gelman, 2014).

One reason people fail to appreciate the role of selection in driving adaptation is that our 
essentialist biases lead us to devalue variation within a species. Members of a species are seen as 
essentially the same, and differences between parents and offspring are viewed as unlikely or 
inconsequential (Shtulman & Schulz, 2008). Generic descriptions of traits, like “giraffes have 
spots” or “tigers have stripes,” are understood as implying that the traits are ubiquitous (Gelman 
& Roberts, 2017). Another reason people fail to appreciate selection is that we are generally 
unaware of resource limitations and the struggle for survival (Shtulman, 2019). Ecosystems are 
viewed as harmonious environments where organisms have ample food, water, and shelter and 
where species exist in mutually beneficial relationships with the earth and with each other 
(Zimmerman & Cuddington, 2007).

Absent an understanding of selection, most people reason about adaptation 
teleologically—that organisms evolve the traits they need to evolve in order to survive. Such 
misconceptions are robust in the face of instruction, with most teaching interventions yielding 
little improvement (Legare et al., 2018). Their ineffectiveness may stem from the fact that 
students are not introduced to evolution until high school, after they have spent over a decade 
encoding biological information in teleo-essentialist terms. Attempts to teach evolution to 
younger students—elementary schoolers—have proven more successful (Kelemen et al., 2014; 
Shtulman et al., 2016). While children are predisposed to provide need-based explanations for 
adaptation and creationist explanations for speciation, these inclinations can be countered with 
early interventions that provide a population-based framework for reasoning about evolution.
UNDERSTANDING SCIENCE

Domain-General Skills: Science as a Method of Inquiry

Developing an understanding of science requires more than acquiring domain-specific knowledge; learners must also possess domain-general inquiry skills to identify gaps and inconsistencies in their understanding and design strategies to address them (Klahr & Nigam, 2004; Mayer, 2004). The misconceptions outlined in the previous section highlight the need to examine the mechanisms by which earlier, intuitive beliefs undergo revision over the course of development. This inquiry process cuts across specific content domains. It includes the skills and habits of mind needed to undertake and interpret science, ultimately leading to theory change and science literacy (Zimmerman, 2007).

The development of scientific thinking as a method of inquiry has been explored in two overlapping, but historically disparate, research traditions: one considering the acquisition of causal theories through the lens of cognitive development and the other examining scientific reasoning skills through the lens of education (Kuhn & Dean, 2004). Comparing the conclusions of these two literatures highlights a tension between children’s early competence as “little scientists” and their later difficulties generating and interpreting evidence in line with formal experimentation. In the remainder of this review, we provide an overview of this tension between intuitive and explicit scientific practices and consider scientific inquiry skills that highlight this contrast. We also summarize research suggesting how learners’ intuitive understanding might be better harnessed to support explicit reasoning skills.

Early Competence in Intuitive Science

Children are proficient causal learners. By age five, they have developed abstract, hierarchically-organized causal theories that allow them to generate inferences, make predictions, and design informative interventions (Gopnik & Wellman, 2012; Kuhn, 2012; Sobel & Legare, 2014). Even infants are sensitive to the statistical regularities in the data they observe.
(Denison & Xu, 2019; Xu & Garcia, 2008), and can use those patterns to infer hidden or abstract causes (Saxe & Carey, 2006; Walker & Gopnik, 2014). By preschool, children interpret data generated from their own actions to learn about causal structure (Lapidow & Walker, 2020a), and use dependence information to infer causes, even when that evidence conflicts with their prior knowledge (Gopnik et al., 2004; Schulz et al., 2007). Researchers in the field of cognitive development have long advanced an analogy between the processes underlying knowledge acquisition and formal scientific theory change (Carey, 1985; Gopnik, 2012). This analogy is supported by decades of empirical findings, as well as computational models that provide more precise descriptions of the representations and mechanisms underlying this process (Gopnik et al., 2004; Griffiths et al., 2011; Xu, 2019).

According to this view, children, like scientists, test and revise their existing causal theories in light of new evidence. Children are able to generate this evidence for themselves by conducting intuitive experiments (Cook et al., 2011; Lapidow & Walker, 2020a), asking discriminating questions (Chouinard, 2007; Ruggeri & Lombrozo, 2011), and seeking out reliable informants (Mills, 2013). They can rationally interpret data that is generated by the actions of others (Buchsbaum et al., 2011; Meltzoff et al., 2012), considering how the data were sampled, who sampled it, and why (Bonawitz et al., 2011; Butler & Markman, 2012). Children are also sensitive to pedagogical cues in the learning environment, such as the causal affordances of a novel artifact (Walker et al., 2020), and can flexibly adapt their learning strategies to maximize information gain (Stahl & Feigensen, 2015; Ruggeri et al., 2017). Collectively, this work suggests that even young children have sophisticated abilities for acquiring and revising knowledge and that these abilities rely on mechanisms that are surprisingly similar to those used in formal science.

**Later Challenges in Explicit Scientific Reasoning**
In line with the conclusion that children are natural scientists, the U.S. National Research Council (2000) recommends that inquiry-based learning be used to teach scientific reasoning skills. They propose that children learn to use the scientific method through their self-guided exploration. Puzzlingly, however, education research has found little evidence for the effectiveness of this approach. Rather, the research suggests that children require substantial training before they are equipped to engage in formal scientific inquiry (Klahr & Nigam, 2004). In the absence of heavy-handed instruction, even school-aged children conduct uninformative experiments that fail to control variables (Tschirgi, 1980), yield confounded evidence (Chen & Klahr, 1999), and prioritize demonstrable effects (Croker & Buchanan, 2011). Children also appear to conflate hypotheses and evidence (Valanides et al., 2014) and generate inappropriate conclusions from the data they observe (Zimmerman, 2007).

Over the years, a variety of approaches have been used to foster formal scientific reasoning skills, including minimizing the role of domain knowledge, allowing children to observe the effects of their experiments, and increasing or decreasing the valence of hypotheses or outcomes (Zimmerman, 2007). While some research finds that guided practice and scaffolding can increase valid experimentation practices (Schwichow et al., 2016), other work shows little evidence of improvement, even after extensive training (Kuhn et al., 1995).

**Bridging the Gap Between Intuitive and Formal Science**

How can we reconcile these two, very different portraits of scientific understanding in childhood? One attempt at resolution has emphasized the vast differences in experimental task demands between these literatures. Although research on children’s causal learning suggests that children are adept and sophisticated learners, the methods used differ substantially from traditional measures of formal scientific reasoning. Causal reasoning tasks generally rely on implicit inferences, using exploratory behavior or a forced choice among predefined options,
whereas scientific reasoning tasks require explicit (often verbal) reports. And causal learning
tasks tend to be decontextualized, relying on little content knowledge, whereas empirical studies
of scientific reasoning tend to draw heavily upon children’s prior concepts.

Of course, these differences exist by design. Most of the methods used in modern
cognitive development research exist as a response to Piaget’s description of young children as
perceptually-bound, illogical, and pre-causal (Piaget, 1929). Piaget designed complex,
multivariate tasks with high verbal demands. Although advances in developmental methods that
remove these demands have provided evidence for earlier competence in nearly every knowledge
domain, some have argued that it is precisely these demands that are central to assessing true
scientific understanding. In other words, it has been argued that scientific inquiry simply is the
intentional process of seeking knowledge by comparing the effects of multiple, interacting
variables (Kuhn et al., 2015). After all, engaging in scientific reasoning in the real world is rarely
protected against the influence of strongly-held prior beliefs, biases, and the desire to produce
positive, tangible outcomes.

From this perspective, although developmental findings reporting early competence
demonstrate nascent abilities and implicit sensitivity to informativeness in preschoolers, it is not
clear that school-aged children have an explicit understanding of science as a method of inquiry
(Sandoval et al., 2014) or are metacognitively aware of the reasons for their success when
engaged in intuitive experimentation (e.g., Kuhn & Dean, 2005; Schneider, 2008). It has thus
been suggested that simple, knowledge-lean tasks may vastly overestimate children’s proficiency
in science understanding, as learners likely proceed without conscious awareness or control
(Kuhn, 2012). In other words, having the ability to reason about causal interactions among
variables does not necessarily imply that children are able to undertake explicit belief change. It
might be possible, however, to harness children’s scientific intuition to support explicit reasoning
about the scientific process and facilitate belief change. Below, we review some of the literature on scientific experimentation to highlight this relationship between intuitive and formal science.

**Hypothesis Testing.** In everyday reasoning, it is often impossible to infer causal relationships from observation alone. A gardener may observe that her flowers wilt when there is direct sunlight and dry soil, but this co-occurrence cannot provide information about which of those variables are causal, or how they are related to one another. Instead, this observation must be paired with an intervention, such as adding water to the soil, to discriminate among several possible hypotheses about the system’s causal structure. Growing evidence suggests that children intuitively seek this type of information when they are provided with the opportunity to explore a novel causal system (Schulz & Bonawitz, 2007; Lapidow & Walker, 2020a). In fact, when the evidence they observe is ambiguous or violates their current beliefs, children spontaneously engage in a greater amount of causally-relevant exploration (Bonawitz et al., 2012; Schulz & Bonawitz, 2007; van Schijndel et al., 2015; Stahl & Feigensen, 2015).

Despite this natural inclination to maximize information gain and identify causal relationships, it remains unclear whether children understand these activities as a process of searching for additional knowledge (Sobel & Letourneau, 2018). According to some, in order to properly engage in hypothesis testing, children must first recognize the epistemic distinction between the hypotheses they consider and the evidence they generate (Kuhn & Katz, 2009; Zimmerman, 2007). Indeed, the ability to explicitly coordinate hypotheses and evidence has long been considered a central feature of mature scientific thinking (Kuhn, 2012). Although this type of conscious control is typically considered to be late developing, research suggests that even young children (aged 6-8) implicitly differentiate between practical and epistemic goals when selecting actions (e.g., the difference between feeding a mouse and learning something about the mouse’s size from its food intake, Sodian et al., 1991; Piekny & Maehler, 2013). The distinction
between intuitive and formal hypothesis testing may therefore rest on the learner’s developing ability to think *about*—rather than merely *with*—a theory.

**Control of Variables Strategy.** Research on scientific experimentation has largely focused on children’s acquisition of the control of variables strategy. This involves isolating a single variable while holding all others constant to assess the causal relationship between this focal variable and some outcome of interest (Klahr et al., 2011). The majority of research examining the development of this skill has concluded that elementary-aged students do *not* spontaneously control variables in explicit contexts, and often manipulate too many variables at once, generating confounded tests of a hypothesis (Klahr & Nigam, 2004; Zimmerman, 2007). In fact, mastering the control of variables strategy typically requires extensive training (Schwichow et al., 2016), and afterwards, children are still unlikely to transfer this skill to novel problems. Children’s intuitive experimentation is far less systematic (Klahr, 2000). Children often privilege “soft interventions,” where a variable is pushed toward one extreme or another but not held constant, or they conduct multiple interventions at once (Gopnik & Wellman, 2012).

Why might learners’ intuitions about experimentation differ so significantly from this widely-used scientific practice? One possibility is that controlling variables is not actually the most efficient strategy for negotiating systems with multiple variables that operate probabilistically and interactively (Kuhn et al., 2015). For example, when causes are sparse, testing one variable at a time is *less* informative than intervening on multiple variables at once (Coenen et al., 2019). As noted above, children consider the informativeness of their actions when exploring a variety of novel contexts (Cook et al., 2011; Lapidow & Walker, 2020a; Ruggeri et al., 2019), and this behavior leads to a surprising amount of discovery, often yielding reliable information about real-world causal relations.
Another possibility is that assessments of how children control of variables in formal learning environments are artificially constrained. When learners are engaged in intuitive experimentation, additional pragmatic concerns often help determine which actions are most informative. As a result, many of children’s “errors” in the classroom may arise from differences between the criteria used to evaluate successful experimentation and their goals as causal learners. For example, children often pursue positive tests of their hypotheses, or actions intended to generate an effect if their existing hypothesis is correct (McCormack et al., 2016; Zimmerman, 2007). In formal science, these experiments are typically viewed as uninformative, since positive tests often cannot distinguish between a current hypothesis and potential alternatives. Children’s fixation on positive tests is believed to stem from their misunderstanding of the epistemic goals of experimentation (Tschirgi, 1980), their desire to demonstrate the accuracy of their hypotheses (Klahr et al., 1993), or their focus on producing tangible outcomes, akin to engineering (Schauble et al., 1991; Masnick et al., 2017).

Viewed through the lens of causal learning, however, repeatedly activating a hypothesized cause and assessing whether its effects occur across different permutations of the system may provide useful information. After all, learners are primarily concerned with discovering causal knowledge that generalizes across contexts, supporting prediction and action in a variety of situations (Lapidow & Walker, 2020b). If learners are typically searching for causal invariants, then positive testing may be a valuable approach to causal learning. By better aligning the information-seeking goals of causal learning with the formal practices of scientific inquiry, educators could leverage this intuition to their advantage.

**Evaluation of Evidence and Belief Revision.** In addition to generating their own evidence, learners must also be able to interpret and evaluate that evidence, which requires recognizing the difference between confounded and unconfounded tests of a hypothesis (van der
Graaf et al., 2016), diagnosing likely causes from observed effects (Sobel et al., 2017), and overturning incorrect beliefs in light of compelling counterevidence (Chinn & Brewer, 1998). Although elementary-aged children cannot produce a controlled experiment on their own, they can select an informative experiment when provided with a choice between confounded and unconfounded evidence (Bullock & Ziegler, 1999). Similarly, while preschool-aged children typically fail to differentiate empirically-warranted inferences from unwarranted ones (Zimmerman, 2007), they preferentially explore confounded evidence (Schulz & Bonawitz, 2007), selectively isolate confounded causes (Cook et al., 2011), and prefer to present unconfounded evidence when arguing against a false claim (Koksal-Tuncer & Sodian, 2018). This literature suggests that young children have a nascent ability to critically evaluate the informativeness of the evidence they observe.

What happens when young learners encounter evidence that is incompatible with their existing theories? According to rational models of belief revision, learners’ responsiveness to anomalous data should depend on the strength of the counterevidence relative to that of their theories (Kimura & Gopnik, 2019; Tenenbaum et al., 2006). In some cases, even preschoolers use belief-violating evidence to update their intuitive theories, including their theories of balance (Bonawitz et al., 2012) and their theories of mind (Amsterlaw & Wellman, 2006). In other cases, belief revision is relatively conservative. For example, if children are provided with several instances of a psychosomatic cause (e.g., worry causing a tummy ache), they can update their beliefs to endorse this specific cross-domain relationship but still fail to generalize to new psychosomatic events (Schulz et al., 2007).

Sometimes, however, children appear reluctant to abandon their prior beliefs when confronted with conflicting data and instead try to assimilate those data into their theories (Penner & Klahr, 1996). Similar failures have been documented in adults (Kuhn, 2012;
Shtulman, 2017). Counterintuitively, this tendency for learners to stubbornly maintain their existing beliefs in the face of conflicting evidence may be part of what makes learning so powerful and efficient. Schulz and colleagues (2008) argue that the ability to learn robust causal principles from sparse data supports rapid knowledge acquisition. After only a handful of observations, children can infer abstract principles that make sense of incoming data and constrain future inferences. But these abstract principles, once inferred, can interfere with further learning, impeding children’s ability to detect and respond to counterevidence to their initial generalizations and thus hampering the development of mature scientific theories (Koslowski, 1996; Schauble, 1990).

**Using Intuition to Support Scientific Reasoning**

The research reviewed above highlights disconnects between an intuitive understanding of natural phenomena and a scientific understanding, but it also highlights useful overlaps. Scientific knowledge can build on intuitive knowledge if the latter is harnessed in appropriate ways, with the right aspects of intuition emphasized, the right scaffolds provided, and the right connections made (Clement et al., 1989; Vosniadou, 2009). Below, we discuss three mechanisms that may be used to bridge science and intuition, along with research pointing to their efficacy.

**Metacognition**

All children reason *with* their concepts, but not all children reason *about* their concepts. Taking a meta-level perspective on conceptual knowledge may help children distinguish intuitive ideas from scientific ones and work toward mastering the latter. Consistent with this possibility, children with superior executive function skills demonstrate earlier understanding of counterintuitive scientific ideas (Zaitchik et al., 2014) and also learn more from science instruction (Mason & Zaccoletti, 2020; Tardiff et al., 2020). Indeed, science learning selectively recruits areas of the brain associated with executive function (Nenciovici et al., 2018). The
executive function skills most critical to science learning appear to be set-shifting ability and inhibitory control (Tardiff et al., 2020; Vosniadou et al., 2018). Set shifting may be required to move between intuitive and scientific conceptions of the domain, and inhibition may be required to suppress the intuitive conceptions. These skills are important not only for learning science content but also inquiry skills, including hypothesis testing and evidence evaluation (Gropen et al., 2011). Recognizing the presence of confounded evidence likely requires awareness of one’s own ignorance or uncertainty.

Children’s mastery of counterintuitive scientific ideas is also predicted by how cognitively reflective they are. Cognitive reflection is the tendency to reflect on one’s own thinking. It is measured by trick questions that elicit an intuitive, yet incorrect, response that must be inhibited in order to derive the correct response (Frederick, 2005). A sample item from the Cognitive Reflection Test—Developmental Version (CRT-D), developed by Young and Shtulman (2020a), is “What do cows drink?” The correct answer is water, but the intuitive lure response is milk. Children who answer these brain teasers correctly demonstrate greater understanding of counterintuitive scientific ideas, independent of their age (Young & Shtulman, 2020a). They also learn more from instruction, when tutored on scientific alternatives to their intuitive theories (Young & Shtulman, 2020b). Children predisposed to reflect on their intuition are thus better equipped to learn science. It remains an open question, though, whether improving children’s metacognitive skills, either their cognitive reflection or their executive function, would facilitate their science learning.

**Questions**

A growing body of research demonstrates the efficacy of questions in supporting children’s ability to access and apply inferential reasoning skills in the context of formal science (Walker & Nyhout, 2020). The benefits of asking “Why?” questions for science learning have
been observed across a broad range of learners, knowledge domains, and reasoning contexts (Chi, 2000; Legare & Lombrozo, 2014). Explaining facilitates learning by helping learners identify gaps in their existing knowledge and ways of remedying those gaps (Chi, 2000). Explaining also affects causal inference, drawing learners’ attention to hypotheses that are broad (Walker et al., 2016; Williams & Lombrozo, 2010), generalizable (Walker et al., 2014), parsimonious (Walker et al., 2017), and abstract (Ruggeri et al., 2019; Walker & Lombrozo, 2017). The benefits of explanation are thus contingent on the learner’s goals, as well as the relationship between the strength of their prior knowledge and the quality of the evidence they observe. In fact, in some contexts, a prompt to explain may lead learners to discount evidence that is incompatible with their priori beliefs (Kuhn & Katz, 2009) or overlook plausible hypotheses that account for too few observations or posit too many causes (Pacer & Lombrozo, 2017).

In these situations, other types of questions may provide better pedagogical support, such as questions that engage children in the evaluation of alternatives (“What if?”) or questions that prompt counter-explanations (“Why else?”). These prompts have been found to attenuate confirmation bias in adult learners, shifting their attention away from salient hypotheses to other possibilities (Galinsky & Moskowitz, 2000). Prompting children to reason about alternative outcomes may provide similar benefits for scientific reasoning, supporting their use of the control of variables strategy (Nyhout et al., 2019) and scaffolding their recognition of confounded evidence (Engle & Walker, 2018).

**Targeted Instruction**

Learning science requires instruction, formal or informal, but not all instruction is effective. Free exploration of a domain allows students to ignore aspects of a domain they fail to understand and focus on those they do, or at least think they do (Kirschner et al., 2006). Problem
sets allow students to bypass the difficult work of conceptual change and focus on the easier task of applying well-rehearsed solution strategies (Kim & Pak, 2002). Instruction that actually facilitates conceptual change forces students to confront their prescientific intuitions and consider how those intuitions differ from scientific conceptions of the same task or domain. Examples include instruction that highlights the difference between holistic and particulate conceptions of matter (Smith, 2007), planar and spherical models of the earth (Hayes et al., 2003), or microbial and behavioral explanations for illness (Au et al., 2009), as well as instruction that contrasts direct and emergent processes (Slotta & Chi, 2006) or univariate and multivariate effects (Kuhn et al., 2015).

Such instruction is effective when it addresses how students intuitively reason about a domain or task, how that reasoning differs from normative reasoning, and how students can be led from one to the other. There are typically multiple paths between intuitive and scientific ideas, but students cannot be expected to find them on their own. Those paths must be highlighted with the right explanations (Au et al., 2008; Slotta & Chi, 2006; Vosniadou et al., 2001), the right discoveries (Schulz et al., 2007; Slaughter & Lyons, 2003; Springer, 1995), the right anomalies (Bonawitz et al., 2012; Siegal et al., 2004; Smith, 2007) or the right analogies (Clement, 1993; Jee & Anggoro, 2019; Shtulman et al., 2016).

Just as the process of conceptual change is difficult, so is the process of discovering techniques for facilitating conceptual change. It is an empirical question which learning activities are productive for bridging science and intuition, and this question must be addressed separately for each knowledge domain and each inquiry skill. The research reviewed here indicates that the obstacles to understanding science are nuanced, and so are their solutions. The variation in scientific reasoning across domains and contexts highlights the fact that competence hinges on the interaction between learning strategies and learning environments. By designing
environments that foster scientific curiosity (Jirout & Klahr, 2012) and encourage exploration (Callanan et al., 2020), it may be possible to stimulate scientific inquiry in adults.

References


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