ANNUAL REVIEWS

Annual Review of Developmental Psychology

Developing an Understanding of Science

Andrew Shtulman[1] and Caren Walker[2]

[1]Department of Psychology, Occidental College, Los Angeles, California 91104, USA;
email: shtulman@oxy.edu

[2]Department of Psychology, University of California, San Diego, La Jolla, California 92093, USA

Annu. Rev. Dev. Psychol. 2020. 2:111–32

First published as a Review in Advance on August 31, 2020

The *Annual Review of Developmental Psychology* is online at devpsych.annualreviews.org

https://doi.org/10.1146/annurev-devpsych-060320-092346

Keywords

conceptual development, conceptual change, intuitive theories, causal learning, inquiry skills, science education

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? We address this 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.

Contents

INTRODUCTION

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 only 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 (Natl. Sci. Board 2018, Pew Res. Cent. 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, in contrast, 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: SCIENCE AS A BODY OF 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. In the following subsections, 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 homogeneous, like solids appear to be (Chiang & Wynn 2000, Samarapungavan et al. 2017, Smith 2007).

If preschoolers are 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), 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 homogeneous) 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 nonsolids 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 sensations of warmth, such as the difference between the cloth strap and metal clasp of a seatbelt in a hot car, and warmth can change independently 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 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 random interactions at one level of a system can produce systematic patterns at a higher level of the system allows them to think of heat as emerging from matter rather than as a 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 is changes in motion (acceleration) that require 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 free fall (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 such objects 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 that 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 that it is 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 a 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 words 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 nonmoving 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 (Hickling & Gelman 1995, Stavy & Wax 1989). 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 is, 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 (Geerdts 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 2004). 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 life span, 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 twentieth 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 are 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 homogeneous, 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 children's essentialist intuitions, helping them distinguish heritable traits from nonheritable 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 seventeenth 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 dos 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 this observation 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 2009). 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 one another (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.

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 they use dependence information to infer causes, even when that evidence conflicts with their prior knowledge (Gopnik et al. 2004, Schulz et al. 2007). Cognitive developmentalists have long advanced an analogy between knowledge acquisition and theory change in science (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 et al. 2007, Ruggeri & Lombrozo 2011), and seeking out reliable informants (Mills 2013). They can rationally interpret data that are generated by the actions of others (Buchsbaum et al. 2011, Meltzoff et al. 2012), considering how the data were sampled, who sampled them, 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 the informativeness of their interventions (Stahl & Feigenson 2015, Ruggeri et al. 2017). Collectively, this research suggests that even young children have sophisticated abilities to acquire and revise 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 US National Research Council recommends that inquiry-based learning be used to teach scientific reasoning skills (Natl. Res. Counc. 2000). 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-age 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 helping children prioritize hypotheses over 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 task demands between these literatures. Although research on children's causal learning suggests that children are adept and sophisticated learners, the methods used differ 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 (1929) description of young children as perceptually bound, illogical, and precausal. 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 scholars 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). 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.

While developmental studies report early competence at causal intervention and implicit sensitivity to the informativeness of such interventions, it is not clear that school-age 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). Simple, knowledge-lean tasks may thus 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 mean 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, Stahl & Feigenson 2015, van Schijndel et al. 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 researchers, 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). 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 years) implicitly differentiate between practical and epistemic goals when selecting actions, such as the difference between feeding a mouse and learning something about the mouse's size from its food intake (Piekny & Maehler 2013, Sodian et al. 1991). 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 focused largely 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-age 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 afterward, children are still unlikely to transfer this skill to novel problems. Children's intuitive experimentation is far less systematic (Klahr 2000). Children often privilege so-called 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). 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 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 (Masnick et al. 2017, Schauble et al. 1991).

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 concerned primarily 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 strategy. 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 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 school–age 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-age 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 (Köksal-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., the act of worrying 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 et al. (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 metalevel 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 for learning not only 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 & 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, regardless 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 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 contingent on the learner's goals, as well as the trade-off between the strength of their prior beliefs 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 prior 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 counterexplanations ("Why else?"). These prompts have been found to attenuate confirmation bias in adult learners, shifting their attention 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. 2008), 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. Which learning activities are productive for bridging science and intuition is an empirical question that must be addressed separately for each knowledge domain and each inquiry skill. The research reviewed here indicates that 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. Through the design of environments that foster scientific curiosity (Jirout & Klahr 2012) and encourage exploration (Callanan et al. 2020), it may be possible to stimulate scientific inquiry across the life span.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This research was supported by an Understanding Human Cognition Scholars Award from the James S. McDonnell Foundation to Andrew Shtulman.

LITERATURE CITED

Alonzo AC, Steedle JT. 2009. Developing and assessing a force and motion learning progression. *Sci. Educ.* 93:389–421

Amsterlaw J, Wellman HM. 2006. Theories of mind in transition: a microgenetic study of the development of false belief understanding. *J. Cogn. Dev.* 7:139–72

Au TKF, Chan CK, Chan TK, Cheung M, Ho J, Ip G. 2008. Folkbiology meets microbiology: a study of conceptual and behavioral change. *Cogn. Psychol.* 57:1–19

Baillargeon R. 2004. Infants' physical world. *Curr. Dir. Psychol. Sci.* 13:89–94

Blacker KA, LoBue V. 2016. Behavioral avoidance of contagion in childhood. *J. Exp. Child Psychol.* 143:162–70

Bonawitz EB, Schijndel TJV, Friel D, Schulz L. 2012. Children balance theories and evidence in exploration, explanation, and learning. *Cogn. Psychol.* 64:215–34

Bonawitz EB, Shafto P, Gweon H, Goodman ND, Spelke E, Schulz L. 2011. The double-edged sword of pedagogy: Instruction limits spontaneous exploration and discovery. *Cognition* 120:322–30

Borst A, Egelhaaf M. 1989. Principles of visual motion detection. *Trends Neurosci.* 12:297–306

Buchsbaum D, Gopnik A, Griffiths TL, Shafto P. 2011. Children's imitation of causal action sequences is influenced by statistical and pedagogical evidence. *Cognition* 120:331–40

Bullock M, Ziegler A. 1999. Scientific reasoning: developmental and individual differences. In *Individual Development from 3 to 12: Findings from the Munich Longitudinal Study*, ed. FE Weinert, W Schneider, pp. 38–54. Cambridge, UK: Cambridge Univ. Press

Butler LP, Markman EM. 2012. Preschoolers use intentional and pedagogical cues to guide inductive inferences and exploration. *Child Dev.* 83:1416–28

Callanan M, Legare CH, Sobel DM, et al. 2020. Exploration, explanation, and parent–child interaction in museum settings. *Monogr. Soc. Res. Child Dev.* 85:1–137

Carey S. 1985. *Conceptual Change in Childhood*. Cambridge, MA: MIT Press

Carey S. 2009. *The Origin of Concepts*. Oxford, UK: Oxford Univ. Press

Chang HY, Linn MC. 2013. Scaffolding learning from molecular visualizations. *J. Res. Sci. Teach.* 50:858–86

Chen Z, Klahr D. 1999. All other things being equal: acquisition and transfer of the control of variables strategy. *Child Dev.* 70:1098–120

Chi M. 2000. Self-explaining expository texts: the dual processes of generating inferences and repairing mental models. In *Advances in Instructional Psychology: Educational Design and Cognitive Science*, ed. R Glaser, pp. 161–238. Mahwah, NJ: Erlbaum

Chi MT, Roscoe RD, Slotta JD, Roy M, Chase CC. 2012. Misconceived causal explanations for emergent processes. *Cogn. Sci.* 36:1–61

Chiang WC, Wynn K. 2000. Infants' tracking of objects and collections. *Cognition* 77:169–95

Chinn CA, Brewer WF. 1998. An empirical test of a taxonomy of responses to anomalous data in science. *J. Res. Sci. Teach.* 35:623–54

Chouinard MM, Harris PL, Maratsos MP. 2007. Children's questions: a mechanism for cognitive development. *Monogr. Soc. Res. Child Dev.* 72:1–129

Clement J. 1993. Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *J. Res. Sci. Teach.* 30:1241–57

Clement J, Brown DE, Zietsman A. 1989. Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction on students' intuitions. *Int. J. Sci. Educ.* 11:554–65

Clough E, Driver R. 1985. Secondary students' conceptions of the conduction of heat: bringing together scientific and personal views. *Phys. Educ.* 20:176–82

Coenen A, Ruggeri A, Bramley NR, Gureckis TM. 2019. Testing one or multiple: how beliefs about sparsity affect causal experimentation. *J. Exp. Psychol. Learn. Mem. Cogn.* 45:1923–41

Cook C, Goodman ND, Schulz LE. 2011. Where science starts: spontaneous experiments in preschoolers' exploratory play. *Cognition* 120:341–49

Croker S, Buchanan H. 2011. Scientific reasoning in a real-world context: the effect of prior belief and outcome on children's hypothesis-testing strategies. *Br. J. Dev. Psychol.* 29:409–24

Curtis V, Aunger R, Rabie T. 2004. Evidence that disgust evolved to protect from risk of disease. *Proc. R. Soc. B* 271:S131–33

Dar-Nimrod I, Heine SJ. 2011. Genetic essentialism: on the deceptive determinism of DNA. *Psychol. Bull.* 137:800–18

DeJesus JM, Shutts K, Kinzler KD. 2015. Eww she sneezed! Contamination context affects children's food preferences and consumption. *Appetite* 87:303–9

Denison S, Xu F. 2019. Infant statisticians: the origins of reasoning under uncertainty. *Perspect. Psychol. Sci.* 14:499–509

Duncan RG, Reiser BJ. 2007. Reasoning across ontologically distinct levels: students' understandings of molecular genetics. *J. Res. Sci. Teach.* 44:938–59

Engle J, Walker CM. 2018. Considering alternatives facilitates anomaly detection in preschoolers. In *Proceedings of the 40th Annual Conference of the Cognitive Science Society*, ed. N Miyake, D Peebles, RP Cooper, pp. 348–53. Austin, TX: Cogn. Sci. Soc.

Evans EM. 2001. Cognitive and contextual factors in the emergence of diverse belief systems: creation versus evolution. *Cogn. Psychol.* 42:217–66

Fallon AE, Rozin P, Pliner P. 1984. The child's conception of food: the development of food rejections with special reference to disgust and contamination sensitivity. *Child Dev.* 55:566–75

Frederick S. 2005. Cognitive reflection and decision making. *J. Econ. Perspect.* 19:25–42

Fugelsang JA, Thompson VA. 2003. A dual-process model of belief and evidence interactions in causal reasoning. *Mem. Cogn.* 31:800–15

Galinsky AD, Moskowitz GB. 2000. Counterfactuals as behavioral primes: priming the simulation heuristic and consideration of alternatives. *J. Exp. Soc. Psychol.* 36:384–409

Geerdts MS, Van de Walle GA, LoBue V. 2015. Daily animal exposure and children's biological concepts. *J. Exp. Child Psychol.* 130:132–46

Gelman SA, Roberts SO. 2017. How language shapes the cultural inheritance of categories. *PNAS* 114:7900–7

Gelman SA. 2003. *The Essential Child: Origins of Essentialism in Everyday Thought*. Oxford, UK: Oxford Univ. Press

Gopnik A, Glymour C, Sobel DM, Schulz LE, Kushnir T, Danks D. 2004. A theory of causal learning in children: causal maps and Bayes nets. *Psychol. Rev.* 111:3–32

Gopnik A, Wellman HM. 2012. Reconstructing constructivism: causal models, Bayesian learning mechanisms, and the theory theory. *Psychol. Bull.* 138:1085–108

Gopnik A. 2012. Scientific thinking in young children: theoretical advances, empirical research, and policy implications. *Science* 337:1623–27

Griffiths TL, Sobel DM, Tenenbaum JB, Gopnik A. 2011. Bayes and blickets: effects of knowledge on causal induction in children and adults. *Cogn. Sci.* 35:1407–55

Gropen J, Clark-Chiarelli N, Hoisington C, Ehrlich SB. 2011. The importance of executive function in early science education. *Child Dev. Perspect.* 5:298–304

Gutheil G, Vera A, Keil FC. 1998. Do houseflies think? Patterns of induction and biological beliefs in development. *Cognition* 66:33–49

Gweon H, Tenenbaum JB, Schulz LE. 2010. Infants consider both the sample and the sampling process in inductive generalization. *PNAS* 107:9066–71

Hardy I, Jonen A, Möller K, Stern E. 2006. Effects of instructional support within constructivist learning environments for elementary school students' understanding of floating and sinking. *J. Educ. Psychol.* 98:307–26

Harlow DB, Swanson LH, Nylund-Gibson K, Truxler A. 2011. Using latent class analysis to analyze children's responses to the question, "What is a day?" *Sci. Educ.* 95:477–96

Hayes BK, Goodhew A, Heit E, Gillan J. 2003. The role of diverse instruction in conceptual change. *J. Exp. Child Psychol.* 86:253–76

Herrmann P, Waxman SR, Medin DL. 2010. Anthropocentrism is not the first step in children's reasoning about the natural world. *PNAS* 107:9979–84

Hickling AK, Gelman SA. 1995. How does your garden grow? Early conceptualization of seeds and their place in the plant growth cycle. *Child Dev.* 66:856–76

Howe C, Tavares JT, Devine A. 2012. Everyday conceptions of object fall: explicit and tacit understanding during middle childhood. *J. Exp. Child Psychol.* 111:351–66

Inagaki K, Hatano G. 2004. Vitalistic causality in young children's naive biology. *Trends Cogn. Sci.* 8:356–62

Jee BD, Anggoro FK. 2019. Relational scaffolding enhances children's understanding of scientific models. *Psychol. Sci.* 30:1287–302

Jirout J, Klahr D. 2012. Children's scientific curiosity: in search of an operational definition of an elusive concept. *Dev. Rev.* 32:125–60

Kaiser MK, Proffitt DR, McCloskey M. 1985. The development of beliefs about falling objects. *Percept. Psychophys.* 38:533–39

Kalish CW. 1996. Preschoolers' understanding of germs as invisible mechanisms. *Cogn. Dev.* 11:83–106

Kelemen D, Emmons NA, Seston Schillaci R, Ganea PA. 2014. Young children can be taught basic natural selection using a picture-storybook intervention. *Psychol. Sci.* 25:893–902

Kim E, Pak SJ. 2002. Students do not overcome conceptual difficulties after solving 1000 traditional problems. *Am. J. Phys.* 70:759–65

Kimura K, Gopnik A. 2019. Rational higher-order belief revision in young children. *Child Dev.* 90:91–97

Kirschner PA, Sweller J, Clark RE. 2006. Why minimal guidance during instruction does not work: an analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educ. Psychol.* 41:75–86

Klahr D. 2000. *Exploring Science: The Cognition and Development of Discovery Processes*. Cambridge, MA: MIT Press

Klahr D, Fay AL, Dunbar K. 1993. Heuristics for scientific experimentation: a developmental study. *Cogn. Psychol.* 25:111–46

Klahr D, Nigam M. 2004. The equivalence of learning paths in early science instruction: effects of direct instruction and discovery learning. *Psychol. Sci.* 15:661–67

Klahr D, Zimmerman C, Jirout J. 2011. Educational interventions to advance children's scientific thinking. *Science* 333:971–75

Köksal-Tuncer Ö, Sodian B. 2018. The development of scientific reasoning: hypothesis testing and argumentation from evidence in young children. *Cogn. Dev.* 48:135–45

Koslowski B. 1996. *Theory and Evidence: The Development of Scientific Reasoning*. Cambridge, MA: MIT Press

Kuhn D. 2012. The development of causal reasoning. *WIREs Cogn. Sci.* 3:327–35

Kuhn D, Dean JD. 2004. Metacognition: a bridge between cognitive psychology and educational practice. *Theory Pract.* 43:268–73

Kuhn D, Dean JD. 2005. Is developing scientific thinking all about learning to control variables? *Psychol. Sci.* 16:866–70

Kuhn D, Garcia-Mila M, Zohar A, Andersen C, White SH, et al. 1995. Strategies of knowledge acquisition. *Monogr. Soc. Res. Child Dev.* 60:1–157

Kuhn D, Katz J. 2009. Are self-explanations always beneficial? *J. Exp. Child Psychol.* 103:386–94

Kuhn D, Ramsey S, Arvidsson TS. 2015. Developing multivariable thinkers. *Cogn. Dev.* 35:92–110

Lapidow E, Walker CM. 2020a. Informative experimentation in intuitive science: Children select and learn from their own causal interventions. *Cognition* 201:104315

Lapidow E, Walker CM. 2020b. The search for invariance: repeated positive testing serves the goals of causal learning. In *Language and Concept Acquisition from Infancy Through Childhood*, ed. J Childers, pp. 197–219. Berlin: Springer

Lederman JS, Lederman NG, Bartos SA, Bartels SL, Meyer AA, Schwartz RS. 2014. Meaningful assessment of learners' understandings about scientific inquiry: the Views About Scientific Inquiry (VASI) questionnaire. *J. Res. Sci. Teach.* 51:65–83

Legare CH, Lombrozo T. 2014. Selective effects of explanation on learning during early childhood. *J. Exp. Child Psychol.* 126:198–212

Legare CH, Opfer JE, Busch JT, Shtulman A. 2018. A field guide for teaching evolution in the social sciences. *Evol. Hum. Behav.* 39:257–68

Lewis EL, Linn MC. 2003. Heat energy and temperature concepts of adolescents, adults, and experts: implications for curricular improvements. *J. Res. Sci. Teach.* 40:S155–75

Masnick AM, Klahr D, Knowles ER. 2017. Data-driven belief revision in children and adults. *J. Cogn. Dev.* 18:87–109

Mason L, Zaccoletti S. 2020. Inhibition and conceptual learning in science: a review of studies. *Educ. Psychol. Rev.* **https://doi.org/10.1007/s10648-020-09529-x**

Mayer RE. 2004. Should there be a three-strikes rule against pure discovery learning? *Am. Psychol.* 59:14–19

Mayr E. 1982. *The Growth of Biological Thought*. Cambridge, MA: Harvard Univ. Press

McCloskey M. 1983. Naïve theories of motion. In *Mental Models*, ed. D Gentner, AL Stevens, pp. 299–324. Mahwah, NJ: Erlbaum

McCormack T, Bramley NR, Frosch C, Patrick F, Lagnado DA. 2016. Children's use of interventions to learn causal structure. *J. Exp. Child Psychol.* 141:1–22

McPhetres J, Rutjens BT, Weinstein N, Brisson JA. 2019. Modifying attitudes about modified foods: Increased knowledge leads to more positive attitudes. *J. Environ. Psychol.* 64:21–29

Mead LS, Mates A. 2009. Why science standards are important to a strong science curriculum and how states measure up. *Evol. Educ. Outreach* 2:359–71

Medin D, Waxman S, Woodring J, Washinawatok K. 2010. Human-centeredness is not a universal feature of young children's reasoning: Culture and experience matter when reasoning about biological entities. *Cogn. Dev.* 25:197–207

Meltzoff AN, Waismeyer A, Gopnik A. 2012. Learning about causes from people: observational causal learning in 24-month-old infants. *Dev. Psychol.* 48:1215–28

Mills CM. 2013. Knowing when to doubt: developing a critical stance when learning from others. *Dev. Psychol.* 49:404–18

Natl. Res. Counc. 2000. *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning*. Washington, DC: Natl. Acad. Press

Natl. Sci. Board. 2018. *Science & Engineering Indicators–2000*. Arlington, VA: Natl. Sci. Found.

Nenciovici L, Brault Foisy LM, Allaire-Duquette G, Potvin P, Riopel M, Masson S. 2018. Neural correlates associated with novices correcting errors in electricity and mechanics. *Mind Brain Educ.* 12:120–39

Nyhout A, Iannuzziello A, Walker CM, Ganea PA. 2019. Thinking counterfactually supports children's ability to conduct a controlled test of a hypothesis. In *Proceedings of the 41st Annual Meeting of the Cognitive Science Society*, ed. A Goel, C Seifert, C Freska, pp. 2488–94. Austin, TX: Cogn. Sci. Soc.

Pacer M, Lombrozo T. 2017. Ockham's razor cuts to the root: simplicity in causal explanation. *J. Exp. Psychol.* 146:1761–80

Penner DE, Klahr D. 1996. The interaction of domain-specific knowledge and domain-general discovery strategies: a study with sinking objects. *Child Dev.* 67:2709–27

Pew Res. Cent. 2015. *Public and scientists' views on science and society*. Rep., Pew Res. Cent., Washinton, DC

Piaget J. 1929. *The Child's Conception of the World*. London: Routledge

Piekny J, Maehler C. 2013. Scientific reasoning in early and middle childhood: the development of domain-general evidence evaluation, experimentation, and hypothesis generation skills. *Br. J. Dev. Psychol.* 31:153–79

Plummer JD, Krajcik J. 2010. Building a learning progression for celestial motion: elementary levels from an earth-based perspective. *J. Res. Sci. Teach.* 47:768–87

Potvin P, Masson S, Lafortune S, Cyr G. 2015. Persistence of the intuitive conception that heavier objects sink more: a reaction time study with different levels of interference. *Int. J. Sci. Math. Educ.* 13:21–43

Reiner M, Slotta JD, Chi MT, Resnick LB. 2000. Naive physics reasoning: a commitment to substance-based conceptions. *Cogn. Instrum.* 18:1–34

Rosander K, von Hofsten C. 2004. Infants' emerging ability to represent occluded object motion. *Cognition* 91:1–22

Rozin P, Haidt J, McCauley CR. 2008. Disgust. In *Handbook of Emotions*, ed. M Lewis, JM Haviland-Jones, LF Barrett, pp. 757–76. New York: Guilford

Ruggeri A, Lombrozo T. 2011. Children adapt their questions to achieve efficient search. *Cognition* 143:203–16

Ruggeri A, Sim ZL, Xu F. 2017. "Why is Toma late to school again?" Preschoolers identify the most informative questions. *Dev. Psychol.* 53:1620–32

Ruggeri A, Swaboda N, Sim ZL, Gopnik A. 2019. Shake it baby, but only when needed: Preschoolers adapt their exploratory strategies to the information structure of the task. *Cognition* 193:104013

Samarapungavan A, Bryan L, Wills J. 2017. Second graders' emerging particle models of matter in the context of learning through model-based inquiry. *J. Res. Sci. Teach.* 54:988–1023

Samarapungavan A, Vosniadou S, Brewer WF. 1996. Mental models of the earth, sun, and moon: Indian children's cosmologies. *Cogn. Dev.* 11:491–521

Sandoval WA, Sodian B, Koerber S, Wong J. 2014. Developing children's early competencies to engage with science. *Educ. Psychol.* 49:139–52

Saxe R, Carey S. 2006. The perception of causality in infancy. *Acta Psychol.* 123:144–65

Schauble L, Klopfer LE, Raghavan K. 1991. Students transition from an engineering model to a science model of experimentation. *J. Res. Sci. Teach.* 28:859–82

Schauble L. 1990. Belief revision in children: the role of prior knowledge and strategies for generating evidence. *J. Exp. Child Psychol.* 49:31–57

Schneider W. 2008. The development of metacognitive knowledge in children and adolescents: major trends and implications for education. *Mind Brain Educ.* 2:114–21

Scholl BJ, Pylyshyn ZW. 1999. Tracking multiple items through occlusion: clues to visual objecthood. *Cogn. Psychol.* 38:259–90

Schulz LE, Bonawitz E. 2007. Serious fun: Preschoolers engage in more exploratory play when evidence is confounded. *Dev. Psychol.* 43:1045–50

Schulz LE, Goodman ND, Tenenbaum JB, Jenkins AC. 2008. Going beyond the evidence: abstract laws and preschoolers' response to anomalous data. *Cognition* 109:211–23

Schulz LE, Gopnik A, Glymour C. 2007. Preschool children learn about causal structure from conditional interventions. *Dev. Sci.* 10:322–32

Schulz LE, Sommerville J. 2006. God does not play dice: causal determinism and children's inferences about unobserved causes. *Child Dev.* 77:427–42

Schwichow M, Croker S, Zimmerman C, Höffler T, Härtig H. 2016. Teaching the control-of-variables strategy: a meta-analysis. *Dev. Rev.* 39:37–63

Shtulman A. 2006. Qualitative differences between naïve and scientific theories of evolution. *Cogn. Psychol.* 52:170–94

Shtulman A. 2013. Epistemic similarities between students' scientific and supernatural beliefs. *J. Educ. Psychol.* 105:199–212

Shtulman A. 2017. *Scienceblind: Why Our Intuitive Theories About the World Are So Often Wrong*. New York: Basic

Shtulman A. 2019. Doubly counterintuitive: cognitive obstacles to the discovery and the learning of scientific ideas and why they often differ. In *Advances in Experimental Philosophy of Science*, ed. R Samuels, D Wilkenfeld, pp. 97–121. London: Bloomsbury

Shtulman A, Legare CH. 2020. Competing explanations of competing explanations: accounting for conflict between scientific and folk explanations. *Top. Cogn. Sci.* In press. **https://doi.org/10.1111/tops.12483**

Shtulman A, Neal C, Lindquist G. 2016. Children's ability to learn evolutionary explanations for biological adaptation. *Early Educ. Dev.* 27:1222–36

Shtulman A, Schulz L. 2008. The relation between essentialist beliefs and evolutionary reasoning. *Cogn. Sci.* 32:1049–62

Siegal M, Butterworth G, Newcombe PA. 2004. Culture and children's cosmology. *Dev. Sci.* 7:308–24

Slaughter V, Lyons M. 2003. Learning about life and death in early childhood. *Cogn. Psychol.* 46:1–30

Slotta JD, Chi MT, Joram E. 1995. Assessing students' misclassifications of physics concepts: an ontological basis for conceptual change. *Cogn. Instrum.* 13:373–400

Slotta JD, Chi MT. 2006. Helping students understand challenging topics in science through ontology training. *Cogn. Instrum.* 24:261–89

Smith CL. 2007. Bootstrapping processes in the development of students' commonsense matter theories: using analogical mappings, thought experiments, and learning to measure to promote conceptual restructuring. *Cogn. Instrum.* 25:337–98

Smith CL, Solomon GE, Carey S. 2005. Never getting to zero: elementary school students' understanding of the infinite divisibility of number and matter. *Cogn. Psychol.* 51:101–40

Smith CL, Wenk L. 2006. Relations among three aspects of first-year college students' epistemologies of science. *J. Res. Sci. Teach.* 43:747–85

Sobel DM, Erb CD, Tassin T, Weisberg DS. 2017. The development of diagnostic inference about uncertain causes. *J. Cogn. Dev.* 18:556–76

Sobel DM, Legare CH. 2014. Causal learning in children. *WIREs Cogn. Sci.* 5:413–27

Sobel DM, Letourneau SM. 2018. Preschoolers' understanding of how others learn through action and instruction. *Child Dev.* 89:961–70

Sodian B, Zaitchik D, Carey S. 1991. Young children's differentiation of hypothetical beliefs from evidence. *Child Dev.* 62:753–66

Solomon GE, Cassimatis NL. 1999. On facts and conceptual systems: young children's integration of their understandings of germs and contagion. *Dev. Psychol.* 35:113–26

Solomon GE, Johnson SC, Zaitchik D, Carey S. 1996. Like father, like son: young children's understanding of how and why offspring resemble their parents. *Child Dev*. 67:151–71

Sousa P, Atran S, Medin D. 2002. Essentialism and folkbiology: evidence from Brazil. *J. Cogn. Cult.* 2:195–223

Spelke ES. 1994. Initial knowledge: six suggestions. *Cognition* 50:431–45

Springer K. 1995. Acquiring a naive theory of kinship through inference. *Child Dev*. 66:547–58

Stahl AE, Feigenson L. 2015. Observing the unexpected enhances infants' learning and exploration. *Science* 348:91–94

Stavy R, Wax N. 1989. Children's conceptions of plants as living things. *Hum. Dev.* 32:88–94

Tardiff N, Bascandziev I, Carey S, Zaitchik D. 2020. Specifying the domain-general resources that contribute to conceptual construction: evidence from the child's acquisition of vitalist biology. *Cognition* 195:104090

Tenenbaum JB, Griffiths TL, Kemp C. 2006. Theory-based Bayesian models of inductive learning and reasoning. *Trends Cogn. Sci.* 10:309–18

Thagard P. 2000. *How Scientists Explain Disease*. Princeton, NJ: Princeton Univ. Press

Tschirgi JE. 1980. Sensible reasoning: a hypothesis about hypotheses. *Child Dev*. 51:1–10

Valanides N, Papageorgiou M, Angeli C. 2014. Scientific investigations of elementary school children. *J. Sci. Educ. Technol.* 23:26–36

van der Graaf J, Segers E, Verhoeven L. 2016. Scientific reasoning in kindergarten: cognitive factors in experimentation and evidence evaluation. *Learn. Individ. Differ.* 49:190–200

van Schijndel TJV, Visser I, Bers BMV, Raijmakers ME. 2015. Preschoolers perform more informative experiments after observing theory-violating evidence. *J. Exp. Child Psychol.* 131:104–19

Venkadasalam VP, Ganea PA. 2018. Do objects of different weight fall at the same time? Updating naive beliefs about free-falling objects from fictional and informational books in young children. *J. Cogn. Dev.* 19:165–81

Venville G, Gribble SJ, Donovan J. 2005. An exploration of young children's understandings of genetics concepts from ontological and epistemological perspectives. *Sci. Educ.* 89:614–33

Vosniadou S, ed. 2009. *International Handbook of Research on Conceptual Change*. New York: Routledge

Vosniadou S, Brewer WF. 1992. Mental models of the earth: a study of conceptual change in childhood. *Cogn. Psychol.* 24:535–85

Vosniadou S, Ioannides C, Dimitrakopoulou A, Papademetriou E. 2001. Designing learning environments to promote conceptual change in science. *Learn. Instrum.* 11:381–419

Vosniadou S, Pnevmatikos D, Makris N, Lepenioti D, Eikospentaki K, et al. 2018. The recruitment of shifting and inhibition in on-line science and mathematics tasks. *Cogn. Sci.* 42:1860–86

Walker CM, Bonawitz E, Lombrozo T. 2017. Effects of explaining on children's preference for simpler hypotheses. *Psychon. Bull. Rev.* 24:1538–47

Walker CM, Gopnik A. 2014. Toddlers infer higher-order relational principles in causal learning. *Psychol. Sci.* 25:161–69

Walker CM, Lombrozo T, Legare CH, Gopnik A. 2014. Explaining prompts children to privilege inductively rich properties. *Cognition* 133:343–57

Walker CM, Lombrozo T, Williams JJ, Rafferty AN, Gopnik A. 2016. Explaining constrains causal learning in childhood. *Child Dev*. 88:229–46

Walker CM, Lombrozo T. 2017. Explaining the moral of the story. *Cognition* 167:266–81

Walker CM, Nyhout A. 2020. Asking "why?" and "what if?": the influence of questions on children's inferences. In *The Questioning Child: Insights from Psychology and Education*, ed. L Butler, S Ronfard, K Corriveau, pp. 252–80. Cambridge, UK: Cambridge Univ. Press

Walker CM, Rett A, Bonawitz E. 2020. Design drives discovery in causal learning. *Psychol. Sci.* 31:129–38

Ware EA, Gelman SA. 2014. You get what you need: an examination of purpose-based inheritance reasoning in undergraduates, preschoolers, and biological experts. *Cogn. Sci.* 38:197–243

Weissman MD, Kalish CW. 1999. The inheritance of desired characteristics: children's view of the role of intention in parent–offspring resemblance. *J. Exp. Child Psychol.* 73:245–65

Williams JJ, Lombrozo T. 2010. The role of explanation in discovery and generalization: evidence from category learning. *Cogn. Sci.* 34:776–806

Xu F, Garcia V. 2008. Intuitive statistics by 8-month-old infants. *PNAS* 105:5012–15

Xu F. 2019. Towards a rational constructivist theory of cognitive development. *Psychol. Rev.* 126:841–64

Young AG, Shtulman A. 2020a. Children's cognitive reflection predicts conceptual understanding in science and mathematics. *Psychol. Sci.* In press

Young AG, Shtulman A. 2020b. How children's cognitive reflection shapes their science understanding. *Front. Psychol.* 11:1247

Zaitchik D, Iqbal Y, Carey S. 2014. The effect of executive function on biological reasoning in young children: an individual differences study. *Child Dev.* 85:160–75

Zaitchik D, Solomon GE. 2008. Animist thinking in the elderly and in patients with Alzheimer's disease. *Cogn. Neuropsychol.* 25:27–37

Zimmerman C. 2007. The development of scientific thinking skills in elementary and middle school. *Dev. Rev.* 27:172–223

Zimmerman C, Cuddington K. 2007. Ambiguous, circular and polysemous: students' definitions of the "balance of nature" metaphor. *Public Underst. Sci.* 16:393–406

Annual Review of Developmental Psychology

Volume 2, 2020

Contents

Errata

An online log of corrections to *Annual Review of Developmental Psychology* articles may be found at http://www.annualreviews.org/errata/devpsych