Tensions Between Science and Intuition in School-Age Children

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Abstract

Adults with extensive science education exhibit cognitive conflict when reasoning about counterintuitive scientific ideas, such as whether clouds have weight or whether bacteria need nutrients. Here, we investigated whether elementary-school-aged children show the same conflict and whether that conflict can be reduced by targeted instruction. Seventy-eight 5- to 12-year-olds verified, as quickly as possible, statements about life and matter before and after a tutorial on the scientific properties of life or matter. Half the statements were consistent with intuitive theories of the domain (e.g., "frogs reproduce") and half were inconsistent (e.g., "cactuses reproduce"). Participants verified the latter less accurately and more slowly than the former, both before instruction and after. Instruction increased the accuracy of participants' verifications for counterintuitive statements within the domain of instruction but not their speed. These results indicate that children experience conflict between scientific and intuitive conceptions of a domain in the earliest stages of acquiring scientific knowledge but can learn to resolve that conflict in favor of scientific conceptions.

Keywords: conceptual development, scientific reasoning, explanatory coexistence, intuitive theories

Introduction

Our first theories of natural phenomena are often incompatible with the scientific theories we learn later in life. We first conceive of heat as an invisible substance that flows in and out of objects rather than kinetic energy at the molecular level (Reiner, Slotta, Chi, & Resnick, 2000). We conceive of forces as properties imparted to objects, propelling them forward, rather than as interactions between objects, changing their velocity (McCloskey, 1983). Colds and flus are thought to be caused by cold air rather than a virus (Au et al., 2008). And lunar phases are thought to be caused by the earth's shadow on the moon rather than our changing view of the moon's illuminated surface (Trundle, Atwood, & Christopher, 2002).

Our first theories are known as folk theories, naïve theories, or intuitive theories. They are developed by children from a variety of inputs, including innate biases, firsthand experience, cultural artifacts, and cultural beliefs (Carey, 2009; Shtulman, 2017; Vosniadou, 1994). Intuitive theories play the same inferential role as scientific theories, helping us explain past events, predict future events, and intervene on present events (Gopnik & Wellman, 2012). They differ from scientific theories, however, in that they carve up the world into entities and processes that do not align with the true causes of natural phenomena.

One well-studied example of intuitive theories are children's theories of life (Hatano & Inagaki, 1994; Slaughter & Lyons, 2003; Stavy & Wax, 1989). Life is a metabolic state—the consumption of energy to further an organism's survival and reproduction—but young children do not know of the internal components of organisms that make metabolism possible. In the absence of such knowledge, they interpret "life," "living," and "alive" as descriptions of motion. Entities that move on their own are deemed alive, regardless of their metabolic status. Thus, preschoolers mistakenly classify moving but nonliving entities, like the sun and the clouds, as alive, and they mistakenly classify living but nonmoving objects, like plants and trees, as not alive. These mistakes persist until children conceive of life as supported by the interrelated functions of internal organs, typically by age ten.

Another well-studied example are children's theories of matter (Carey, 1991; Nakhleh, Samarapungavan, & Saglam, 2005; Smith, 2007). Matter is anything composed of atoms, but many such substances betray no perceptible sign of their underlying composition. Gases, vapors, and microscopic objects are all composed of atoms, but children can neither see them nor hold them, so they classify them as nonmaterial. They also deny that such entities have weight or take up space. Children also make the converse mistake of classifying nonmaterial entities that they can see or feel as matter, including echoes, shadows, and heat. This pattern persists until early adolescence, when children learn a particulate theory of matter in introductory physical science.

Learning to reinterpret phenomena covered by an intuitive theory through the lens of a scientific theory requires conceptual change, or knowledge revision at the level of individual concepts. Conceptual change has traditionally been viewed as a process of restructuring and replacement (Carey, 1985; Chi, 1992; Nersessian, 1989; Vosniadou, 1994). Intuitive theories are restructured to accommodate counterintuitive scientific information and are thus replaced in the process, in the same way that remodeling a house erases the footprint of its original layout.

This view has been challenged by recent research revealing that intuitive theories are not entirely erased by scientific theories and will, in fact, influence domain-relevant reasoning under cognitive load or cognitive impairment. In the domain of life, for instance, college undergraduates instructed to classify entities as "alive" or "not alive" as quickly as possible are prone to make the kinds of mistakes preschoolers make, classifying moving but nonliving things as alive and living but nonmoving things as not alive (Goldberg & Thompson-Schill, 2009). That is, undergraduates are less accurate at classifying plants as alive relative to animals, and they are less accurate at classifying dynamic objects (like clocks, geysers, comets, and rivers) as not alive relative to static ones. They are also slower to do so. Similar results have been found for Alzheimer's patients with moderate dementia, who not only misclassify moving but nonliving entities as alive but also explicitly define life in terms of motion rather than metabolic activity (Zaitchik & Solomon, 2008). Even elderly adults without Alzheimer's Disease are inclined to make these errors (Tardiff, Bascandziev, Sandor, Carey, & Zaitchik, 2017), indicating that motion-based conceptions of life are pervasive across the lifespan and must be inhibited to reason about life as a metabolic process.

Early intuitions about matter also reemerge under cognitive load. Adults instructed to decide whether something is material or nonmaterial as quickly as possible will mistakenly classify gases and heft-less objects, like dust and snowflakes, as nonmaterial and mistakenly classify perceptible forms of energy, like rainbows and lightning, as material (Shtulman & Legare, 2019). Adults also make systematic mistakes in deciding whether an object will sink or float. An object's buoyancy is related to its density—a property that makes sense only if matter is composed of smaller particles. When adults are shown two balls of equal size, one made of wood and one made of lead, they judge that the wood ball is more likely to float than the lead one. But shown a large ball of wood and a small ball of lead, they take reliably longer to make the same judgment (Potvin & Cyr, 2017; Potvin, Masson, Lafortune, & Cyr, 2015).

Research over the past decade has revealed that this pattern is widespread (Shtulman & Lombrozo, 2016). Adults verify counterintuitive scientific ideas more slowly and less accurately than closely-matched intuitive ones in several domains, including astronomy, genetics, mechanics, thermodynamics, and evolution (Shtulman & Harrington, 2016; Shtulman & Valcarcel, 2012). And these effects been observed in several populations, including high schoolers (Babai, Sekal, & Stavy, 2010), undergraduate science majors (Foisy, Potvin, Riopel, & Masson, 2015), high school science teachers (Potvin & Cyr, 2017), and elderly adults (Barlev, Mermelstein, & German, 2018). Even professional physicists (Kelemen, Rottman, & Seston, 2013) and professional biologists (Goldberg & Thompson-Schill, 2009) exhibit cognitive conflict when reasoning about counterintuitive scientific ideas. Such conflict indicates that early intuitions about natural phenomena survives the acquisition of scientific knowledge in some form or another.

In previous research (Young, Laca, Dieffenbach, Hossain, Mann, & Shtulman, 2018), we sought to determine whether participants could be trained to verify counterintuitive scientific ideas more quickly and more accurately. We focused our investigation on statements about life and statements about matter. Some statements were intuitive (e.g., "bricks have weight," "goats need nutrients"), and others were counterintuitive (e.g., "dust has weight," "yeast needs nutrients"). Participants completed this task before and after a tutorial on the scientific properties of life or matter. The tutorials helped participants close the gap in accuracy between intuitive and counterintuitive statements within the domain of instruction but not the gap in latency. In other words, the tutorials were ineffective at reducing the immediate conflict elicited by counterintuitive statements (as indexed by response times), but they did help participants favor scientific responses over intuitive ones.

In the present study, we extended this line of research to elementary-school-aged children. Our motivation was threefold. First, children are in the earliest stages of learning science, and it's unclear whether their nascent scientific theories would pose a measurable challenge to their well-worn intuitive theories of the same phenomena. Second, any conflict that children experience between science and intuition may be more malleable than that experienced by adults, either because children's scientific theories are less developed (and thus more easily bolstered) or because their intuitive theories are less entrenched. Third, adapting our task for use with children may have pedagogical value if it proves to be an informative measure of early science learning or early scientific reasoning.

Our study followed the same protocol as Young et al. (2018), which included a pretest, a tutorial, and a posttest. At pretest, we expected children to show conflict between science and intuition, given that the children in our age range were beginning to learn about life and matter in school, but it was an open question whether that conflict would manifest itself in both response accuracy and response latency. Children might, for instance, verify counterintuitive statements less accurately than intuitive ones but show no difference in speed. At posttest, we expected children to verify counterintuitive statements more accurately within the domain of instruction, but it was an open question whether they would also verify those statements more quickly.

Method

Participants

Seventy-eight children in kindergarten through 6th grade participated. Their mean age was 8 years and 7 months, and they were approximately balanced for gender (37 female, 41 male). Children were recruited from public playgrounds and a children's museum, and they completed the study onsite.

Materials

Statement-Verification Task. We measured the conflict between science and intuition using a child-modified version of Shtulman and colleagues' statement-verification task. Children were presented with four types of scientific statements and asked to judge those statements as "true" or "false" as quickly as possible. Some statements were true from both a scientific perspective and an intuitive perspective ("tigers need nutrients"); some were false from both perspectives ("forks need nutrients"); some were true from a scientific perspective but false from an intuitive perspective ("bacteria need nutrients"), and some were false from a scientific perspective but true from an intuitive perspective ("fire needs nutrients"). The first two types of statements will be referred to as *intuitive* and the latter two types as *counterintuitive*.

For each domain, statements were generated by pairing three predicates with 32 entities. In the domain of life, the predicates were "reproduces," "needs nutrients," and "grows and develops." In the domain of matter, the predicates were "has weight," "takes up space," and "is made of atoms." The biological predicates apply to all living things, but we predicted that children would be more inclined to apply them to entities that appear to move on their own. Likewise, the physical predicates apply to all material things, but we predicted that children would be more inclined to apply them to entities that can be seen or felt. These predictions were derived from prior work with adults (Young et al., 2018), as well as the extensive literatures on intuitive theories of life and matter referenced above.

We created the four types of statements by pairing predicates with four types of entities, as shown in Table 1. In the domain of life, those entities were animals (deemed alive by both science and intuition), inanimate artifacts and inanimate natural kinds (deemed alive by neither science nor intuition), plants and microorganisms (deemed alive by science but not by intuition), and animate natural kinds (deemed alive by intuition but not science). In the domain of matter, those entities were physical objects (deemed material by both science and intuition), abstract ideas (deemed material by neither science nor intuition), gases and other bulk-less or heft-less objects (deemed material by science but not by intuition), and the visible or tangible components of energy transfer (deemed material by intuition but not science).

Children completed the task on an iPad. Statements were displayed on the screen and children responded via touch screen. Twenty-two children opted into a version of the task that played audio recordings of the statements as they were displayed on the screen, thus supporting children who had difficulty reading independently. Audio recordings of each statement were generated via Apple's macOS text-to-speech engine. Children who listened to the audio-recorded stimuli received only four of the six predicates (randomly selected), due to the additional time required to play the recordings.

Tutorials. Children completed a tutorial on life or matter midway through the experiment. The tutorial on life emphasized that all living things need energy and nutrients, grow and develop, react to stimuli in their environment, and reproduce. It also addressed the misconception that life is synonymous with self-directed motion, providing examples of entities that do not appear to move on their own but are alive (e.g., moss) and entities that move on their own but are not alive (e.g., comets). The tutorial on matter emphasized that all matter occupies space, has weight, is made of atoms, and can undergo phase transitions. It also addressed the misconception that matter is synonymous with visibility or tangibility, providing examples of entities that cannot be seen or felt but are material (e.g., gases) and entities that can be seen or felt but are not material (e.g., lightning). Both tutorials contained a mixture of text, images, and videos and took approximately seven minutes to complete.

Table 1: Sample items used in the biological statements (top) and physical statements (bottom), organized by their role in scientific and intuitive views of the domain.

Is it alive?	Intuition: Yes	Intuition: No
Science: Yes	Rabbits Turtles Snails	Mushrooms Grass Bacteria
Science: No	Sun Wind Fire	Hammers Caves Shells

Is it matter?	Intuition: Yes	Intuition: No
Science: Yes	Bricks Ice Logs	Smoke Snowflakes Air
Science: No	Rainbows Shadows Heat	Dreams Songs Numbers

Procedure

Each study session proceeded in three phases. First, children verified 48 statements about life and 48 statements about matter (pretest). Next, they completed a tutorial on life or matter. Last, they verified 48 additional statements about life and 48 additional statements about matter (posttest). Children were randomized to tutorial condition—41 received the tutorial on life and 37 received the tutorial on matter.

Children completed the pretest and posttest in blocks. They saw a screen introducing a particular predicate (e.g., "Does it grow and develop?"), followed by 16 statements with that predicate (e.g., "Seaweed grows and develops"). Four of the statements were scientifically and intuitively true; four were scientifically and intuitively false; four were scientifically true but intuitively false; and four were scientifically false but intuitively true. The statements were randomly ordered within a block, and the blocks were randomly ordered within the testing phase, meaning that biological and physical predicates were intermixed. Children saw the same predicates at pretest and posttest, but those predicates were paired with 16 new entities. The entities presented at pretest for half the children were presented at posttest for the other half and vice versa. This variable was crossed with whether children received the tutorial on life or the tutorial on matter to ensure that the effects of the tutorial were not confounded with the effects of particular pretest or posttest items.

Results

The statement-verification task yielded two outcome measures: response accuracy and response latency. We analyzed each outcome with a linear mixed model (LMM), with statement type (intuitive or counterintuitive), test (pretest or posttest), instruction (instructed or uninstructed), and their interactions as fixed effects and by-participant and by-predicate random effects. The response latency model additionally adjusted for whether children read or listened to the statements. Models with maximal random effects structures had convergence issues, and thus we followed the procedure recommended by Bates, Kliegl, Vasishth, and Baayen (2015) to guide removal of random effects that were not supported by the data. Inference for fixed effects was carried out via Type 3 likelihood ratio test (LRT) model comparison.

The present analyses collapse across tutorial domain (life or matter) for lack of space and focus instead on whether the statements were targeted by instruction or not. Children did verify biological statements more accurately than physical statements (87% vs. 75%). However, mean response latencies were similar across domains, as were the effects of the tutorial.

Finally, we did not consider age effects in the following analyses. In general, older children were more accurate, faster, and learned more from instruction. However, the overall pattern of reported results was similar across the age distribution of our sample.

Response Accuracy

As seen in Figure 1, there was an effect of statement type, such that children verified intuitive statements more accurately than counterintuitive statements, LRT $\chi^2(1)$ = 12.18, $p < .001$. Overall, accuracy for intuitive statements was 18.4% greater than accuracy for counterintuitive statements, 95% CI [12.1, 24.7].

Additionally, there was a three-way interaction between statement type, test period, and instruction, LRT $\chi^2(1)$ = 25.17, $p < .001$. We were specifically interested in children's response to instruction. In the instructed domain, children's posttest accuracy for counterintuitive statements was 11.9% greater than their pretest performance, 95% CI [9.4, 14.4]. However, pretest and posttest scores were similar for intuitive statements in the instructed domain and similar for both statements types in the uninstructed domain. Thus, instruction was effective at improving children's accuracy at verifying counterintuitive scientific ideas within the targeted domain.

Response Latency

Following prior research, we analyzed response latencies for correctly verified statements only. Before doing so, we first removed latencies shorter than 250 ms, as responses produced that quickly were unlikely to have been deliberate. Second, we calculated the mean response latency across participants and statements (M = 2743 ms) and removed latencies more than two standard deviations above the mean (i.e., latencies greater than 7565 ms). We then calculated the mean latency for each predicate, separating intuitive statements from counterintuitive statements and pretest statements from posttest statements.

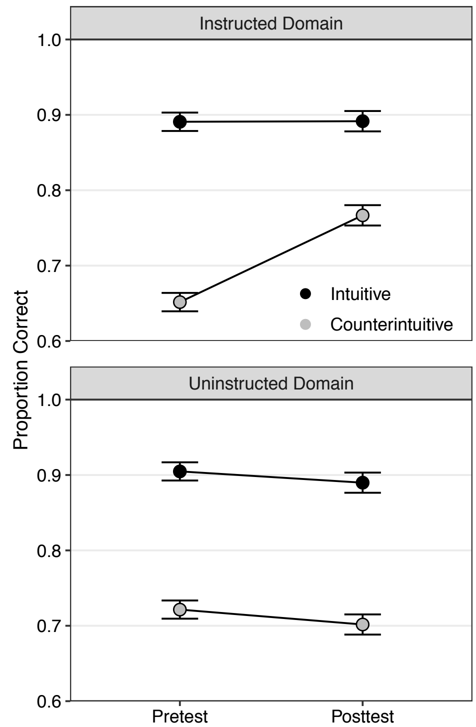

Figure 1: Estimated proportion of correct verifications by statement type, test, and instruction. Error bars represent standard errors.

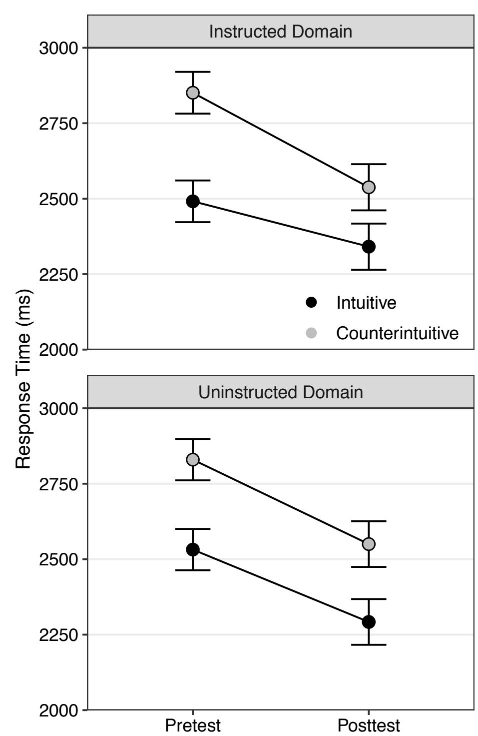

Figure 2: Estimated response latency for correct verifications by statement type, test, and instruction. Error bars represent standard errors.

As seen in Figure 2, there was an effect of statement type, such that children correctly verified counterintuitive statements more slowly than intuitive statements, LRT $\chi^2(1) = 90.16$, $p < .001$. Response latencies for counterintuitive statements were 278 ms slower than response latencies for intuitive statements, 95% CI [222, 335].

Additionally, there was an effect of test, such that children correctly verified statements faster at posttest than pretest, LRT $\chi^2(1) = 6.22$, $p = .013$. Response latencies at posttest were 246 ms faster than response latencies at pretest, 95% CI [70, 421]. We suspect this effect was due to increased familiarity with the task, as it did not vary by instruction and statement type (three-way interaction: LRT $\chi^2(1) = 1.14$, $p = .285$).

Discussion

Do elementary schoolers exhibit cognitive conflict when reasoning about counterintuitive scientific ideas? Our findings suggest they do. Children between ages five and twelve were slower and less accurate at verifying scientific statements that conflict with their intuitive theories of life or matter (e.g., "bacteria grow and develop," "steam is made of atoms") relative to closely-matched statements that accord with those theories (e.g., "tigers grow and develop," "rocks are made of atoms"). Instructing children on the scientific properties of life or matter increased their accuracy for counterintuitive statements in the instructed domain but not in the uninstructed domain. However, instruction did not reduce the gap in response latency between counterintuitive and intuitive statements, at least in comparison to the uninstructed domain. These findings indicate that children experience conflict between scientific ideas and intuitive ideas, despite limited exposure to science, but this conflict can be resolved in favor of scientific ideas with targeted instruction.

Our findings parallel those of Young et al. (2018), who administered the same task to adults. Adults were faster and more accurate overall, but both children and adults verified counterintuitive statements more slowly and less accurately than closely-matched intuitive statements. The effect of instruction was also similar across age groups, increasing participants' accuracy at verifying counterintuitive statements but not their speed. Thus, the same signatures of cognitive conflict observed in adults were observed in children ten to fifteen years younger.

Our findings accord with other findings on the speed and accuracy of children's scientific reasoning, documented by Vosniadou et al. (2018). Vosniadou and colleagues asked third- and fifth-graders to sort physical and biological items into one of two categories: a category that emphasized the item's intuitive features or a category that emphasized its scientific features. The categories were characterized by exemplars rather than by labels. For instance, on one trial participants decided whether water should be grouped with other liquids (coke, lemonade, milk) or with other forms of H_2O (ice, vapor, snow). Children of all ages preferred intuitive categories over scientific categories, and they took longer to make their judgments when they opted for the scientific category instead. Vosniadou et al.'s findings, like our findings, suggest that children must suppress an intuitive conception of the target item in order to endorse a competing scientific conception.

Vosniadou and colleagues did not administer a tutorial to their participants, and it's open question whether instructing participants on the scientific properties of the target items would change the nature of their categorizations. They did, however, measure executive function skills—namely, set-shifting ability and inhibitory control—and they found that children with higher executive function were more likely to categorize the target items by their scientific properties and were also faster to do so. Children with higher executive function have also been found to learn more from science instruction in the domain of vitalist biology (Bascandziev, Tardiff, Zaitchik, & Carey, 2018). Future research is needed to determine whether executive function plays a role in children's statement verifications as well. If it does, executive function tasks could be administered alongside our statement-verification task as a diagnostic for assessing young children's understanding of science and their receptiveness to science instruction.

One limitation of the current study is that we sampled children who had already begun learning the scientific properties of life and matter in school. Younger children (i.e., preschoolers) would likely show a different pattern of results. Without any scientific knowledge of life or matter, they should view statements like "bubbles have weight" and "dandelions need nutrients" as demonstrably false. Their accuracy for such statements would be lower, but their responses should be faster. Thus, in comparison to older children, younger children should show a larger gap in response accuracy between intuitive and counterintuitive statements but a smaller gap in response latency. And teaching preschoolers about the scientific properties of life or matter should increase the gap in latency, not reduce it. There are challenges, however, to adapting the task for use with preschoolers. Preschoolers are unlikely to know the meaning of terms like "atoms," "nutrients," and "reproduces," and the alternative terms they do know may not carry the same meaning. "Has babies," for example, may not be a substitute for "reproduces" because the offspring of plants, fungi, and bacteria are rarely referred to as "babies."

In conclusion, we have shown that tensions between science and intuition emerge early in the acquisition of scientific knowledge. While children can be taught to privilege scientific ideas over intuitive ones, the conflict between them—as manifested in slower response times for statements that elicit both ideas—appears to be immediate and robust.

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