

Children's Ability to Learn Evolutionary Explanations for Biological Adaptation

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ABSTRACT

Research Findings: Evolution by natural selection is often relegated to the high school curriculum on the assumption that younger students cannot grasp its complexity. We sought to test that assumption by teaching children ages 4–12 ($n = 96$) a selection-based explanation for biological adaptation and comparing their success to that of adults ($n = 30$). Participants provided explanations before and after a 10-min, analogy-based tutorial illustrating the principles of variation, differential survival, differential reproduction, inheritance, and population change. Although younger children (ages 4–6) showed minimal evidence of learning these principles, older children (ages 7–12) showed robust evidence of doing so, learning them at rates equivalent to adults. Participants of all ages, however, provided nonevolutionary explanations for biological adaptations (i.e., explanations referencing need, growth, and creation) nearly as often at posttest as they did at pretest. *Practice or Policy:* These results suggest that older elementary school-age children can be taught evolutionary concepts but that learning such concepts does not lead to the automatic replacement of nonevolutionary views of biological adaptation, which must be addressed separately.

Evolution by natural selection is the theory that unifies all biological phenomena, yet evolution is rarely taught to children. Children are expected to begin their biology education without reference to the very principles that structure and organize the field. The U.S. National Research Council, for instance, recommends that elementary school students learn about anatomy, physiology, taxonomy, and ecology but not evolution (National Academy of Sciences, 2013). Evolution is recommended for inclusion only in the high school curriculum. Ideas *related to* evolution are recommended for inclusion in the elementary school curriculum (e.g., heredity, biodiversity, trait variation, extinction), but evolution itself is waylaid for several years. The consequence of this recommendation is that children learn about biological systems (e.g., life cycles, food chains, symbiosis) and biological processes (e.g., digestion, respiration, reproduction) without reference to the historical pressures that gave rise to those phenomena and thus without explanation for their form or function.

Some children may never learn those explanations, even in high school, as evolution is either taught poorly or not taught at all. A recent survey of U.S. high school biology teachers found that only 28% teach evolution as an uncontroversial fact, supported by ample data. Most teachers (60%) avoid the topic as much as possible, and some (12%) explicitly advocate for creationism (Berkman & Plutzer, 2011; see also Nehm, Kim, & Sheppard, 2010). The scientific community has recognized, for several decades now, that “nothing in biology makes sense except in the light of evolution” (Dobzhansky, 1973), yet many students learn biology in the absence of such light.

One reason why children are shielded from the concept of evolution is that evolution is a controversial topic (Blancke, De Smedt, De Cruz, Boudry, & Braeckman, 2012; Lombrozo,

Shtulman, & Weisberg, 2006). Most U.S. citizens deny that humans have evolved from nonhuman ancestors strictly by natural means, favoring either creationist explanations or quasi-creationist explanations in which God guides evolutionary change (Newport, 2010). Many people also see evolution as antithetical to positive social values, like altruism, equality, and self-determination (Brem, Ranney, & Schindel, 2003). But controversy surrounding evolution is not the only reason why children are shielded from the concept. Another is that evolution is difficult to understand, and children are viewed by many as cognitively ill-equipped to handle that complexity (Carmichael, 2009).

Dozens of studies have shown that evolution is difficult to understand even for college-educated adults (for reviews, see Gregory, 2009; Kampourakis, 2014; Shtulman & Calabi, 2012). Evolution, or population-level changes in the frequency of heritable traits, is driven by selection, or the differential survival and reproduction of the varied organisms within a population, yet most adults do not conceive of evolution in these terms. Rather, most adults conceive of evolution as the uniform transformation of all members of the species, with each organism producing offspring more adapted to the environment than the organism itself was at birth. According to this view, mutations are not random; they occur in a direction that would benefit the organism, and all organisms within the population are assumed to acquire the same mutations at the same time (Bishop & Anderson, 1990; Brumby, 1984; Shtulman, 2006; Shtulman & Calabi, 2013; Shtulman & Schulz, 2008).

Underlying this misconceived view of evolution are three widespread and early developing inductive biases: teleology, essentialism, and intentionality. *Teleology* is the idea that an organism's traits can be explained by their function (Kelemen, 2012; Lombrozo & Carey, 2006). Teleology allows people to recognize that wings exist for flying and that lungs exist for breathing, but it causes them to ignore the historical origin of those traits (i.e., selection over a population of individuals who once possessed only the precursors of those traits). *Essentialism* is the idea that an organism's traits are byproducts of its hidden nature or essence (Gelman, 2003; Gelman & Rhodes, 2012). Essentialism allows people to recognize that gray baby flamingos will grow to be pink and that flat-nosed baby rhinos will grow to have horns, but it causes them to ignore variation in those traits and the consequences of such variation (i.e., differential survival and differential reproduction). And *intentionality* is the idea that organisms act on the environment in ways that further their goals and desires (Evans, 2008; Johnson, 2000). Intentionality allows people to recognize that holes in the beach are the handiwork of crabs and dams in the river are the handiwork of beavers, but it causes them to interpret crabs and beavers as intentionally designed themselves (e.g., by a divine force or divine intelligence). Intentionality can also cause people to assume that evolution is driven by the intentions of the evolving organisms (Legare, Lane, & Evans, 2013).

Each of these biases serves a valuable function when applied to the properties of individual organisms but can lead to misconceptions when applied to the properties of entire species, causing adults to misconceive evolution (Sinatra, Brem, & Evans, 2008). These biases are widespread and early developing, emerging prior to any formal instruction in biology (Coley & Tanner, 2012). Children are thus vulnerable to the same kinds of evolutionary misconceptions as those observed among adults. Indeed, young elementary school-age children have been shown to prefer intentional (i.e., creationist) explanations of biological adaptation to evolutionary explanations (Evans, 2001), and older elementary school-age children have been shown to prefer essentialist explanations (Samarapungavan & Wiers, 1997) and teleological explanations (Berti, Toneatti, & Rosati, 2010) to strictly selection-based explanations.

Evolution is thus difficult to grasp at all ages, but no study has shown that evolution is *more difficult* to grasp at younger ages than at older ages. Evolution may actually be easier to grasp at younger ages, before children have acquired as much experience viewing the biological world through the lenses of teleology, essentialism, and intentionality. When students are introduced to evolution in high school (or college), they have spent more than a decade of their lives reasoning about biological phenomena in explicitly nonevolutionary terms. Introducing younger students to evolution could potentially bypass this obstacle, as they have yet to encode as much biological information in those terms. Children are predisposed to construing biological traits as purpose-based, nonvariable, and intentionally designed,

just as adolescents and adults are, but they may have less conceptual baggage to work through on the whole (see Kelemen, Emmons, Schillaci, & Ganea, 2014, for a similar argument).

To date, no studies have compared children's receptiveness to evolutionary ideas to that of adults. However, two studies have explored whether children can be taught evolutionary ideas at all. In the first, Legare et al. (2013) provided children between the ages of 5 and 12 with explanations for biological adaptation that illustrated five key evolutionary principles: variation, inheritance, selection, time, and adaptation. Some children received explanations cloaked in anthropomorphic, desire-based language (e.g., "some eagles *wanted* to change," "they *tried* to be bigger"); some received explanations cloaked in teleological, need-based language (e.g., "some eagles *needed* to change," "they *needed* to be bigger"); and some received explanations containing only selection-based language (e.g., "chicks that were bigger lived longer, and they had more chicks").

After listening to three sample explanations, children were asked to reiterate those explanations. Children who had received desire-based explanations recalled significantly fewer evolutionary principles than those who had received need-based or selection-based explanations. These findings indicate that children can encode and recall evolutionary explanations, particularly if those explanations are framed in non-anthropomorphic terms, but they do not indicate whether children can generate those explanations on their own.

Following Legare et al. (2013), Kelemen et al. (2014) documented that children can indeed generate evolutionary explanations on their own. These researchers read a storybook illustrating an evolutionary explanation of biological adaptation to children between the ages of 5 and 8. The biological adaptation was novel—the evolution of thin trunks in a fictional species of elephant-like creatures ("pilosas")—and the explanation for its origin entailed six concepts: trait variation, resource limitation, differential survival, differential reproduction, trait inheritance, and population-level changes in trait frequency. Following the storybook, children were asked to explain two new instances of biological adaptation, one presented that same day (an immediate posttest) and another presented 3 months later (a delayed posttest).

Children's explanations were elicited in the form of a clinical interview consisting of five closed-ended questions and five open-ended questions. Responses to the interview were coded for one of five levels of understanding, ranging from no retention of the instructional materials (Level 0), to retention of isolated facts (Level 1), to understanding differential survival but not differential reproduction (Level 2), to understanding differential survival and differential reproduction in one generation but not multiple generations (Level 3), to understanding differential survival and differential reproduction across multiple generations and thus how these processes give rise to population-level change (Level 4).

The researchers found that children's understanding of evolution increased dramatically with the intervention. Before the intervention, only around 10% of 5- and 6-year-olds and 40% of 7- and 8-year-olds were able to articulate a Level 2 understanding of evolution or better. After the intervention, those figures rose to 40% and 90%, respectively, both at the immediate posttest and delayed posttest. That said, few children were able to articulate a Level 4 understanding at posttest; most went from a Level 0 understanding to a Level 2 understanding.

Kelemen et al.'s (2014) findings are promising with respect to the pedagogical goal of introducing evolution earlier in school, but those findings are limited in several respects. First, Kelemen and colleagues (2014) did not compare children's ability to learn evolutionary principles to that of adults, and it remains unclear whether children are more or less adept at this. Second, Kelemen and colleagues (2014) assessed children's understanding of the evolution of only one type of trait—traits that aid foraging—and it remains unclear whether children would be able to apply that understanding to other types of traits, like traits that aid predator avoidance. Third, Kelemen and colleagues (2014) coded children's explanations as a single unit, and it remains unclear whether children were capable of learning all evolutionary concepts equally well or were inclined to learn some concepts (e.g., differential survival) better than others (e.g., within-species variation).

Fourth, and most important, Kelemen and colleagues (2014) probed children's understanding of evolution with up to 10 different prompts, and it remains unclear whether children would have been equally successful with fewer prompts. For instance, children who mentioned trait variation but not differential survival were prompted for more information along those lines (e.g., "Which group of pilosas got more food?"). Likewise, children who mentioned differential survival but not differential reproduction were prompted for more information (e.g., "Which group of pilosas had more babies?"), as were children who mentioned differential survival and reproduction in one generation but not differential survival and reproduction across several generations (e.g., "If this pilosa had a baby, what kind of trunk would its baby have?").

In the present study, we sought to replicate Kelemen et al.'s (2014) findings, assessing children's explanations for biological adaptation before and after a storybook-based tutorial on evolution by natural selection, but we also sought to address the aforementioned limitations in their study. We did so by implementing the following changes. First, we explicitly compared children's ability to learn evolutionary principles to that of adults, controlling for differences in prior knowledge at pretest. Second, we varied the type of traits under consideration, including not only foraging-related traits (which increase an organism's chances of finding food) but also camouflage-related traits (which decrease an organism's chances of *becoming* food). Third, we coded participants' explanations analytically rather than holistically, tabulating how frequently they mentioned each of the five evolutionary principles illustrated in the tutorial. Fourth, we elicited children's explanations for biological adaptation with a single prompt, namely, "How did [this particular animal] come to have [this particular trait]?"

One additional change we made to Kelemen et al.'s (2014) methodology was to include a second training example in our tutorial, presenting children with two illustrations of evolution rather than one. We added a second example for several reasons. First, we wanted to vary whether our training examples covered the same type of trait (two foraging-related traits) or different types of traits (one foraging-related trait and one camouflage-related trait), which we discuss in more detail later. Second, we wanted to create an opportunity to measure how well children abstracted a general schema from the specific examples at hand, and we did so by asking them whether they noticed any commonalities between the two training examples and, if so, what. Including a measure of schema abstraction is standard practice in the analogy literature (Gentner, Loewenstein, & Thompson, 2003; Novick & Holyoak, 1991), as it can provide direct evidence of the relation between schema abstraction and schema transfer.

Finally, we were concerned that a single training example would be ineffective at illustrating an abstract schema. Although a single example proved sufficient in Kelemen et al.'s (2014) study, other studies have shown that multiple examples are typically more effective than a single example, particularly if participants are encouraged to compare those examples (Catrambone & Holyoak, 1989; Christie & Gentner, 2010; Kurtz, Miao, & Gentner, 2001; Son, Smith, & Goldstone, 2011). By comparing examples, learners are able to ignore superficial differences in the examples' content and focus on the more substantive commonalities in their underlying structure. This form of instruction, known as *analogical encoding*, has proven effective at helping learners abstract "a coherent and portable relational structure" from specific instantiations of that structure (Gentner et al., 2003, p. 402).

Given these changes to Kelemen et al.'s (2014) methodology, we predicted that children would still be able to learn evolutionary principles but were unclear on whether children would be able to learn those principles as well as adults. We were also unclear on whether children would be able to learn all evolutionary principles equally well and whether they would be able to apply those principles to all traits equally well. Nevertheless, we strongly expected that children's ability to abstract an evolutionary schema from the training examples would predict their ability to apply that schema to new instances of biological adaptation, not only because previous studies have demonstrated similar effects in other domains (e.g., Gentner et al., 2003; Novick & Holyoak, 1991) but also because our decision to elicit evolutionary explanations with minimal prompting put the onus of generating such explanations squarely on the participant.

Method

Participants

The participants were 96 children recruited from playgrounds in Pasadena, California, and 30 college undergraduates recruited from introductory psychology courses at Occidental College. The children ranged in age from 4 to 12 and were sampled from a racially diverse population (42% Caucasian, 25% Latino, 10% African American, 10% Asian, and 13% other). For the purpose of data analysis, we split the children into two groups: those between the ages of 4 and 6 (M age = 5 years, 6 months; range = 4 years, 0 months, to 6 years, 9 months) and those between the ages of 7 and 12 (M age = 9 years, 0 months; range = 7 years, 0 months, to 12 years, 8 months).

Children in the first age group ($n = 52$) are referred to as *younger children*, and those in the second ($n = 44$) are referred to as *older children*. The age range for the older children was twice as large as that for the younger children only because we did not want to exclude the 10% of children who participated in our study but happened to be older than the age of 9. (Recruiting participants at parks by sight did not allow us to be as restrictive with age as is possible with registry-based or school-based methods of recruitment.) Excluding those children from the analysis would not, however, have altered any of the reported differences between our younger group and our older group.

Approximately half of the children in each group were girls and half were boys. Preliminary analyses revealed no effects of gender on either pretest scores or posttest scores, so gender was not included as a variable in the final analyses.

With respect to the adults, they ranged in age from 18 to 22 and came from a variety of academic majors, though primarily social science majors. Prior to the study, they had taken an average of 1.6 biology courses in high school and 1.4 biology courses in college. All had taken at least one high school-level course, and 14 of the 30 had taken at least one college-level course. In addition, 21 were women and nine were men. They were compensated with extra credit in a psychology or cognitive science course.

Procedure

All participants—children and adults alike—received the assessment and training materials in the form of a picture book. The first section of picture book contained two pretest items, the second contained two training items, and the third contained two posttest items. Pretest and posttest items consisted of a picture of an animal, a description of one of its traits, and a prompt to explain where that trait came from. An example is as follows:

This is a panda. Pandas have thumbs. Why do you think they have thumbs? Pandas have thumbs so that they can grab bamboo, which is the only food they eat. Did you know that the ancestors of pandas—who lived long, long ago—did not have thumbs? How do you think they came to have thumbs?

We provided children with function information about each trait before asking them to explain the origin of that trait because previous studies have shown that children treat only functional traits as heritable (Springer & Keil, 1989; Ware & Gelman, 2014). That said, providing children with function information may have primed teleological conceptions of trait inheritance, thereby limiting children's access to evolutionary ones. Emmons and Kelemen (2015), for instance, have found that children are less likely to accept that a trait can vary across members of the same species if that trait is described in functional terms. Future studies are needed to determine whether the inclusion of function information did more harm than good, as this type of information could easily be excluded.

Participants were asked to explain the origin of one foraging-related trait and one camouflage-related trait at each assessment period (pretest and posttest). The foraging-related traits were the thumb of the panda and the beak of the pelican, and the camouflage-related traits were the striped

coat of the zebra and the leaf-like wing of the katydid. Each trait was included as a pretest item for half of the children and as a posttest item for the other half, and the ordering of those traits was counterbalanced across participants.

The training items, like the assessment items, focused participants' attention on a particular animal and a particular trait, but they differed from the training items in that participants were not asked to explain the origin of the trait; they were provided with an explanation by the experimenter. Each explanation entailed the combination of five evolutionary principles: variation, differential survival, differential reproduction, inheritance, and population change. The following is a sample training item, with each principle listed in brackets following its illustration:

This is a Guinea turaco. Guinea turacos are green. Why do you think they're green? Guinea turacos are green so they can blend into the jungle and avoid being eaten by hawks and snakes. The ancestors of Guinea turaco—who lived long, long ago—were not green. They were gray. Let me tell you how green turacos came from gray turacos. Once, by chance, some turacos were born with green feathers [*variation*]. The green turacos lived longer than the gray turacos because they were better able to hide from hawks and snakes [*differential survival*]. Because the green turacos lived longer than the gray turacos, the green turacos had more babies [*differential reproduction*]. The babies of the green turacos had green feathers, just like their parents [*inheritance*]. After many, many years, all the gray turacos were replaced by green ones [*population change*].

Each evolutionary principle included in the training items was illustrated visually. Variation was illustrated with a picture of 10 turacos in which nine were gray and one was green. Differential survival was illustrated with a picture of two arrows depicting relative lifespan: a long arrow appearing beneath a green turaco and a short arrow appearing beneath a gray turaco. Differential reproduction was illustrated with a picture of two broods of baby turacos: a small brood of gray turacos and a large brood of green turacos. Inheritance was illustrated with a picture of the parent turaco for each brood. And population change was illustrated with a series of five pictures. Each picture displayed 10 turacos, in which the ratio of green turacos to gray turacos changed from 1:9 to 3:7 to 5:5 to 8:2 to 10:0.

Children were presented with two training items back to back. The training items covered either foraging-related traits (the long snout of the anteater, the long neck of the giraffe) or camouflage-related traits (the green feathers of a Guinea turaco, the white fur of the Arctic hare). A third of the children were shown two foraging-related traits, a third were shown two camouflage-related traits, and a third were shown one foraging-related trait and one camouflage-related trait.

We had predicted that children who received a mixed pair of traits would learn more than those who received only foraging-related traits or only camouflage-related traits, as other studies have shown that materials with dissimilar surface-level content are more pedagogically effective than materials with similar surface-level content (e.g., Gick & Holyoak, 1983; Vasilyeva & Bowers, 2010). However, we found no such effect either on posttest scores as a whole or on posttest scores for particular types of traits. We therefore pooled the data across training conditions.

At the end of the training phase, participants were asked whether they had noticed any similarities between the two training items. Participants' responses were coded for evidence of the five illustrated principles—variation, differential survival, differential reproduction, inheritance, and population change—and constituted a measure of schema abstraction. Note that schema abstraction was not our focal measure of learning. Our focal measure was how many more evolutionary principles participants cited at posttest compared to pretest. This measure captures participants' ability to apply the five-principle evolutionary schema, conveyed during training, to new examples of biological adaptation after controlling for baseline differences in prior knowledge of that schema.

Regardless of whether participants were able to abstract the schema on their own, the experimenter articulated that schema before moving to the posttest. For instance, in the training condition involving two camouflage-related traits, the experimenter told participants the following:

Did you notice any similarities between the story about the turacos and the story about the hares? Did both kinds of animals change over time for similar reasons? They did! In both stories, there were differences among the animals, and the animals that could hide better from predators lived longer than the other animals. And because they lived longer, they had more babies. And those babies had the same traits as their parents. After many, many years, the animals that could hide better from predators replaced the other animals.

The tutorial took approximately 10 min, and the entire interview took approximately 20 min. Across the interview, participants provided a total of five explanations for biological adaptation: two at pretest, one at training, and two at posttest. All explanations were audio recorded and transcribed at a later date.

It should be noted that the same protocol was used for both children and adults, meaning that adults, like children, provided their explanations verbally in the context of a one-on-one interview with the experimenter. We collected adults' responses in this manner to minimize differences in the format of our training and assessment materials across age groups and, accordingly, format-related differences in responding.

Coding

Participants' explanations were coded for inclusion of the five evolutionary principles taught during the training period. The following explanation, provided by an 11-year-old girl, is an example of an explanation that included all five:

One of them probably had thumbs [*variation*], and they were able to eat more bamboo, and so they lived longer [*differential survival*], and they passed on the genes because they lived longer [*inheritance*]. Their babies, since they had more babies than the other ones [*differential reproduction*], lived longer too because they had thumbs and they had more babies and more babies until all of them had thumbs. All the pandas without thumbs died because they couldn't get enough food [*population change*].

Participants' explanations were also coded for alternative, nonevolutionary considerations. The three most commonly cited considerations were need, growth, and creation. *Need-based explanations* appealed to the needs of an organism as an explanation, in and of itself, for the origin of a trait that met those needs. Examples include "because they need to hold the bamboo" and "because they need to catch fish." *Growth-based explanations* appealed to ontogenetic development as an explanation, in and of itself, for the origin of a new trait. Examples include "they got older and grew them" and "they just grew thumbs; they grew fur and then they grew thumbs." Finally, *creation-based explanations* appealed to a divine creator as the source of the trait. Examples include "because God gave them thumbs" and "because God made them like that." In total, 52% of children and 60% of adults provided at least one need-based explanation, 43% of children and 17% of adults provided at least one growth-based explanation, and 19% of children (but none of the adults) provided at least one creation-based explanation.

Our reasons for focusing on need-based, growth-based, and creation-based explanations were not only empirical but also theoretical. Each type of explanation exemplifies a pattern of reasoning discussed earlier as an impediment to evolutionary reasoning. Need-based explanations exemplify *teleological* reasoning in that they cite a trait's purpose as an explanation for its existence. Growth-based explanations exemplify *essentialist* reasoning in that they cite an organism's innate potential to develop a certain trait as an explanation for the origin of that trait. And creation-based explanations exemplify *intentional* reasoning in that they cite the intentions of a divine creator as an explanation for the creator's handiwork.

One final piece of data extracted from the interview transcripts was how often the experimenters prompted participants for additional information. These prompts took two forms: general prompts and schema reminders. *General prompts* included requests for an answer ("Can you make a guess?"), requests for an elaboration ("Can you tell me more?"), and requests for additional ideas in cases in which participants spontaneously cited only nonevolutionary considerations ("Can you think of any other way pandas came to have thumbs?"). *Schema reminders*, in contrast, were explicit requests to relate the posttest items to the training items and the principles illustrated therein ("Can you think of

a way zebras got their stripes that's similar to how Guinea turacos got their green feathers and Arctic hares got their white fur?"). Both types of prompts were tabulated and compared to participants' responses to determine whether they influenced how often participants cited evolutionary considerations at each assessment period.

All explanations were coded by two independent coders. Intercoder agreement was uniformly high across the 10 coding categories: 91% agreement for how often participants mentioned variation, 90% for differential survival, 95% for differential reproduction, 97% for inheritance, 94% for population change, 87% for need, 96% for growth, 98% for creation, 81% for general prompts, and 98% for schema reminders. All disagreements were resolved through discussion.

Results

Here we analyze participants' evolutionary explanations for effects of age and training, followed by their nonevolutionary explanations. Composite scores for the two analyses had different ranges given that we coded for different numbers of evolutionary and nonevolutionary considerations. Composite scores for the first analysis could range from 0 to 10 at each assessment period (five principles across two items), whereas those for the second analysis could range from 0 to 6 (three considerations across two items).

Effects of training on evolutionary explanations

The mean number of evolutionary principles cited before and after training is displayed in Figure 1 as a function of age. Participants in all age groups benefited from training, though younger children benefited less than did older children and adults. The reliability of these effects was assessed with a repeated measures analysis of variance in which assessment period (pretest vs. posttest) was treated as a within-participants factor and age group (younger children vs. older children vs. adults) was treated as a between-participants factor. This analysis revealed a significant effect of assessment period, a significant effect of age group, and a significant interaction between assessment period and age group: assessment period, $F(1, 123) = 95.02, p < .001$; age group, $F(2, 123) = 14.79, p < .001$; assessment period \times age group, $F(2, 123) = 47.35, p < .001$.

We explored the main effect of age group with Bonferroni comparisons, which revealed that younger children cited significantly fewer evolutionary principles than did older children and that older children cited significantly fewer evolutionary principles than did adults. We explored the interaction with paired-samples t tests comparing pretest scores to posttest scores for each age group by itself. These analyses revealed significant effects for all three groups: younger children, $t(51) = 2.91, p < .01$; older children, $t(43) = 6.23, p < .001$; adults, $t(29) = 5.94,$

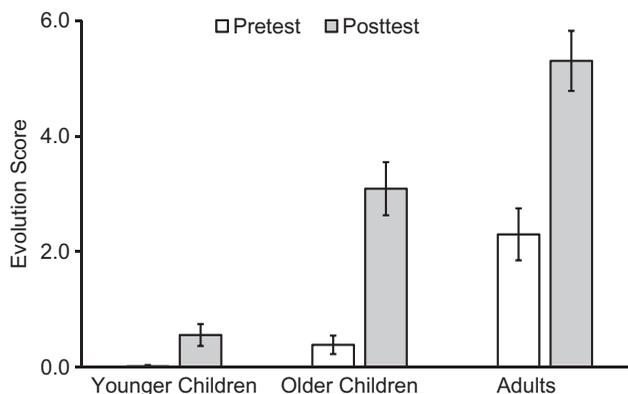


Figure 1. Mean evolution scores as a function of age and training (range = 0–10). Error bars represent the standard error.

$p < .001$. Nevertheless, the size of this effect was substantially smaller for younger children ($d = 0.55$) than it was for either older children ($d = 1.19$) or adults ($d = 1.13$).

This last set of analyses demonstrates that participants cited more evolutionary considerations after training than before, but did training affect their ability to cite all considerations equally? We addressed this question by comparing pretest scores to posttest scores for each evolutionary principle on its own. The results of this analysis are displayed in Table 1. Younger children were more likely to cite three of the five principles at posttest than at pretest (variation, differential survival, and differential reproduction); older children and adults were significantly more likely to cite all five. Thus, the effects of training appeared to be widespread.

The data in Table 1 suggest not only that effects of training were widespread but also that they were similar for older children and adults. To verify this observation statistically, we submitted participants' posttest scores to an analysis of covariance in which age group (younger children vs. older children vs. adults) was treated as a between-subjects factor and pretest score was treated as a covariate. It is not surprising that this analysis revealed a significant effect of age group, $F(2, 122) = 97.52, p < .001$. However, follow-up comparisons with Bonferroni corrections revealed that when we controlled for pretest scores, younger children scored significantly lower than did older children (M difference = 2.3, $p < .001$) and adults (M difference = 3.3, $p < .001$), but older children scored the same as adults (M difference = 1.0, *ns*).

Thus, even though adults cited more evolutionary principles than did older children at pretest, the *difference* in the number of principles cited from pretest to posttest was the nearly same. This finding cannot be attributed to a ceiling effect on behalf of the adults because adults' average score at posttest (5.3) was only half of what it could have been (10).

Effects of training on alternative conceptions

The mean number of alternative (nonevolutionary) conceptions cited before and after training is displayed in Figure 2 as a function of age. Across age groups, training had a minimal effect on how often participants cited such considerations. Indeed, a repeated measures analysis of variance revealed no effect of assessment period on the number of alternative conceptions cited, $F(1, 123) = 3.27, ns$. It did, however, reveal a significant effect of age group and a near-significant interaction between assessment period and age group: age group, $F(2, 123) = 3.15, p < .05$; assessment period \times age group, $F(2, 123) = 2.92, p < .06$. We explored the main effect of age group with Bonferroni comparisons, which revealed that younger children provided significantly fewer alternative conceptions than did adults but that older children provided approximately the same number

Table 1. The Mean Frequency With Which Each Evolutionary Principle Was Mentioned at Each Assessment Period by Participants in Each Age Group (Range = 0–2).

| Group | Concept | Pretest | Posttest | Difference |
|------------------|---------------------------|---------|----------|------------|
| Younger children | Variation | 0.02 | 0.13 | 0.12* |
| | Differential survival | 0.00 | 0.21 | 0.21* |
| | Differential reproduction | 0.00 | 0.12 | 0.12* |
| | Inheritance | 0.00 | 0.04 | 0.04 |
| | Population change | 0.00 | 0.06 | 0.06 |
| Older children | Variation | 0.16 | 0.84 | 0.68*** |
| | Differential survival | 0.05 | 0.75 | 0.71*** |
| | Differential reproduction | 0.00 | 0.41 | 0.41** |
| | Inheritance | 0.05 | 0.23 | 0.18* |
| | Population change | 0.14 | 0.86 | 0.72*** |
| Adults | Variation | 0.23 | 1.17 | 0.93*** |
| | Differential survival | 1.13 | 1.53 | 0.40* |
| | Differential reproduction | 0.43 | 1.03 | 0.60*** |
| | Inheritance | 0.30 | 0.60 | 0.30* |
| | Population change | 0.20 | 0.97 | 0.77*** |

* $p < .05$. ** $p < .01$. *** $p < .001$.

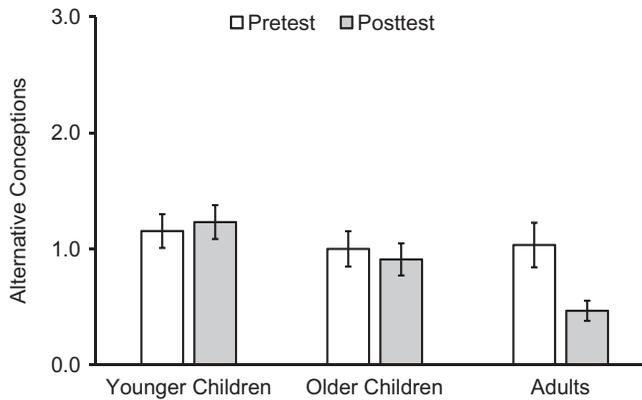


Figure 2. Mean alternative conception scores as a function of age and training (range = 0–6). Error bars represent the standard error.

of alternative conceptions as did both younger children and adults. We explored the interaction effect with paired-samples *t* tests comparing pretest scores to posttest scores for each age group by itself. These analyses revealed a significant pre/post difference for adults but no significant differences for younger children or for older children: adults, $t(29) = 2.81$, $p < .01$; younger children, $t(51) < 1.0$, *ns*; older children, $t(43) < 1.0$, *ns*.

These patterns were investigated at the level of individual conceptions as well. Table 2 displays the frequency with which participants in each age group cited need, growth, and creation at each assessment period. These frequencies remained constant for younger children and older children but decreased for adults in the category of need. Still, the size of this solitary effect was small ($d = 0.53$).

Effects of schema abstraction and schema reminders

During the training phase of the study, participants were asked whether they noticed any similarities between the two training examples before those similarities were highlighted for them. Their responses were coded for the same five evolutionary principles coded for at each assessment period. On average, younger children spontaneously abstracted 0.2 evolutionary principles from the training materials ($SD = 0.4$), older children spontaneously abstracted 1.0 ($SD = 1.1$), and adults spontaneously abstracted 1.5 ($SD = 1.2$). These differences were statistically significant, $F(2, 123) = 18.56$, $p < .001$. Follow-up comparisons with Bonferroni corrections revealed that although younger children abstracted significantly fewer principles than older children, older children did not abstract significantly fewer principles than adults.

Table 2. The Mean Frequency With Which Each Alternative Conception Was Mentioned at Each Assessment Period by Participants in Each Age Group (Range = 0–2).

| Group | Concept | Pretest | Posttest | Difference |
|------------------|----------|---------|----------|------------|
| Younger children | Need | 0.50 | 0.65 | 0.15 |
| | Growth | 0.37 | 0.44 | 0.08 |
| | Creation | 0.29 | 0.13 | –0.15 |
| Older children | Need | 0.41 | 0.32 | –0.09 |
| | Growth | 0.43 | 0.52 | 0.09 |
| | Creation | 0.16 | 0.07 | –0.09 |
| Adults | Need | 0.87 | 0.43 | –0.43* |
| | Growth | 0.17 | 0.03 | –0.13 |
| | Creation | 0.00 | 0.00 | 0.00 |

* $p < .05$.

Individual participants varied widely in how many principles they abstracted, and we sought to determine whether this variation tracked participants' ability to apply those principles at posttest. We did so with a hierarchical regression in which we regressed participants' evolution scores at posttest against their evolution scores at training after first controlling for their evolution scores at pretest. This analysis revealed significant effects of both pretest scores and training scores: pretest scores, $\beta = 0.80$, $t(125) = 5.63$, $p < .001$; training scores, $\beta = 0.96$, $t(125) = 4.32$, $p < .001$. Moreover, training scores explained significantly more variance in posttest scores than did pretest scores alone (R^2 for pretest scores = .28, R^2 for pretest scores + training scores = .37), $\Delta F(1, 123) = 18.68$, $p < .001$. This finding remained largely unchanged even when adults were excluded from the analysis (R^2 for pretest scores = .14, R^2 for pretest scores + training scores = .23), $\Delta F(1, 93) = 11.04$, $p < .001$. In short, the more evolutionary principles participants spontaneously abstracted at training, the more evolutionary principles they cited at posttest, regardless of how many evolutionary principles they cited at pretest.

At posttest, if participants failed to provide an evolutionary explanation, they were encouraged to think back to the training examples and the principles illustrated by those examples. Younger children required the same number of schema reminders as older children (younger children: $M = 1.2$, $SD = 0.1$; older children: $M = 1.2$, $SD = 0.1$), and adults never required such reminders, as they cited at least some evolutionary principles on each posttest item. Schema reminders did not, however, prove helpful. The more schema reminders children required, the fewer evolutionary principles they cited, $r(94) = -.30$, $p < .01$. In other words, children who provided evolutionary explanations at posttest did so without prompting, and children who provided nonevolutionary explanations at posttest did not provide evolutionary ones following prompting.

General prompts (e.g., "Can you make a guess?" "Can you tell me more?") were also ineffective at eliciting evolutionary explanations, as their frequency was not correlated with children's evolution scores either at pretest or at posttest: pretest, $r(94) = .05$, *ns*; posttest, $r(94) = .05$, *ns*. The prompts in our study were thus minimal in both number and effect.

Discussion

Can elementary school-age children learn evolutionary explanations for biological adaptation? The answer appears to be yes, at least for children on the older side of this age range. When left to their own devices, children tend to explain biological adaptation in terms of need, growth, or creation. However, after being shown two instances of how differential survival and differential reproduction of the varied organisms within a population can lead to heritable changes across the entire population, children were able to articulate those principles in general terms and apply them to new instances of adaptation, particularly children over the age of 7. In fact, children of this age were able to apply newly learned evolutionary principles as well as adults. Adults may have cited more evolutionary principles at pretest, but both groups increased their propensity to cite evolutionary principles, from pretest to posttest, by about the same amount.

Our findings replicate Kelemen et al.'s (2014) findings that elementary school-age children can learn evolutionary principles from a brief, storybook-based tutorial. And they extend those findings by showing that children's receptivity to evolutionary information encompasses different types of traits (not just foraging-related traits) and different types of principles (when knowledge of those principles is assessed separately, principle by principle). They also extend those findings by showing that children's receptivity to evolutionary information tracks their ability to abstract an evolutionary schema from specific instances of evolutionary change, thus pointing to analogical encoding as a possible method for teaching evolutionary concepts.

However, our findings do not replicate one key finding from Kelemen et al.'s (2014) study: that children younger than the age of 6 are (robustly) capable of learning evolutionary explanations. In Kelemen et al.'s (2014) study (Study 1), children younger than the age of 6 increased their scores on

an evolution assessment by an average of 1.1 points on a 4-point scale (or 28%), whereas children of the same age in our study increased their scores by only 0.6 points on a 5-point scale (or 12%). The difference was reliable but too small to be of much practical significance. Only 15% of our younger children increased their score by 1 point or more.

What factors might account for this discrepancy between our findings and Kelemen et al.'s (2014) findings? First, we included 4-year-olds (12 in total, or 23% of the younger age group), whereas Kelemen and colleagues (2014) did not. Second, we probed children's understanding of evolution with minimal prompting, whereas Kelemen and colleagues (2014) used more extensive prompting. Third, we taught children evolutionary explanations using two rather lengthy training examples, whereas Kelemen and colleagues (2014) did so using only one training example. Fourth, we required children to generalize their newfound knowledge to two types of traits, whereas Kelemen and colleagues (2014) required that children generalize their knowledge to just one type. These last few points suggest that our task placed a greater cognitive load on children than did Kelemen et al.'s (2014) task—an ecologically valid load but a load nonetheless—and younger children's ability to learn evolutionary principles under such a load proved too fragile.

This fragility makes sense in light of what we know about young children's understanding of folkbiology more generally. Preschool- and early elementary school-age children tend to construe life and its properties in animistic terms (Carey, 1985; Hatano & Inagaki, 1994; Solomon & Zaitchik, 2012). They identify life with the capacity for self-directed motion (as opposed to metabolic processing), and they identify biological properties with the psychological experiences that accompany those properties (as opposed to their role in sustaining vital functions). Children of this age are still in the process of constructing a vitalist conception of bodily functions and a mechanistic conception of bodily structures, and such conceptions may need to be in place before children can learn higher-order conceptions, like evolution and natural selection.

One of the more surprising findings from our study was that learning evolutionary explanations for biological adaptation had little effect on participants' endorsement of nonevolutionary explanations, referencing the needs of individual organisms, the growth of individual organisms, or the intentions of a divine creator. These explanations were cited not only at pretest but also at posttest, often in combination with newly learned evolutionary principles, as in the following example:

They were all born to have something different about each other [*variation*], and they all need something to use to eat [*need*]. And then they have babies, and the babies have the same traits as their parents [*inheritance*]. And then, the ones that live longer replace for the ones that don't [*population change*].

Other studies have found similar results in that people typically endorse several explanations for biological adaptation when given the opportunity to do so, some evolutionary and some not (Evans et al., 2010; Legare et al., 2013). Tensions between evolutionary and nonevolutionary explanations either go unrecognized by those who endorse both or are reconciled in terms of a synthetic model of evolution that captures aspects of both intuitive and scientific reasoning, such as a theistic model of evolution in which evolutionary change is *intentionally* and *teleologically* guided by a divine agent (Evans & Lane, 2011).

One interpretation of these findings is that participants did not learn an evolutionary schema for biological adaptation to a satisfactory degree. If they had, they should have recognized the inadequacy of nonevolutionary explanations and stopped providing them. This interpretation, though plausible from a *logical* point of view, is less plausible from a *psychological* point of view, as recent research in science education has revealed that scientific conceptions rarely replace intuitive ones. The coexistence of intuitive knowledge and scientific knowledge appears to be the rule, rather than the exception, in how people conceptualize natural phenomena (Shtulman & Harrington, 2016; Shtulman & Valcarcel, 2012).

Even adults with extensive backgrounds in science never appear to relinquish their intuitive beliefs. Under time pressure or cognitive load, they reveal nonscientific, childlike conceptions of several domains,

including life (Goldberg & Thompson-Schill, 2009), matter (Potvin, Masson, Lafortune, & Cyr, 2015), motion (Foisy, Potvin, Riopel, & Masson, 2015), rational number (Vamvakoussi, Van Dooren, & Verschaffel, 2012), and physical causality (Kelemen, Rottman, & Seston, 2013). Findings of this nature suggest that the goal of science education should not be to supplant intuitive conceptions of the world with more scientific ones but to teach students when and how to discriminate between the two types of conceptions (Potvin, 2013; Shtulman & Lombrozo, *in press*).

Overall, our findings indicate that older elementary school-age children can be taught an evolutionary schema that (a) covers multiple evolutionary principles, (b) can be applied to multiple types of traits, and (c) can be elicited with minimal prompting, but our findings do raise several questions for further research.

First, how stable are these schemas? Kelemen et al. (2014) showed that elementary school-age children can retrieve evolutionary schemas 3 months after training, but their prompting was extensive, and it is not clear whether children would be equally successful with less prompting, as done in the present study. Second, how comprehensive are these schemas? Children in the present study were able to apply evolutionary schemas to instances of biological adaptation that differed in form and function from those used at training, but they may not be able to apply those schemas to other instances of biological change (e.g., the loss of a trait over evolutionary time or the evolution of traits in nonanimal species; Opfer, Nehm, & Ha, 2012). Third, how coherent are these schemas? As a group, the older children in our study demonstrated evidence of learning all key evolutionary principles on offer, but individual children varied in how many principles they learned, and it is not clear that a child who learned only a subset of those principles acquired a “coherent and portable relational structure,” as is the goal of schema abstraction (Gentner et al., 2003, p. 402).

These questions are perhaps best pursued in the context of a longitudinal study, in which children’s ability to learn evolution is assessed not just once but across several assessments periods and several tasks. That said, it should be noted that all available data—data from this study, data from Kelemen et al. (2014), and data from Legare et al. (2013)—suggest that older elementary school-age children are in fact capable of learning evolutionary ideas and should not therefore be shielded from those ideas until adolescence or even adulthood. Evolution by natural selection is foundational to the biological sciences and should thus be foundational to children’s biological education as well.

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References

- Berkman, M. B., & Plutzer, E. (2011, January 28). Defeating creationism in the courtroom, but not in the classroom. *Science*, 331, 404–405. doi:10.1126/science.1198902
- Berti, A. E., Toneatti, L., & Rosati, V. (2010). Children’s conceptions about the origin of species: A study of Italian children’s conceptions with and without instruction. *Journal of the Learning Sciences*, 19, 506–538. doi:10.1080/10508406.2010.508027
- Bishop, B., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, 27, 415–427. doi:10.1002/(ISSN)1098-2736
- Blancke, S., De Smedt, J., De Cruz, H., Boudry, M., & Braeckman, J. (2012). The implications of the cognitive sciences for the relation between religion and science education: The case of evolutionary theory. *Science & Education*, 21, 1167–1184. doi:10.1007/s11191-011-9402-z
- Brem, S. K., Ranney, M., & Schindel, J. (2003). Perceived consequences of evolution: College students perceive negative personal and social impact in evolutionary theory. *Science Education*, 87, 181–206. doi:10.1002/(ISSN)1098-237X
- Brumby, M. N. (1984). Misconceptions about the concept of natural selection by medical biology students. *Science Education*, 68, 493–503. doi:10.1002/(ISSN)1098-237X
- Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.

- Carmichael, M. (2009, November 22). Why evolution should be taught to younger kids. *Newsweek*. Retrieved from <http://www.newsweek.com/why-evolution-should-be-taught-youngerkids-76885>
- Catrambone, R., & Holyoak, K. J. (1989). Overcoming contextual limitations on problem-solving transfer. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 1147–1156.
- Christie, S., & Gentner, D. (2010). Where hypotheses come from: Learning new relations by structural alignment. *Journal of Cognition and Development*, *11*, 356–373. doi:10.1080/15248371003700015
- Coley, J. D., & Tanner, K. D. (2012). Common origins of diverse misconceptions: Cognitive principles and the development of biology thinking. *CBE-Life Sciences Education*, *11*, 209–215. doi:10.1187/cbe.12-06-0074
- Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *The American Biology Teacher*, *35*, 125–129. doi:10.2307/4444260
- Emmons, N. A., & Kelemen, D. A. (2015). Young children's acceptance of within-species variation: Implications for essentialism and teaching evolution. *Journal of Experimental Child Psychology*, *139*, 148–160. doi:10.1016/j.jecp.2015.05.011
- Evans, E. M. (2001). Cognitive and contextual factors in the emergence of diverse belief systems: Creation versus evolution. *Cognitive Psychology*, *42*, 217–266. doi:10.1006/cogp.2001.0749
- Evans, E. M. (2008). Conceptual change and evolutionary biology: A developmental analysis. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 263–294). New York, NY: Routledge.
- Evans, E. M., & Lane, J. D. (2011). Contradictory or complementary? Creationist and evolutionist explanations of the origin(s) of species. *Human Development*, *54*, 144–159. doi:10.1159/000329130
- Evans, E. M., Spiegel, A. N., Gram, W., Frazier, B. N., Tare, M., Thompson, S., & Diamond, J. (2010). A conceptual guide to natural history museum visitors' understanding of evolution. *Journal of Research in Science Teaching*, *47* (3), 326–353.
- Foisy, L.-M., Potvin, P., Riopel, M., & Masson, S. (2015). Is inhibition involved in overcoming a common physics misconception in mechanics? *Trends in Neuroscience and Education*, *4*, 26–36. doi:10.1016/j.tine.2015.03.001
- Gelman, S. A. (2003). *The essential child*. Oxford, UK: Oxford University Press.
- Gelman, S. A., & Rhodes, M. (2012). “Two-thousand years of stasis”: How psychological essentialism impedes evolution understanding. In K. S. Rosengren, S. Brem, E. M. Evans, & G. Sinatra (Eds.), *Evolution challenges: Integrating research and practice in teaching and learning about evolution* (pp. 3–21). Cambridge, UK: Oxford University Press.
- Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology*, *95*, 393–408. doi:10.1037/0022-0663.95.2.393
- Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, *15*, 1–38. doi:10.1016/0010-0285(83)90002-6
- Goldberg, R. F., & Thompson-Schill, S. L. (2009). Developmental “roots” in mature biological knowledge. *Psychological Science*, *20*, 480–487. doi:10.1111/psci.2009.20.issue-4
- Gregory, T. R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach*, *2*, 156–175.
- Hatano, G., & Inagaki, K. (1994). Young children's naive theory of biology. *Cognition*, *50*, 171–188. doi:10.1016/0010-0277(94)90027-2
- Johnson, S. C. (2000). The recognition of mentalistic agents in infancy. *Trends in Cognitive Sciences*, *4*, 22–28. doi:10.1016/S1364-6613(99)01414-X
- Kampourakis, K. (2014). *Understanding evolution*. Cambridge, UK: Cambridge University Press.
- Kelemen, D. (2012). Teleological minds: How natural intuitions about agency and purpose influence learning about evolution. In K. S. Rosengren, S. Brem, E. M. Evans, & G. Sinatra (Eds.), *Evolution challenges: Integrating research and practice in teaching and learning about evolution* (pp. 66–92). Cambridge, UK: Oxford University Press.
- Kelemen, D., Emmons, N. A., Schillaci, R. S., & Ganea, P. A. (2014). Young children can be taught basic natural selection using a picture-storybook intervention. *Psychological Science*, *25*, 893–902. doi:10.1177/0956797613516009
- Kelemen, D., Rottman, J., & Seston, R. (2013). Professional physical scientists display tenacious teleological tendencies: Purpose-based reasoning as a cognitive default. *Journal of Experimental Psychology: General*, *142*, 1074–1083. doi:10.1037/a0030399
- Kurtz, K. J., Miao, C.-H., & Gentner, D. (2001). Learning by analogical bootstrapping. *Journal of the Learning Sciences*, *10*, 417–446. doi:10.1207/S15327809JLS1004new_2
- Legare, C. H., Lane, J. D., & Evans, E. M. (2013). Anthropomorphizing science: How does it affect the development of evolutionary concepts? *Merrill-Palmer Quarterly*, *59*, 168–197. doi:10.1353/mpq.2013.0009
- Lombrozo, T., & Carey, S. (2006). Functional explanation and the function of explanation. *Cognition*, *99*, 167–204. doi:10.1016/j.cognition.2004.12.009
- Lombrozo, T., Shtulman, A., & Weisberg, M. (2006). The intelligent design controversy: Lessons from psychology and education. *Trends in Cognitive Sciences*, *10*, 56–57. doi:10.1016/j.tics.2005.12.001
- National Academy of Sciences. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.
- Nehm, R. H., Kim, S. Y., & Sheppard, K. (2010). Academic preparation in biology and advocacy for teaching evolution: Biology versus non-biology teachers. *Science Education*, *93*, 1122–1146. doi:10.1002/sce.20340

- Newport, F. (2010). *Four in 10 Americans believe in strict creationism*. Princeton, NJ: Gallup Organization.
- Novick, L. R., & Holyoak, K. J. (1991). Mathematical problem solving by analogy. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*, 398–415.
- Opfer, J. E., Nehm, R. H., & Ha, M. (2012). Cognitive foundations for science assessment design: Knowing what students know about evolution. *Journal of Research in Science Teaching*, *49*, 744–777. doi:10.1002/tea.v49.6
- Potvin, P. (2013). Proposition for improving the classical models of conceptual change based on neuroeducational evidence: Conceptual prevalence. *Neuroeducation*, *1*, 16–43.
- 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. *International Journal of Science and Mathematics Education*, *13*, 21–43. doi:10.1007/s10763-014-9520-6
- Samarapungavan, A., & Wiers, R. W. (1997). Children's thoughts on the origin of species: A study of explanatory coherence. *Cognitive Science*, *21*, 147–177. doi:10.1207/s15516709cog2102_2
- Shtulman, A. (2006). Qualitative differences between naïve and scientific theories of evolution. *Cognitive Psychology*, *52*, 170–194. doi:10.1016/j.cogpsych.2005.10.001
- Shtulman, A., & Calabi, P. (2012). Cognitive constraints on the understanding and acceptance of evolution. In K. S. Rosengren, S. Brem, E. M. Evans, & G. Sinatra (Eds.), *Evolution challenges: Integrating research and practice in teaching and learning about evolution* (pp. 47–65). Cambridge, UK: Oxford University Press.
- Shtulman, A., & Calabi, P. (2013). Tuition vs. intuition: effects of instruction on naïve theories of evolution. *Merrill-Palmer Quarterly*, *59*, 141–167.
- Shtulman, A., & Harrington, K. (2016). Tensions between science and intuition across the lifespan. *Topics in Cognitive Science*, *8*, 118–137. doi:10.1111/tops.2016.8.issue-1
- Shtulman, A., & Lombrozo, T. (in press). Bundles of contradiction: A coexistence view of conceptual change. In D. Barner & A. Baron (Eds.), *Core knowledge and conceptual change*. Oxford, UK: Oxford University Press.
- Shtulman, A., & Schulz, L. (2008). The relation between essentialist beliefs and evolutionary reasoning. *Cognitive Science*, *32*, 1049–1062. doi:10.1080/03640210801897864
- Shtulman, A., & Valcarcel, J. (2012). Scientific knowledge suppresses but does not supplant earlier intuitions. *Cognition*, *124*, 209–215. doi:10.1016/j.cognition.2012.04.005
- Sinatra, G. M., Brem, S. K., & Evans, E. M. (2008). Changing minds? Implications of conceptual change for teaching and learning about biological evolution. *Evolution: Education and Outreach*, *1*, 189–195.
- Solomon, G. E. A., & Zaitchik, D. (2012). Folkbiology. *Wiley Interdisciplinary Reviews: Cognitive Science*, *3*, 105–115. doi:10.1002/wcs.150
- Son, J. Y., Smith, L. B., & Goldstone, R. L. (2011). Connecting instances to promote children's relational reasoning. *Journal of Experimental Child Psychology*, *108*, 260–277. doi:10.1016/j.jecp.2010.08.011
- Springer, K., & Keil, F. C. (1989). On the development of biologically specific beliefs: The case of inheritance. *Child Development*, *60*, 637–648. doi:10.2307/1130729
- Vamvakoussi, X., Van Dooren, W., & Verschaffel, L. (2012). Naturally biased? In search for reaction time evidence for a natural number bias in adults. *Journal of Mathematical Behavior*, *31*, 344–355. doi:10.1016/j.jmathb.2012.02.001
- Vasilyeva, M., & Bowers, E. (2010). Exploring the effects of similarity on mapping spatial relations. *Journal of Experimental Child Psychology*, *106*, 221–239. doi:10.1016/j.jecp.2010.04.003
- Ware, E. A., & Gelman, S. A. (2014). You get what you need: An examination of purpose-based inheritance reasoning in undergraduates, preschoolers, and biological experts. *Cognitive Science*, *38*, 197–243. doi:10.1111/cogs.2014.38.issue-2