Changing Minds with the Story of Adaptation:
Strategies for Teaching Young Children about Adaptation.

Natalie Emmons
Boston University

Hayley Smith
University of Massachusetts, Boston

Deborah Kelemen
Boston University

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Correspondence to:

Natalie Emmons
Boston University
Department of Psychological and Brain Sciences
64 Cummington Mall
Boston MA 02215
nemmons@bu.edu

Abstract

Educational guidelines recommend a delayed, piecemeal approach to instruction on adaptation by natural selection. This approach is questionable given suggestions that older students' pervasive misunderstandings about adaptation are rooted in cognitive biases that develop early. In response to this, Kelemen et al. (2014) recently showed that young children can learn a basic yet comprehensive explanation of adaptation by natural selection from a picture storybook intervention. However, this research was conducted in a laboratory-based setting with children from middle and higher socio-economic backgrounds. To further explore the intervention's efficacy, this investigation examined whether Kelemen et al.'s (2014, Experiment 2) findings extend to a more diverse sample of children tested in a more distracting school-like setting, namely after-school programs. After a ten-minute picture storybook reading, which described adaptation within a fictitious but realistic mammal species, 5- to 6- and 7- to 8-year-old children's learning of adaptation was examined. Results revealed that younger and older children benefitted from the intervention; however, older children displayed pronounced learning and generalization of basic natural selection. Findings confirm that children are capable of learning complex biological ideas and that comprehensive storybook interventions are simple but powerful teaching tools. Implications for instruction on natural selection are discussed.

Keywords: evolution learning, education, folk biology, cognitive development

Changing minds with the story of adaptation:
Strategies for teaching young children about natural selection

Understanding adaptation by natural selection is fundamental to understanding the process by which species change and diversify over time. This knowledge is more than academic: In a world where economies are increasingly fuelled by medical and biotechnological responses to rapidly adapting disease pathogens, pesticide-resistant insects, and ecosystems unbalanced by climate change, a grasp of evolutionary processes is becoming prerequisite for many careers and to making informed decisions about societal and bio-ethical issues. It is therefore sobering to note that over thirty years of research has demonstrated that most high school students and adults misunderstand adaptation, even after formal classroom instruction (see Gregory, 2009, for review). The fact that misunderstandings hold among biology teachers who are expected to provide instruction on the topic serves to deepen the concern (Asghar, Wiles, & Alters, 2007; Cofré, Jiménez, Santibáñez, & Vergara, 2014; Nehm, Kim, & Sheppard, 2009; Nehm & Schonfeld, 2007; Rutledge & Warden 2000).

What accounts for the difficulty in mastering an accurate understanding of adaptation? Findings suggest that many factors may be at play. In the United States, for example, resistance can stem in part from the perception that evolutionary concepts challenge personal religious ideologies and commitments (Evans et al., 2010; Griffith & Brem, 2004; Guliuzza, 2014; Poling & Evans, 2004). The ambiguous or misleading language that textbooks employ in their descriptions of adaptation can further contribute to misunderstandings (Kampourakis, 2013). However, increasingly, there is a sense that even these issues might stem from a deeper underlying factor, in particular, biases in our everyday thinking. Although adaptation by natural selection is a non-random systematic process, crucially, it is also entirely non-purposive and nongoal-directed. Despite this, individuals tend to hold purpose-based teleological misconceptions about how adaptation occurs. Specifically, rather than understanding it as a population-based process involving differential survival and reproduction, they often reason that populations become functionally specialized through transformational events. These include, for example, ideas that ancestral individuals acquired beneficial traits via deliberate actions during their lifetimes (e.g., the idea that giraffes acquired long necks because they stretched them out while reaching for food) or because the anthropomorphized forces of “Nature” or “Evolution” transformed them in goal-directed ways (see Gregory, 2009, for review).

Notably, such incorrect notions held by older students echo the kinds of cognitive biases about the natural world present from at least early childhood (Gregory, 2009; Kelemen, 2004; Rosengren, Brem, Evans, & Sinatra, 2012; Sinatra, Brem, & Evans, 2008). These reasoning biases include tendencies to teleologically assume that natural phenomena exist in order to perform functions and that the natural world is agentive and operates in intentional, designed, and purpose-driven ways (e.g., Evans, 2000, 2001; Keil, 1989; Kelemen, 1999a, 1999b, 2012; Poling & Evans, 2002). They further include assumptions that species members share an immutable underlying reality that is responsible for their shared, invariant, and unchanging traits—an implicit belief known as essentialism (Gelman & Rhodes, 2012; Shtulman & Shultz, 2008; Emmons & Kelemen, 2015). Although these biases are useful as everyday reasoning heuristics, they can present difficulties when it comes to understanding counterintuitive scientific mechanisms like natural selection.

For example, recent evidence suggests that while teleological and essentialist biases may start out as separate early-arising impediments to evolution learning, by at least 7 to 8 years of age, they show signs of coalescing. Specifically, around this age, priming children’s teleological intuitions that animals possess traits by virtue of their survival-relevant functions serves to deepen their essentialist commitments that species members do not vary (Emmons & Kelemen, 2015; see also Shtulman & Schultz, 2008). This is problematic because representing phenotypic variation is prerequisite to understanding adaptation as a population-based selectionist process: within-species variation is what allows the process of differential survival and reproduction to occur. Furthermore, when young children's coalescing intuitive ideas are left unchallenged, they can become habitual and entrenched. In time, they can create the foundation for the commonsense theoretical ideas that contribute to older students' incorrect beliefs about adaptation as a goal-directed transformational event within the lifetime of an individual.

In short, the presence of intuitive theoretical frameworks in early childhood raises two major concerns about current standards on teaching adaptation by natural selection: The first relates to the recommended timing of teaching about adaptation and the second relates to the method of presentation. In the United States, current science education standards suggest that a comprehensive presentation of adaptation by natural selection should happen between grades 8 and 12 (Achieve, Inc., 2013; American Association for the Advancement of Science, 2009; National Research Council, 2012). That is, while it is recommended that teaching about conceptual pieces of the theory occur prior to that point, guidelines propose delaying the introduction of a comprehensive explanation of adaptation that clearly and explicitly theoretically integrates facts about within-species variation, environmental context, inheritance, and differential survival and reproduction over multiple generations until junior high or high school. This delayed and piecemeal approach presumably derives from concerns about children's conceptual limitations (Metz, 1995) and lack of background biological knowledge and appears even in countries that now place evolutionary teaching earlier in the curriculum (National

Curriculum for England, 2014; but see Berkman, Sandell Pacheco, & Plutzer, 2008, for uneven implementation of evolution standards).

On the positive side, this recommended component-by-component approach affords teachers latitude in terms of deciding the pacing of instruction on individual component biological facts, for example, tutoring on the relationship between access to nutritious food and health and between health and survival. It also permits gradual expertise building before requiring students to combine concepts into a multi-faceted causal explanation (e.g., Kampourakis, 2013). However, from another perspective this approach is a concern: To the extent that they are rooted in inherent human cognitive biases, children's early-developing intuitive theories about nature are likely to be difficult to revise or suppress once constructed. In the absence of competition from accurate theoretical alternatives that are sufficiently coherent to effectively challenge them, children's untaught intuitions can become long-term obstacles for elaborating a scientifically accurate understanding of adaptation (see Järnefelt, Canfield, & Kelemen, 2015; Kelemen & Rosset, 2009, for more on this dual processing perspective). Prior developmental research also suggests that, theoretically, young children should be conceptually capable of constructing coherent scientific theoretical alternatives. Namely, they acquire biological factual knowledge readily (Carey, 1985; Inagaki & Hatano, 2002; Siegal & Peterson, 1999) and have robust explanatory drives and capacities for abstract theory building (Carey, 1985; Gopnik & Meltzoff, 1997; Keil, 1989; Samarapungavan & Wiers, 1997; Wellman & Gelman, 1992).

In light of these considerations, interdisciplinary research has recently begun to explore the viability of leveraging young children's explanatory capacities and interest in biological information to teach them a basic but accurate comprehensive explanation of adaptation by natural selection. Drawing on findings from cognitive developmental psychology, the learning sciences, and science education research, Kelemen, Emmons, Seston Schillaci, and Ganea (2014) designed a picture storybook-based intervention in which 5- to 8-year-old children listened to a custom-made factual narrative about adaptation within a novel species called the "pilosas" and then answered questions about it. The picture book causally and cohesively wove together a series of biological facts to mechanistically explain how—through the process of differential survival and reproduction—a particular trait (i.e., thinner trunks) came to predominate in the phenotypically variable population of pilosas. Specifically, following climate change-induced effects on the behavior of their insect food source, which migrated into thin underground tunnels, species members who happened to have thinner trunks were more successful at reaching their prey and thus out-survived and out-reproduced members with wider trunks over generations and time.

Results from the first of two studies revealed that both 5- to 6-year-old and 7- to 8-year-old children benefitted from the intervention (Kelemen et al., 2014). While nearly all of the younger children and a majority of older children did not understand adaptation at pre-test, following the storybook, many younger children and nearly all of the older children provided an accurate selectionist explanation of adaptation absent any misconception. Furthermore, in crucial tests of deeper learning, children correctly generalized their understanding to explain adaptation within an entirely different novel species, and their learning endured following a delay of three months. Perhaps because the initial storybook described a case of rapid natural selection resulting from the rapid die off of pilosas with wider trunks, children's selectionist explanations of adaptation centered heavily on the concept of differential survival. Thus, to further explore whether children could more fully incorporate the concept of differential reproduction in their explanations, a revised storybook that emphasized a more gradual process of adaptation occurring over many successive generations was used in the second study. After hearing this version of the book, most of the younger children and all of the older children incorporated both differential survival and reproduction in their responses when reasoning about the pilosas: Older children successfully generalized this level of understanding to a novel animal, but younger children, while largely successful at generalizing, showed a slight decrease in performance. Indeed, across both studies, older children outperformed younger children, presumably in part because of their enhanced cognitive and language abilities (Kelemen et al., 2014).

Cumulatively, these results supported the idea that young children can engage in theoretical learning about complex biological processes when presented with age-appropriate, causally cohesive mechanistic explanations. However, one limitation of Kelemen et al. (2014) was that it was conducted in a laboratory setting, which offered an optimal learning environment free from visual and auditory distractions (see e.g., Fischer, Godwin, & Seltman, 2014). While this environment was chosen as a measure of caution given that this initial research significantly departed from accepted educational wisdom about children's learning abilities (e.g., Bransford, Brown, & Cocking, 2000; Metz, 1995; Schweingruber, Duschl, & Shouse, 2007), it did not represent a typical learning environment. A further limitation was an unintended artifact of most laboratory-based volunteer samples: Children were predominantly monolingual Caucasians from middle and higher socio-economic status (SES) backgrounds (e.g., 48% of parents in Experiment 2 had a graduate-level degree). In consequence, although most of the children's parents were unable to accurately describe natural selection (77%, Experiment 2), other factors related to their higher SES and monolingual backgrounds meant they were probably at an advantage for learning complex material from a storybook. For example, SES is associated with the amount of time children are read to, children's linguistic and academic performance (e.g., receptive vocabulary (PPVT), reading recognition (PIAT), grade retention rates) and children's semantic knowledge (Bereiter & Englemann, 1966; Bradley & Corwyn, 2002; Deutsch, Katz, & Jensen, 1968; Duncan & Brooks-Gunn, 1997; Fernald, Marchman, & Weisleder, 2012; Jensen, 2012; Lee & Burkam, 2002). Bilingualism is also associated with delayed literacy abilities in preschool and kindergarten, although such delays begin to disappear by the end of kindergarten (Hammer, Lawrence, Miccio, 2007; Hammer, Scheffner, & Miccio, 2006; Páez, Tabors, López, 2007).

In short, results from Kelemen et al. (2014) may have reflected the type of learning that can occur among children who *a priori* had heightened abilities to comprehend and self-explain the multi-step causal logic of natural selection whilst suppressing any potential competing misconceptions that they had. Given this possibility and given that the goal of this research program is to develop an intervention with far-reaching benefits for all children, it was of interest to know the extent to which children's learning gains generalize to other populations and testing environments. The present investigation therefore sought to replicate Experiment 2 of Kelemen et al. (2014) by examining learning among children from far more diverse socio-economic and language backgrounds and in the context of a more typical learning environment. Specifically, 5- to 6- and 7- to 8-year-old children from within urban school districts that predominantly serve members of underrepresented minority groups participated in the intervention at their local afterschool programs.

Method

Participants

Sixteen 5- to 6-year-old kindergarten (8 boys, 8 girls, M_{age} = 6 years, 2 months, *SD* = 6 months) and sixteen 7- to 8-year-old second-grade children (7 boys, 9 girls, M_{age} = 8 years, 3 months, *SD* = 3 months) were recruited from three Boston-area afterschool programs. Children were racially and ethnically diverse (50% Hispanic, 22% Multi-racial, 16% Caucasian, 9% African American, 3% unknown). Of the children whose parents reported details about their child's language(s) (78%), 60% were identified as speaking a second language: Most of those children (87%) were bilingual Spanish-English speakers.

Information about household income and parent education was collected to provide SES indices: Average annual household income was between $50-$60,000 (*SD* = $50,000; 50% response rate), and the average level of parent education included some college (it ranged from less than 7th grade to graduate-level degree; 53% response rate). This indicated that children came from diverse economic and educational backgrounds, with many lower SES families represented. Finally, parent responses to a question about the type of explanation they would provide their child about adaptation confirmed that children were not from backgrounds in which they were likely to receive extensive or accurate explanations of natural selection (94% of parents did not accurately describe natural selection; 56% response rate).[1]

Materials and Procedure

Study environment. As in Kelemen et al. (2014), trained experimenters individually tested children. However, all testing procedures occurred at the child's afterschool program rather than in a controlled laboratory environment. Two of the three afterschool programs were located within a public school. Children were either tested in an unused classroom or a space that closely resembled a typical classroom in that it contained visual media on the walls and learning materials (e.g., books, games, and toys) on shelves and other surfaces. While it is common practice for learning spaces to include these features, learning can be impaired in these kinds of

[1] Parents were asked to write down what they would tell their child if their child asked them, "How did the giraffe get its long neck?" Their open-ended responses were classified using the same criteria used to classify children's responses with the exception that knowledge of the facts was not evaluated and thus not included in the criteria.

visually distracting environments (e.g., Fischer, Godwin, & Seltman, 2014). Additionally, children were also subject to auditory distractions arising from the busy environment that included program activities taking place nearby, individuals or groups passing through the hallways, and occasional announcements coming over the intercom. This school-like environment was highly distinct from the calm, quiet, and visually undistracted bare-walled laboratory-testing environment of Kelemen et al. (2014).

Storybook. A custom-made picture storybook was employed because of the absence of commercially available picture books that accurately and comprehensively explain the logic of adaptation by natural selection. The book used was the same as that used in Experiment 2 of Kelemen et al. (2014). In general, a picture book format was implemented because it has numerous benefits: Children are naturally interested in picture books, and they invite a beneficial joint attentional learning context (e.g., Moore & Dunham, 1995; Tomasello & Farrar, 1986). Furthermore, by presenting a verbal narrative enriched by visual images, a picture book reduces children's cognitive load (Mayer & Moreno, 2003) while simultaneously supporting the paced sequential unfolding of a multifaceted causal explanation that fluidly incorporates new conceptual elements on a page-by-page basis (see also Kelemen et al., 2014).

The book employed color drawings of a fictional realistic species in their habitat. All illustrations were attractive yet deliberately unembellished by unnecessary detail, extraneous features, or garish color to avoid distracting from the causal explanation presented in the narrative text and images (DeLoache, 2004; Tare, Chiong, Ganea, & DeLoache, 2010). Across 12 pages, the book explained how the fictitious "pilosas" species went from having mostly wider trunks in the past to having mostly thinner trunks in the present due the process of differential survival and reproduction. Text was simply worded and deliberately devoid of any intentional or teleological language that might lead to misinterpretation or a misconception (see Emmons & Kelemen, 2015). Seven key biological concepts were causally woven together in the text: (1) the inherent variation of traits within a population; (2) habitat and food-source change as a result of climate change; (3) differential health and survival due to differential access to food; (4) differential reproduction due to differential health; (5) the reliable transmission of heritable physical traits across generations; (6) the stability and constancy of inherited traits over the lifespan; (7) trait-frequency changes over multiple generations.

The gradualness of adaptation was depicted across several pages showing that, over successive generations, pilosas with the disadvantageous trait (wider trunks) slowly diminished in number due to their reduced access to food and thus reduced survival and reproduction rates. Meanwhile, pilosas with the more advantageous trait (thinner trunks) gradually increased due to their enhanced survival and reproduction rates. The text further highlighted the concept of trait constancy because children are known to accept physical transformations over the lifespan as a function of inevitable growth (Hermann, French, DeHart, & Rosengren, 2013; Rosengren, Gelman, Kalish, McCormick, 1991). By making this concept explicit, the text was intended to reduce the likelihood children might incorrectly teleologically reason that beneficial traits could be tranformationally acquired over the lifespan in response to need. The storybook reading took about ten minutes.

Assessments. Children’s understanding of natural selection was assessed a total of three times: Once with a novel species before they heard the storybook (pre-test) and twice following the storybook reading in two post-tests: A comprehension post-test evaluated their understanding of adaptation within the pilosa species and a generalization post-test examined their ability to apply the logic of natural selection to another unfamiliar novel species that underwent adaptation. Materials used in the pre-test and generalization post-test were counterbalanced. Because of variable and unavoidable testing practicalities at different afterschool programs, some children completed the pre- and post-tests on one day (10 children) and some completed the pre-test on one day and both post-tests on another day (22 children). However, the storybook reading always immediately preceded the comprehension post-test. Unlike in Kelemen et al. (2014, Experiment 2), there was no ten-minute break between comprehension and generalization post-tests for any children due to time constraints. All assessments involved realistically drawn but visually distinct novel mammal species that underwent adaptation on a trait relevant to gaining access to food (necks, legs, facial parts). High structural alignment was maintained across assessments because children's ability to abstract concepts across examples is facilitated by deep structural similarities (Brown & Kane, 1988; Gentner & Loewenstein, 2003).

The questions used in each assessment were identical to Kelemen et al. (2014, Experiment 2). For each test, children were first asked a fixed set of six closed-ended questions to probe whether they grasped the isolated facts prerequisite to supporting an understanding of natural selection (see Table 1). Before any questions were asked, children were given information about and shown images of the past and present populations and habitats of the respective species. While viewing the habitat images and two species members—one with the advantageous trait and one with the disadvantageous trait—children answered four of the close-ended questions (i.e., two questions about differential survival and two about differential reproduction). To succeed on these questions, children had to consider the past and present trait frequency distributions (e.g., the distribution of pilosas with wider and thinner trunks) and the location of the species' food source in the past and present (e.g., where the insect food source lived). Children also had to infer that the trait of interest was relevant to gaining access to food, which was never explicitly stated during any assessment. The two other close-ended questions probed children's understanding of inheritance and trait constancy and were not directly tied to information about the past and present populations and habitats. Children were asked to justify their responses to all close-ended questions to see if their reasoning was correct or incorrect, and this justification—rather than their initial forced-choice response—determined whether they were credited with knowing the concept. Importantly, corrective feedback was never provided at any point in the assessment.

Following the isolated fact questions, children were asked four open-ended questions to examine their ability to self-generate an explanation of adaptation by natural selection (see Table 2). Children answered these questions while viewing the past and present populations. To encourage children to elaborate on their reasoning, they received prompts to expand their answers when self-generating explanations to the open-ended questions (see Table 2). Over the course of testing, all but one child interacted with two experimenters. This experimental feature was introduced in Kelemen et al. (2014, Experiment 2) to discourage children from shortcutting their answers when asked similar forms of a question repeatedly (over the course of three structurally aligned assessments) by the same person. All but six children were introduced to the second experimenter at the point of the storybook reading: The remaining children interacted with a new experimenter at the point of the generalization post-test.

Coding. As in Kelemen et al. (2014, Experiment 2), children's responses to all closed- and open-ended questions were coded based on a conceptual checklist and conservative coding rubric to determine their overall level of understanding of natural selection at each test time (see Table 3 for details and sample responses). This type of individual-based classification scheme looks at the whole of each child's theoretical understanding and permits examining individual learning of the complete causal mechanism of adaptation. By contrast, research using other, less conservative evaluation approaches have explored children's learning about individual evolutionary concepts in the absence of examining each child's complete theoretical framework, which has meant children have received credit for understanding evolutionary concepts even whilst displaying a misconception (e.g., Browning & Hohenstein, 2013; Legare, Evans, & Lane, 2013).

For each assessment, children's understanding was classified into one of five hierarchical levels. Children's understanding was categorized as Level 0, "no isolated facts," when responses to the close-ended isolated fact questions demonstrated insufficient knowledge of the requisite facts needed to support an understanding of natural selection, regardless of responses to open-ended questions. Children who did not respond correctly to at least five out of six of the close-ended questions fell into this category. Understanding was categorized as Level 1, "isolated facts but no natural-selection understanding," when it met the minimum criteria for factual understanding (five or more of the closed-ended questions) but did not reveal a correct selectionist-based understanding of adaptation by natural selection in the open-ended questions due to a lack of knowledge about the population-based process or as a result of stating a misconception. The three remaining levels (Levels 2 – 4) were reserved for responses that met the minimum criteria for factual understanding and also contained an accurate population-based selectionist description of adaptation absence any misconception: However, the degree of sophistication differed for each level.

In Level 2, "foundation for natural-selection understanding," children's responses focused on adaptation resulting from differential survival, that is, the concept that species members with disadvantageous traits died while those with advantageous traits survived. In

Level 3, “natural-selection understanding in one generation,” children’s responses explained adaptation both in terms of differential survival and differential reproduction, but ideas about the relative reproductive success of species members with advantageous traits were limited to considerations of the first generation after the climate change and their immediate descendants. Finally, in Level 4, “natural-selection understanding for multiple generations,” children’s responses were expanded such that they explicitly acknowledged that adaptation occurs over multiple generations. Crucially, a Level 2 or higher categorization was only assigned if children gave no signs of holding transformationist misconceptions that individuals acquire advantageous traits within their lifetimes at any point in the assessment. Interrater reliability between two coders was excellent ($\kappa = .97$).

Results

As in Kelemen et al. (2014), data were analyzed using repeated measures ordinal logistic regressions. These regressions examine how the distribution of children across the five hierarchical levels of natural selection understanding changed across the three assessment times (i.e., pretest, comprehension, and generalization). Odds ratio statistics from these analyses further indicated the magnitude of change in the odds that children’s understanding of natural selection improved by one or more levels between two specific assessment times.

Younger children. Repeated measures ordinal logistic regressions revealed that the storybook intervention induced learning, Wald $\chi^2(2) = 12.59$, $p < 0.01$ (see Figure 1). Given younger children’s starting levels of understanding at pretest, their odds of being in a higher level of natural selection understanding at comprehension increased twenty-two fold, OR = 22.57, $p < 0.001$, 95% CI [3.94, 129.32]: At pretest, 88% of children lacked sufficient knowledge of the individual biological facts. After hearing the storybook, 69% of children had acquired these isolated facts and 50% also displayed a Level 2 or higher population-based understanding. Indeed, 44% of children incorporated not only differential survival but also differential reproduction into their selectionist explanations such that they were in Levels 3 or 4. At generalization, 56% of children still demonstrated knowledge of isolated facts. However, reflecting the difficulties of generalization (Brown, Kane, & Long, 1989; Gentner, 1989), there was a significant three-fold decrease in children's odds of being in a higher level of natural selection understanding between the comprehension and generalization post-tests, OR = 0.30, $p = 0.02$, 95% CI [0.11, 0.81].

Older children. Repeated measures ordinal logistic regressions revealed that the revised storybook also induced learning in older children, Wald $\chi^2(2) = 31.41$, $p < 0.001$ (see Figure 1). Older children's odds of being in a higher level of natural selection understanding increased a substantial sixty-six fold from pretest to comprehension, OR = 66.36, $p < 0.001$, 95% CI [15.29, 287.98]. Among older children, 75% lacked sufficient knowledge of the individual facts at pretest and another 19% had the isolated facts but had not integrated this knowledge into a population-based explanation. After hearing the storybook, 100% of children had the individual facts and 81% had a selectionist understanding of adaptation that incorporated both differential survival and reproduction. Notably, 44% percent of these children displayed the highest level of understanding (Level 4) by describing natural selection occurring over multiple generations. Children also successfully applied what they learned from the storybook to a novel animal, demonstrating a non-significant change in their odds of being in a higher level of natural selection understanding from comprehension to generalization, $p = 0.09$.

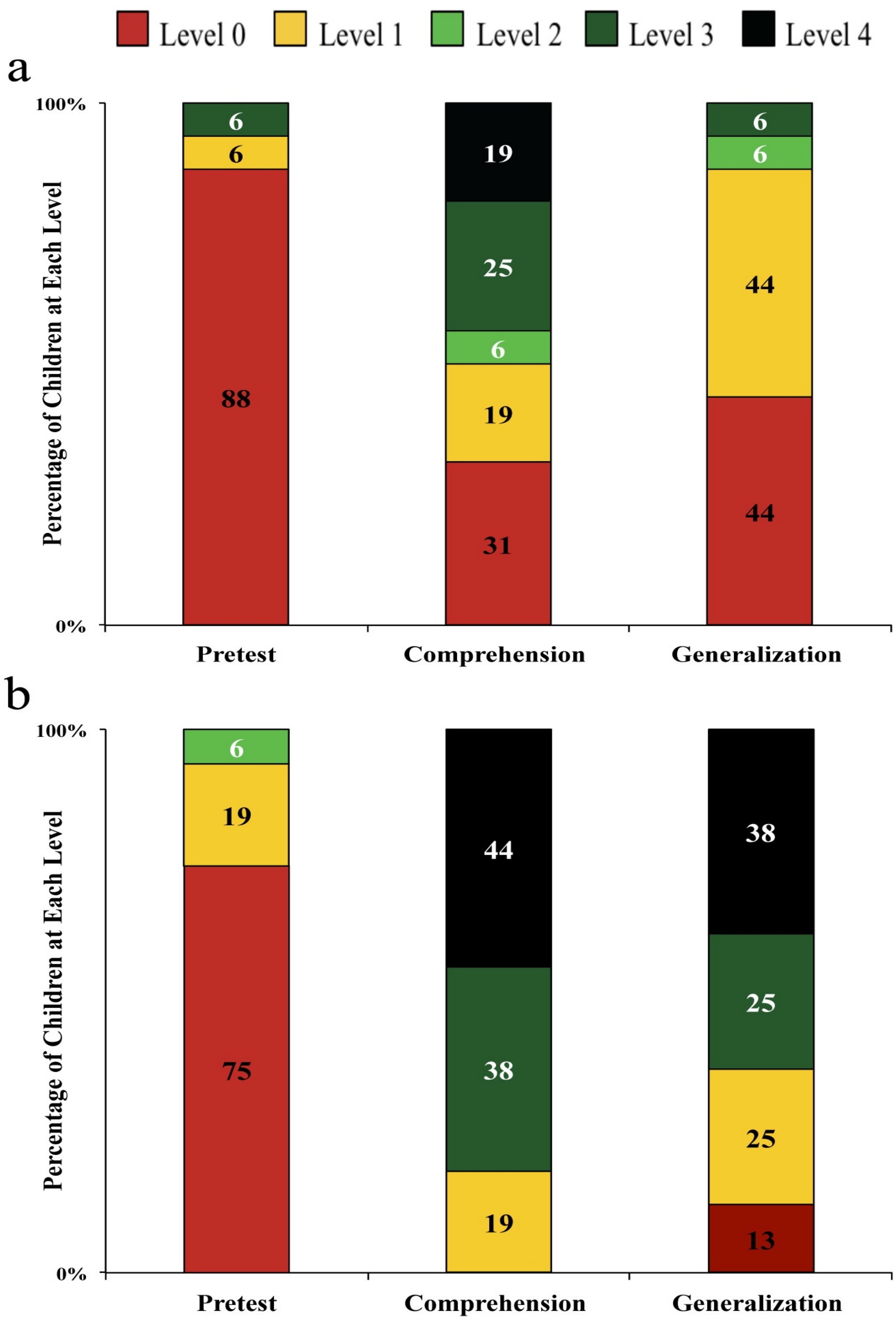

Figure 1. Percentages of (a) younger and (b) older children classified into the five levels of natural-selection understanding as a function of assessment. Because of rounding, percentages do not always add up to 100. Level 0 = no isolated facts; Level 1: isolated facts but no natural selection understanding; Level 2 = foundation for natural selection understanding; Level 3 = natural selection understanding in one generation; Level 4 = natural selection understanding for multiple generations.

Discussion

This investigation extends earlier lab-based research by showing that young children from a range of socio-economic, often bilingual, backgrounds can understand and apply the basic mechanism of within-species adaptation by natural selection when learning takes place in a typical school-like environment. Notably, as in Kelemen et al. (2014), older children outperformed younger children. However, in many respects, older children's performance in the present study was even more striking than that found in Kelemen et al. This is because in contrast to the 7- to 8-year-olds in the original research, the current sample of older children entered the study displaying far less background biological knowledge. Indeed, their level of factual knowledge at pre-test was more similar to that of younger kindergarten children in the present study than older children in the original laboratory-based sample. Like their younger counterparts then, before hearing the storybook, these older children did not initially display the prerequisite biological knowledge that would make them well prepared to understand the logic of adaptation. Despite this, after engaging with the storybook once, the majority of them not only achieved the two most sophisticated levels of natural selection understanding at the comprehension post-test but also demonstrated deep learning by generalizing their learning to a different novel animal.

By comparison, the concentration of younger kindergarten children's gains was in their acquisition and generalization of the isolated biological facts rather than in their deep coherent learning of the population-based selectionist theory of natural selection. While noting this, however, 51% of younger children nevertheless displayed a coherent understanding of the mechanism of adaptation during the comprehension test despite their difficulty abstracting the theory and generalizing it to a novel animal. Furthermore, when younger children gave a correct population-based explanation of natural selection, they generally provided a more sophisticated account that referenced both differential survival and reproduction (Level 3) or went further by incorporating the idea that the process occurs over multiple generations (Level 4). Thus, while younger children did not demonstrate the same learning gains as older children, a substantial proportion were able to grasp the selectionist logic and articulate the multi-step causal process outlined in the storybook.

Older children's marked abilities to learn and generalize the selectionist logic of natural selection both in the present study and Kelemen et al. (2014) raise questions about the source of their enhanced learning. More developed cognitive and linguistic abilities—including improved working memory, attention, and expressive language—presumably contributed to their stronger performance (see also Kelemen et al., 2014). However, there is an additional explanation for older children's more pronounced grasp of the selectionist mechanism. Prior research has shown that 7- to 8-year-old children are better able to represent a key evolutionary concept—within-species biological variation—than 5- to 6-year-olds (Emmons & Kelemen, 2015; see also Legare et al., 2013). Within-species variation is the condition that allows the selectionist process of differential survival and reproduction to occur. Given this, children who can inhibit their essentialist tendencies such that they can represent variation should be in a better position to learn the logic of natural selection and avoid the transformationist misconceptions that contributed to many younger children's failures and that are widely observed among older students (Gregory, 2009). In light of this tentative interpretation, future research should seek to directly explore the relation between children's understanding of within-species variation and their abilities to learn natural selection. At least among adults, a connection between variation and adaptation understanding has been established (Shtulman & Schulz, 2008).

Based on the developmental patterns in the present findings, one interpretation is that the storybook intervention would be most effective when introduced in second grade. While that may be true, it may also be the case that an earlier, and possibly repeated, introduction to the storybook may help to support younger children's grasp of biological facts that have the potential to not only aid in their learning about natural selection but also in their ability to more deeply understand living things in a general sense, including understanding the biological processes they undergo (e.g., genetic inheritance). Additional work is needed to see what, if any, far-reaching benefits kindergarten children might gain from the storybook intervention given that the current afterschool-based sample did not display marked abilities to comprehend and generalize the comprehensive selectionist logic of natural selection following engagement with a single storybook reading.

Implications for Education and Practitioners

Thirty years of research has shown that older students, adults, and educators have pervasive misconceptions about natural selection (Gregory, 2009). These misconceptions appear to be rooted in early emerging cognitive biases to essentialize species and teleologically explain the natural world (e.g., Kelemen, 2012; Rosengren et al., 2012) that when left unchallenged can become habitual and entrenched (Kelemen et al., 2014). Results from the current study combined with those from Kelemen et al. (2014) challenge conventional educational wisdom that young children are largely incapable of understanding casually complex abstract ideas. They therefore also challenge educational guidelines recommending that instruction should focus on gradual, piecemeal expertise-building before presenting information on complex theories as a comprehensive whole. Instead, what the present findings support is that more comprehensive theoretical content can be introduced earlier in the curriculum as part of a long-term strategy that involves spaced, progressive revisitations of concepts to improve scientific literacy. By virtue of starting earlier, interventions targeting young children might help to increase the chances that a scientifically accurate understanding is acquired and maintained longer term (Emmons & Kelemen, 2015; Kelemen et al., 2014). With this in mind, how then might educators implement strategies to successfully teach counterintuitive biological concepts to young learners?

First, children's abilities to extract abstract theoretical content from educational materials should not be underestimated. Children have natural drives to understand how the world works and possess robust theory building capacities (Carey, 1985; Gopnik & Meltzoff, 1997; Keil, 1992; Wellman & Gelman, 1992). They are also naturally interested in animals and the biological world (e.g., LoBue, Pickard, Sherman, Axford, & DeLoache, 2012; Kelemen, Callanan, Casler, & Pérez-Granados, 2005). Educators can leverage these factors when introducing biological content. In particular, they can aim to provide mechanistically detailed scientific explanations that both build young children's factual knowledge and their theoretical understanding. As shown in the present study, children are capable of extracting biological factual information when it is embedded within a more extensive causally cohesive theoretical explanation: Thus, it may be entirely unnecessary—and perhaps even less ideal—to provide tutoring on individual component facts out of context of a larger theoretical framework. Importantly, the explanations provided should be simple but cohesive and complete to avoid explanatory gaps that could be subject to reinterpretation by children's intuitive and often incorrect causal frameworks.

Relatedly, educators should be mindful of the explanatory biases children possess and avoid language that can perpetuate an incorrect understanding of biological processes such as natural selection. For example, when describing how species change, it seems advisable to avoid language that could be misconstrued as suggesting that change occurs at that individual level (e.g., "giraffes necks grew longer over time") or is driven by need (e.g., "giraffes' necks changed because they needed to reach high leaves"). Although commonly used, these expressions were deliberately avoided in the storybook due to their ambiguity and connection to older students' transformationist misconceptions about adaptation (Emmons & Kelemen, 2015; Gregory, 2009; but see Evans, Legare, & Rosengren, 2011; Legare et al., 2013; Zohar & Ginossar, 1998). Instead, a focus on within-species variation and the idea change occurs at a population, rather than individual, level may help to limit children's misunderstandings about adaptation.

Educators may also consider developing curriculum around scientifically sound narrative-based materials such as the picture storybook used here. As demonstrated by the present results, image-supported narrative explanations can go a long way in facilitating understanding of complex material. Children like stories, and they can provide a pragmatically useful entry point for active scientific inquiry guided by elementary-school teachers who might otherwise feel uncomfortable or unfamiliar with the specific details of certain scientific content. However, educators should exercise care when selecting narrative materials to utilize in the classroom given that many may contain the very misconceptions that teachers are working against yet they may themselves non-reflectively hold and inadvertently convey in their teaching practices (Ansberry & Morgan, 2010). Finally, although narrative-based materials can be simple but powerful learning tools, incorporating additional active-learning activities may help to promote deeper understanding and enduring learning. Putting aside discussion of the potential benefits of supplementary hands-on learning opportunities, simply encouraging young children to self-explain what they have learned is likely to facilitate deeper processing and abstraction of information (e.g., Ainsworth & Loizou, 2003; Chi, De Leeuw, Chiu, & Lavancher, 2010).

Although additional research is needed, opportunities for self-explanation—like those offered by the present assessments—may be a central part of children's learning and retention of complex theoretical ideas.

Conclusion

In sum, the present study demonstrates that young children from a range of backgrounds can successfully acquire biological facts and a basic comprehensive understanding of natural selection when learning and evaluation occurs in a school-like environment. These results illustrate the potential of early education interventions that derive from synthesizing and implementing findings from cognitive development, the learning sciences, and science education research. They also have numerous implications for biology education specifically. Our hope is that these findings will serve to foster interdisciplinary discussions about the best ways to promote long-term understanding of counter-intuitive ideas and further the development of progressive theory-based education tools targeting learning from earlier ages.

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Table 1

Closed-ended Isolated Fact Questions with Sample Justifications

Concept	Question	Accurate Justification	Inaccurate Justification
Differential Survival	Nowadays, will a *wilkie with shorter legs* probably be healthy and live for a long time? Why/Why not?	No, because they can't reach up to the yellow berries.	No, I don't know. I'm not sure.
	Nowadays, will a *rudoo with a longer neck* probably be healthy and live for a long time? Why/Why not?	Yeah, because it has a longer neck and it can reach food that's higher.	No, because it's an adult, and when you're an adult, you have to die.
Differential Reproduction	Nowadays, will a *rudoo with a shorter neck* probably have lots of children? Why/Why not?	No, because the fruit is growing on top and they they're too small to reach it.	No, um because they might be too old to have children.
	Nowadays, will a *wilkie with longer legs* probably have lots of children? Why/Why not?	Yeah, cause it has a lot of energy inside it.	Yeah, because it's like an adult, so it might have babies, cause adults always have babies.
Trait Knowledge: Inheritance	These grown-up *wilkies* both have *shorter legs*. If these two *wilkies* had a child, what kind of *legs [longer or shorter]* would their child probably have? Why?	Shorter, cause when it is born it has the same legs as its parents.	Shorter, because it's little.
Trait Knowledge: Trait Constancy	See this young *rudoo*. It was born with *a shorter neck*. When this *rudoo* grows up to be an adult, what kind of *neck* will it have *[longer or shorter]*? Why?	Shorter, because …its just gonna be them [the rudoo] when they're like bigger so they're not gonna change that much…	A longer neck, cause when you grow, you grow bigger.

Note. Italicized information differed depending on the animal species under consideration.

Table 2

Open-ended Questions

Questions
Many hundreds of years ago most of the grown-up *pilosas* had *wider trunks* but now most of the grown-up *pilosas* have *thinner trunks*. How do you think that happened?
What happened to *pilosas* with *thinner trunks*? Why? What happened next after…? [E repeats P's response to previous question] Why? What happened next after…? [E repeats P's response to previous question] Why?
What happened to *pilosas* with *wider trunks*? Why? What happened next after…? [E repeats P's response to previous question] Why? What happened next after…? [E repeats P's response to previous question] Why?
Did it take a short time or a long time for *pilosas* to go from having mostly *wider trunks* in the past to having mostly *thinner trunks* now? Why?

Note. Italicized information differed depending on the animal species under consideration. Question orders about advantaged and disadvantaged animals were counterbalanced.

Table 3

Conceptual Checklist of Natural Selection (NS) Understanding and Sample Partial Open-Ended Responses

Levels and Checklist	Partial Open-ended Responses Following One or More of the Four Open-ended Questions[1]
Level 0: No isolated facts Does not meet criteria for isolated facts[1]	N/A
Level 1: Isolated facts but no NS understanding Meets criteria for isolated facts[2] but one, or more, of the following are present: (1) Misconception; (2) No mention of differential survival advantage; (3) Inaccurate mention of differential survival or reproduction	*Misconception:* E: …How do you think that happened? P: Cause they're grown up. See, see how it had short body (points to animals in past population) and see some of these have bigger bodies (points to animals in present population). And look it's all grown up. *Inaccurate mention of differential survival:* E: So, what happened to pilosas with wider trunks? P: They stayed alive for a lot of days. E: And why is that? P: Because they can reach the food.
Level 2: Foundation for NS understanding All of the following are present: (1) Meets criteria for isolated facts; (2) No misconception; (3) Accurate mention of differential survival	*Differential survival, no differential reproduction:* E. What happened to pilosas with wider trunks? P: They died. E: Why's that? P: Because they didn't eat. They like ate only one each day. E: What happened to pilosas with thinner trunks? P: They keep, they had, they lived a long time. E: Why's that? P: Because they ate a lot of it, like eleven each day. E: So what happened after they lived a long time? P: They died. E: Why's that? P: Because they got old and old and weak.
Level 3: NS understanding in one generation All of the following are present: (1) Meets criteria for isolated facts; (2) No misconception; (3) Accurate mention of differential survival; (4) Accurate mention of differential reproduction in	*Differential survival and differential reproduction:* What happened to pilosas with wider trunks? P: Then they had one baby or none because they died. E: And why did they only have one baby or no babies because they might've died? P: Um because they couldn't reach the milli bugs when it got really hot. It was all the way, they were all the way down under the ground.

one generation	E: So, what happened to pilosas with thinner trunks? P: They were really healthy and got two children. E: Why is that? P: Because they were healthier and they ate a lot more milli bugs.
Level 4: NS understanding for multiple generations All of the following are present: (1) Meets criteria for isolated facts; (2) No misconception; (3) Accurate mention of differential survival; (4) Accurate mention of differential reproduction in one generation; (5) Accurate mention of differential reproduction in multiple generations	*Differential survival and reproduction in multiple generations* E: …How do you think that happened? P: When the um, the ones that had thinner, the grown-ups that had thinner ones got to eat a lot and they had a lot of children so the children had a lot of, were a lot healthy and had a lot of energy so they had a lot of children. But the ones that um have um thicker trunks they um, they couldn't eat so much so they only could have one baby so they could um, so the ones that have less, the ones that have less babies are then um, get one more baby again and then they'll just die, but the ones with um, thinner ones, thinner trunks are gonna live longer.

Note. E = Experimenter; P = Participant. Italicized information differed depending species. [1] The initial open-ended question, "How do you think that (population change) happened?" was followed by subsequent requests for elaboration (see Table 2). Sample responses reported here have been edited for length such that only partial responses, often in connection to requests for elaboration, are shown to illustrate specific concepts that were coded as part of the conceptual checklist; however, these partial responses do not reflect any one child's entire open-ended response. [2] "Meets criteria for isolated facts" was defined as correctly answering and justifying 5 out of 6 of the closed-ended questions.