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Young Children Can Be Taught Basic Natural Selection Using a Picture-Storybook Intervention

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Abstract

Adaptation by natural selection is a core mechanism of evolution. It is also one of the most widely misunderstood scientific processes. Misconceptions are rooted in cognitive biases found in preschoolers, yet concerns about complexity mean that adaptation by natural selection is generally not comprehensively taught until adolescence. This is long after untutored theoretical misunderstandings are likely to have become entrenched. In a novel approach, we explored 5- to 8-year-olds' capacities to learn a basic but theoretically coherent mechanistic explanation of adaptation through a custom storybook intervention. Experiment 1 showed that children understood the population-based logic of natural selection and also generalized it. Furthermore, learning endured 3 months later. Experiment 2 replicated these results and showed that children understood and applied an even more nuanced mechanistic causal explanation. The findings demonstrate that, contrary to conventional educational wisdom, basic natural selection is teachable in early childhood. Theory-driven interventions using picture storybooks with rich explanatory structure are beneficial.

Keywords

evolution, natural selection, learning, children, childhood development, science education, cognition

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Adaptation by natural selection is central to understanding the complexity and functional specialization of living things. However, decades of studies have demonstrated that adaptation by natural selection is one of the most widely misunderstood concepts in science. Misconceptions are widespread not only among high-school students and undergraduates (Bishop & Anderson, 1990; Brumby, 1984; Nehm & Reilly, 2007; for a review, see Gregory, 2009), who are often targets of instruction on the topic, but also, disturbingly, among many of the teachers expected to teach natural selection (Nehm, Kim, & Sheppard, 2009; Nehm & Schonfeld, 2007).

The misconceptions about adaptation are varied. Instead of construing it as a change in trait frequency that occurs because some organisms in a phenotypically variable population survive and reproduce more successfully in an environment over time, students tend to focus on individuals rather than populations as the locus of change. A classic example is the teleological idea that giraffes evolved long necks because they needed to reach high leaves. The error here rests not in the belief that trait functionality is relevant to adaptation but instead in the mistaken frameworks of untutored causal assumptions, or *intuitive theories*, in which that belief is embedded. These include ideas that effortful action on the part of individuals or the personified force of "Evolution" is capable of transforming species members' essential nature so that they attain functionally beneficial, heritable traits (Gregory, 2009). Problematically, these ideas, which focus on goal-directed transformations of individuals within a lifetime rather than the non-goal-directed population-based process of differential survival and reproduction, are resistant

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to change: Students demonstrate only modest improvements in understanding after sometimes extended instruction on natural selection (Ferrari & Chi, 1998; Jensen & Finley, 1995; Vlaardingerbroek & Roederer, 1997). This educational challenge has broad implications given that natural selection is relevant to understanding not only within-species adaptation—the focus of the current article—but also larger-scale macroevolutionary change, such as speciation.

With regard to understanding the source of the problem, developmental research points in an important direction. From early in development, young children display conceptual biases that can be useful in everyday reasoning but can also begin to interact to yield older students' theoretical misconceptions about adaptation (Coley & Tanner, 2012; Rosengren, Brem, Evans, & Sinatra, 2012). For example, children in preschool and early elementary school show teleological biases to explain the origins of natural objects' properties by reference to functions (Keil, 1995; Kelemen, 2004), intentionality biases to construe events and objects as intentionally caused (Evans, 2001; Rosset & Rottman, 2014), and essentialist biases to view species members as sharing an invariant, inviolable essence (Gelman, 2003; Shtulman & Shulz, 2008). Children are natural explanation seekers who organize their knowledge into theoretical frameworks (Carey, 1985; Gopnik & Meltzoff, 1997; Wellman & Gelman, 1992), and by the time children are 6 to 10 years old, these potentially independent conceptual biases show signs of integrating into intuitive causal theories that connect ideas about biological functionality in nature with notions of invariant essences (Shtulman & Shulz, 2008) and goal-directed design (Kelemen & DiYanni, 2005). In short, a by-product of useful everyday cognition is that untutored theories that impede older students' understanding of natural selection are already beginning to coalesce in early elementary school, if not before.

Given these findings, recommended timetables for exposing children to explanations of adaptation are a cause for concern. In the United States, science education standards for kindergarten through grade 12 suggest that a comprehensive presentation of the logic of adaptation by natural selection should occur between grades 8 and 12 (Achieve, Inc., 2013; American Association for the Advancement of Science, 2009; National Research Council, 2012). That is, although teaching about some conceptual components of the theory is recommended for younger children, instruction that explicitly explains adaptation using a comprehensive population-based mechanism that integrates the concepts of within-species variation, environmental context, inheritance, differential survival, and differential reproduction is typically delayed until students are 13 to 18 years old (Achieve, Inc., 2013, Section HS-LS4; National Research Council, 2012, Section LS4.B; but see Scott, 2012, on the uneven implementation of evolution standards). The rationale underlying the recommended timing is understandable: Even in its simplest form, adaptation by natural selection is a multifaceted, causally complex mechanism. It is therefore assumed that children first need gradual tutoring on isolated component facts, such as the connection between food and survival or between trait variation and differential survival, before progressing to tutoring on the selectionist mechanism as a coherent integrated whole.

However, given children's emerging scientifically inaccurate, untutored theories, it is questionable whether this piecemeal approach to instruction is ideal, especially considering the potential advantages of offering children an age-appropriate but accurate and causally comprehensive version of the theory. The latter alternative would not only familiarize children with the individual facts but also begin to establish a coherent population-based explanatory framework that, with repeated familiarization, might become habitual enough to resist reinterpretation by biases and competition from typically developing intuitive theoretical ideas. According to this view, then, an optimal time to begin comprehensively familiarizing children with counterintuitive scientific explanations is relatively early, during ages at which alternative commonsense explanatory frameworks are still relatively fragmentary (e.g., Kelemen & DiYanni, 2005).

Furthermore, considered together, individual developmental findings suggest that delaying comprehensive instruction on adaptation until adolescence may be unnecessary: By kindergarten, many children already know some isolated biological facts that collectively might support a grasp of the theory. For example, they know that body parts perform survival functions (Jaakkola & Slaughter, 2002; Keil, 1995; Kelemen, 1999), that animals need food to remain healthy and alive (Inagaki & Hatano, 2002), and that offspring tend to resemble their birth parents (Gelman & Wellman, 1991; Solomon, Johnson, Zaitchik, & Carey, 1996; Springer & Keil, 1989). Although children have some of these facts, what they do not possess is an alternative to commonsense ways of combining them when they explain why animals have functional traits and show signs of apparent design. In this research, we therefore sought to capitalize on young children's natural theory-building drives to offer them such an alternative.

Taking advantage of findings on young children's factual biological knowledge (see also Gripshover & Markman, 2013), their natural interest in the function of traits, and the likely fragility of emerging intuitive theories, in two experiments we explored the effectiveness of a custom picture-storybook intervention in facilitating 5- to 8-year-olds' abilities to understand and apply a basic but comprehensive explanation of within-species adaptation by natural selection. We used a picture storybook because the format is child friendly and invites a beneficial joint-attentional learning context. Furthermore, the image-enriched narrative reduces cognitive load (Mayer & Moreno, 2003) but supports a multifaceted causal explanation (for other narrative-based approaches with related but different goals, see Brown, Kane, & Long, 1989; Browning & Hohenstein, 2013; Legare, Lane, & Evans, 2013). Finally, young children have been found to learn simple biological facts from picture books and to generalize those facts to real animals (Ganea, Ma, & DeLoache, 2011).

Despite the theoretical reasons for targeting children in early elementary school, young children's information-processing limitations (Bjorklund, 2005; Friedman, 1977) nevertheless gave us reasons to suspect that even a basic version of the logic of adaptation would be too hard. In Experiment 1, we therefore began with a storybook describing a more easily conceptualized case: rapid natural selection in a fictional mammalian population ("pilosas") that experienced sudden die-off because of the effects of extreme climate change on the location of their food source. The narrative focused on how the population of pilosas was immediately affected by having their food source of insects move underground into deep, narrow tunnels. Each page of the narrative incorporated a new fact that mechanistically elaborated how differential survival and reproduction caused the highly variable trunk size of the population of pilosas (wide and thin trunks were equally common), to become less variable (thin trunks came to predominate). After a pretest assessment, children's comprehension and generalization of the storybook explanation was evaluated with two assessments immediately after they heard the storybook and two more 3 months later. Based on the results of Experiment 1, Experiment 2 explored children's comprehension and generalization of an even more nuanced explanation of adaptation: Rather than focusing on the initial population and their immediate offspring, the storybook emphasized gradual natural selection over multiple generations.

Experiment 1

Method

Participants. Twenty-eight 5- to 6-year-olds (17 boys, 11 girls; mean age = 5 years 9 months, *SD* = 6 months) and thirty-three 7- to 8-year-olds (15 boys, 18 girls; mean age = 7 years 9 months, *SD* = 5 months) were recruited from Boston (73% White, 10% Asian, 2% Hispanic, 2% Black, and 13% other or unreported race). Children were tested individually for 60 min on Day 1. A subset (younger children: *n* = 21; older children: *n* = 23) returned 3 months later for Day 2 testing. These children were tested individually for 30 min on Day 2. Questionnaires assessing parental explanations of adaptation indicated that the children came from backgrounds in which marked knowledge of natural selection was absent.

Materials and procedure. The custom 10-page storybook used realistic pictures and factual narrative with nonteleological, nonintentional language to answer the question posed at the book's beginning: Why did pilosas change from having highly variable trunk widths in the past to having predominantly thin trunks now? The explanation then unfolded, tightly causally connecting information on six natural selection concepts: trait variation within a population, habitat and food-source change in response to abrupt climate change, differential health and survival due to differential food access, differential reproduction due to differential health, trait inheritance, and trait-frequency change over multiple generations. Although multiple generations were depicted, most of the book focused on describing adaptation in the initial population and their immediate offspring. Reading the book to children took 10 min.

The children's understanding of basic natural selection was assessed with a novel animal population before they read the storybook (Day 1 pretest) and twice immediately afterward: once to explore the children's comprehension of the population-based logic of the pilosa storybook (Day 1 comprehension test) and once to explore their ability to generalize it to a novel species (Day 1 generalization test). Long-term retention was explored in a subset of children 3 months later through a second assessment of comprehension about the pilosas (Day 2 comprehension test) and a second assessment of generalization to yet another novel species (Day 2 generalization test). Each conceptually parallel assessment was composed of five closed-ended questions and five open-ended questions. The closed-ended questions, which also requested justifications for the children's answers, evaluated the children's knowledge of isolated component facts relevant to the natural-selection explanation (e.g., the relationship between food and health or between health and fecundity). The open-ended questions probed the children's capacity to self-generate a causally coherent explanation of adaptation that integrated knowledge of the isolated component facts.

The most central of the open-ended questions directly asked the children to explain the change in trait frequency across time (e.g., why do pilosas have only thin trunks now?). Self-generating accurate explanations after hearing the storybook was assumed to facilitate the children's comprehension and abstraction of the causal logic. However, the children never received corrective feedback: Those who failed to grasp the causal logic were therefore likely to falter across all posttest assessments. Furthermore, open-ended questions and follow-up prompts were structured so that they would elicit the children's potentially underlying inaccurate causal ideas (e.g., transformationist misconceptions) as well as their accurate ones. Tables S1, S2, and S3 in the Supplemental Material available online provide all questions used in Experiment 1 along with sample responses.

We began each assessment by introducing the children to the fictional species under question via four realistic pictures that showed the ancestral population, the ancestral habitat, the contemporary population, and the contemporary habitat. The children then received the standard set of 10 assessment questions. The response options for each of the five closed-ended questions about isolated facts consisted of two pictures. The children answered by pointing to one of the pictures and justifying their response. Credit for understanding each isolated fact was given only if a child selected the correct picture and correctly justified his or her choice. Open-ended questions were accompanied by pictures of the ancestral and contemporary populations to which the children could refer when causally explaining why the species changed over time and what happened to physically disadvantaged and advantaged members. The species presented in the pretest, comprehension tests, and generalization tests were physically dissimilar (e.g., birds, okapi-like mammals) and had unique habitats. Because of the numerous disparities in surface structure that resulted from using dissimilar species and environmental contexts in each assessment, a focus on explaining adaptation of traits somehow related to food acquisition (e.g., necks, trunks, beaks) held across all assessments. We maintained this focus because generalization is recognized as one of the hardest tasks in education, and prior research (e.g., Gentner, 1989) indicated that we were already substantially challenging the children's transfer abilities with the variabilities in surface structure already introduced.

A conceptual checklist and conservative coding rubric that considered responses to all 10 closed- and open-ended questions were applied to each assessment. The overall understanding of natural selection displayed on an assessment was then categorized into one of five hierarchical levels. Table S3 in the Supplemental Material provides details on the checklist. The Supplemental Material provides further details on the coding. Given our view that correct factual knowledge was prerequisite to any accurate population-based understanding of adaptation, a code of Level 0, "no isolated facts," was assigned when responses to the closed-ended questions demonstrated insufficient knowledge of the requisite isolated facts (fewer than four correct answers to the five closed-ended questions) regardless of responses to open-ended questions. A code of Level 1, "isolated facts but no natural-selection understanding," was assigned when responses to the closed-ended questions revealed sufficient knowledge of isolated facts (four or more correct answers to the five closed-ended questions) but an inability to integrate those facts into a coherent, accurate, self-generated explanation of population-based change when responding to open-ended questions.

In Level 2, "foundation for natural-selection understanding," closed-ended responses demonstrated sufficient isolated factual knowledge (four or more correct answers to the five closed-ended questions), and open-ended responses revealed an accurate, causally coherent, yet incomplete self-generated population-based explanation focused on adaptations arising through differential survival. In Level 3, "natural-selection understanding in one generation," responses revealed sufficient factual knowledge (four or more correct answers to the five closed-ended questions) and open-ended responses revealed an accurate, self-generated, population-based explanation that adaptations arise through differential survival and differential reproduction, but the explanation was limited to referencing the initial population and their immediate descendants. Level 4, "natural selection-understanding in multiple generations," was similar to Level 3, but self-generated explanations to open-ended questions also indicated that natural selection occurs over multiple generations.

In contrast to other explorations of children's evolutionary ideas (e.g., Browning & Hohenstein, 2013; Legare et al., 2013), in this study, children were credited with understanding of natural selection (Level 2 or higher) only when, at minimum, they correctly integrated information about differential survival and showed no signs, at any point on an assessment, of transformationist misconceptions that individuals acquire advantageous traits within their lifetimes. Interrater reliability between two coders was excellent ($\kappa = .84$).

Results

Repeated measures ordinal logistic regressions examined how the distribution of children across the five hierarchical levels of natural-selection understanding changed across the five assessment times. 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. Analyses revealed that the intervention induced learning among younger children, Wald $\chi^2(4, N = 126) = 33.29$, $p < .001$ (see Fig. 1a). Given their starting levels of understanding at the pretest, the odds

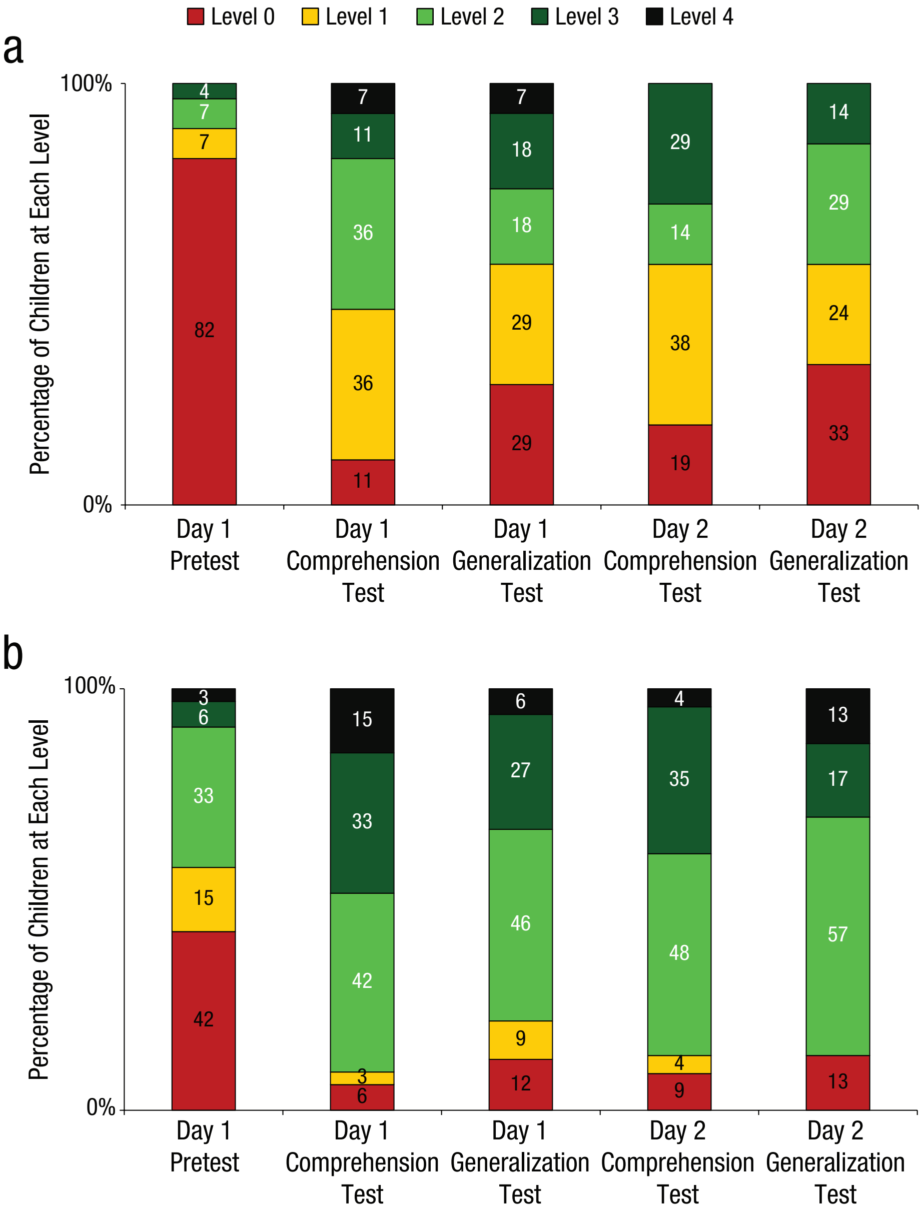

Fig. 1. Results from Experiment 1: percentages of (a) younger and (b) older children classified into the five levels of natural-selection understanding as a function of assessment. Because of rounding, percentages do not always add up to 100. Level 0 = no isolated facts; Level 1 = isolated facts but 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.

ratio for children's exhibiting a higher level of natural-selection understanding on the comprehension test on Day 1 was 18.68, $p < .001$, 95% confidence interval (CI) = [6.74, 51.73]. Specifically, on the pretest, 82% of the children were at Level 0, displaying insufficient knowledge of the facts to be credited with any natural-selection understanding; after hearing the storybook, only 11% were at that level. This change did not occur simply because children acquired an atheoretical understanding of isolated facts. Before hearing the story, only 11% of children displayed a population-based logic (Level 2 or higher). After hearing the story, 54% had integrated the facts into an accurate population-based explanation that incorporated, at minimum, the concept of differential survival.

In addition to being able to understand the population-level logic of the storybook, the children successfully generalized this logic to an entirely new animal despite the challenges of transfer (Brown et al., 1989): There was no significant change in children's odds of exhibiting a higher level of natural-selection understanding between the Day 1 comprehension and generalization tests, $p = .14$. The younger children's learning also endured over 3 months: They showed no significant change in odds between the comprehension test on Day 1 and either the comprehension test on Day 2, $p = .06$, or the more challenging generalization test on Day 2, $p = .39$.

Older children. The intervention also induced learning among older children, Wald $\chi^2(4, N = 145) = 31.51$, $p < .001$ (see Fig. 1b). Many older children entered the experiment already possessing sufficient knowledge of the isolated facts and even some theory. Nevertheless, the odds ratio for children's exhibiting a higher level of natural-selection understanding on the comprehension test on Day 1, relative to the pretest, was 11.54, $p < .001$, 95% CI = [4.78, 27.86]. This was because the storybook intervention bolstered their factual knowledge and ability to integrate those facts into a coherent population-based theory. The percentage of children with sufficient knowledge of the isolated facts (Level 1 and above) increased from 57% to 93% after exposure to the storybook, 90% of children displaying a Level 2 or higher understanding of natural selection on the Day 1 comprehension test. Although only 9% of children displayed a Level 3 or 4 understanding of natural selection on the pretest, this percentage rose to 48% on the comprehension test.

Although children's odds of being in a higher level of natural-selection understanding showed a small decrease between the comprehension and generalization tests on Day 1, odds ratio = 0.47, $p = .03$, 95% CI = [0.24, 0.91], the children remained largely successful in applying what they learned from the storybook to a novel animal: Seventy-nine percent continued to display a Level 2 or higher understanding of natural selection on the Day 1 generalization test. This small drop in performance disappeared when the children were assessed again 3 months later. Specifically, there was no difference in their odds of exhibiting a higher level of natural-selection understanding between the comprehension tests on Days 1 and 2, $p = .14$, or between the comprehension test on Day 2 and the generalization test on Day 2, $p = .22$. Like younger children, the older children therefore showed learning that was not only robust and generalizable but also enduring.

Discussion

Experiment 1 provided initial evidence that, contrary to conventional educational wisdom, young children can grasp the population-based logic of natural selection when it is presented in a basic, cohesive, comprehensive way: Five- to 8-year-olds showed substantial learning from hearing and explaining the 10-page storybook. Furthermore, their understanding was coherent. Not only did the children demonstrate increased knowledge of isolated biological facts, but they also integrated those facts into a cogent population-based understanding of adaptation when they self-generated explanations to open-ended questions that pushed them to reveal the accuracy of their underlying reasoning. Despite the absence of corrective feedback, this understanding was then transferred to new cases and retained over time, and the children's levels of understanding remained constant over 3 months. Comprehension and the challenging task of generalization were particularly pronounced among the 7- to 8-year-olds. Transcripts suggested that this was due to their enhanced verbal and information-processing skills.

Such results offered substantial reasons for optimism about children's explanatory capabilities and the instructional format represented by the storybook intervention. However, the unanticipated degree of learning raised questions about children's potential for even greater mechanistic sophistication. Because of concerns about children's information-processing limitations, including limitations on their abilities to represent extended time (e.g., Friedman, 1977), in Experiment 1 we used a storybook that presented a case of rapid natural selection wherein adaptation occurred largely because of differential survival and reproduction in the first generation of pilosas born after the weather changed. Perhaps unsurprisingly, many children focused their explanations on the initial generation too. In Experiment 2, we therefore modified the storybook to present a more gradual process that emphasized differential reproduction over multiple generations. This allowed us to explore children's ability to understand a more nuanced, complex explanation of adaptation, and it also provided a test of the replicability of Experiment 1.

Experiment 2

Method

Participants. Sixteen 5- to 6-year-olds (10 boys, 6 girls; mean age = 6 years 0 months, *SD* = 4 months) and sixteen 7- to 8-year-olds (7 boys, 9 girls; mean age = 8 years 3 months, *SD* = 3 months) were recruited from Boston (75% White, 6% Asian, 3% Hispanic, 6% Black, and 9% other race). Testing took about 60 min. Questionnaires assessing parental explanations of adaptation indicated that the children came from backgrounds in which marked knowledge of natural selection was absent.

Materials and procedure. Experiment 2 had the same design as Experiment 1 but focused on immediate comprehension and generalization: Children completed a pretest involving a novel species, a comprehension test on the pilosas, and a generalization test involving another novel species, all on the same day. A delayed assessment at 3 months was not possible because of high participant attrition over summer vacation. Tables S1, S2, and S3 in the Supplemental Material provide all questions used in Experiment 2 along with sample responses.

The revised storybook causally connected the same six concepts as the earlier version. In addition, the book explicitly incorporated the concept of trait constancy to highlight that the kind of inherited traits displayed by offspring at birth do not change during an individual's lifetime in response to need. To emphasize a gradualist process of natural selection, we modified the story: Disadvantaged pilosas no longer experienced immediate die-off when the climate and location of their food changed. Instead, the number of animals that inherited the more disadvantaged trait diminished over time as a result of gradual differential reproduction. Images visually represented the numerical takeover of reproductively successful pilosas over successive generations.

The assessments were structured as in Experiment 1, but each consisted of six closed-ended, isolated-fact questions and four open-ended questions that explored the children's capacities to self-generate the logic of natural selection. Compared to the children in Experiment 1, the children in Experiment 2 received more prompts when self-generating their explanations to open-ended questions (e.g., "What happened next?") in each assessment. Because prompts encouraged the children to elaborate on their own prior utterances, they performed two functions. First, they could more clearly reveal misconceptions underlying an abbreviated, apparently accurate, initial response. Second, they could reveal greater mechanistic understanding than initial utterances implied (see examples in the Supplemental Material). Finally, conversational pragmatics that potentially caused older children's mild performance dip between the Day 1 comprehension and generalization tests in Experiment 1 were addressed: In Experiment 2, one experimenter performed the pretest, read the storybook, and conducted the comprehension test, but another conducted the generalization test to counteract the possibility that the children might want to avoid repeating themselves to one person and therefore might provide abbreviated answers to the generalization questions. Interrater reliability between two coders was excellent ($\kappa = .89$).

Results

Younger children. Repeated measures ordinal logistic regression revealed that the revised storybook induced learning, Wald $\chi^2(2, N = 48) = 25.25$, $p < .001$ (see Fig. 2a). Given their starting levels of understanding at pretest, the odds ratio of children's exhibiting a higher level of natural-selection understanding on the comprehension test was 42.17, $p < .001$, 95% CI = [9.73, 182.78]. At the pretest, 69% of the younger children were at Level 0, and no child displayed a population-based grasp of natural selection (Level 2 or higher). After hearing the storybook, only 13% of the children lacked the isolated facts, and 82% displayed a population-based understanding. Indeed, 69% of the children incorporated differential reproduction into their explanations to reach Levels 3 or 4. At the generalization test, 51% of the children continued to describe a population-based mechanism. Even with these impressive gains, however, children's odds of being in a higher level of natural-selection understanding decreased slightly between the comprehension test and the generalization test, odds ratio = 0.27, $p = .01$, 95% CI = [0.11, 0.71].

Older children. The revised intervention also induced learning in older children, Wald $\chi^2(2, N = 48) = 16.72$, $p < .001$ (see Fig. 2b). The odds ratio of children's exhibiting a higher level of natural-selection understanding on the comprehension test, relative to the pretest, was 38.98, $p < .001$, 95% CI = [5.64, 269.67]. Among the older children, 63% performed at Level 0 or 1 on the pretest, providing no population-based explanation. After exposure to the storybook, this percentage dropped to 0 because 100% of the children incorporated differential survival and reproduction into their explanations of adaptation. Fifty percent displayed the highest level of understanding (Level 4), in that they described natural selection in multiple generations. The children also successfully applied what they learned to a novel animal; there was no difference in their odds of being in a higher level of natural-selection understanding between the comprehension and generalization tests, $p = .19$.

Discussion

Experiment 2 replicated and extended the findings of Experiment 1. The results confirm that children in early elementary school can be taught the basic logic of adaptation by natural selection via a brief but comprehensive storybook intervention. Furthermore, the theoretical logic of natural selection that children can grasp is relatively nuanced. Both younger and older children showed abilities to understand that adaptation involves an extended process that combines differential survival and reproduction. Older children in particular showed substantial capacities to generalize the explanation to novel animals. Indeed, the more detailed theoretical explanation in the

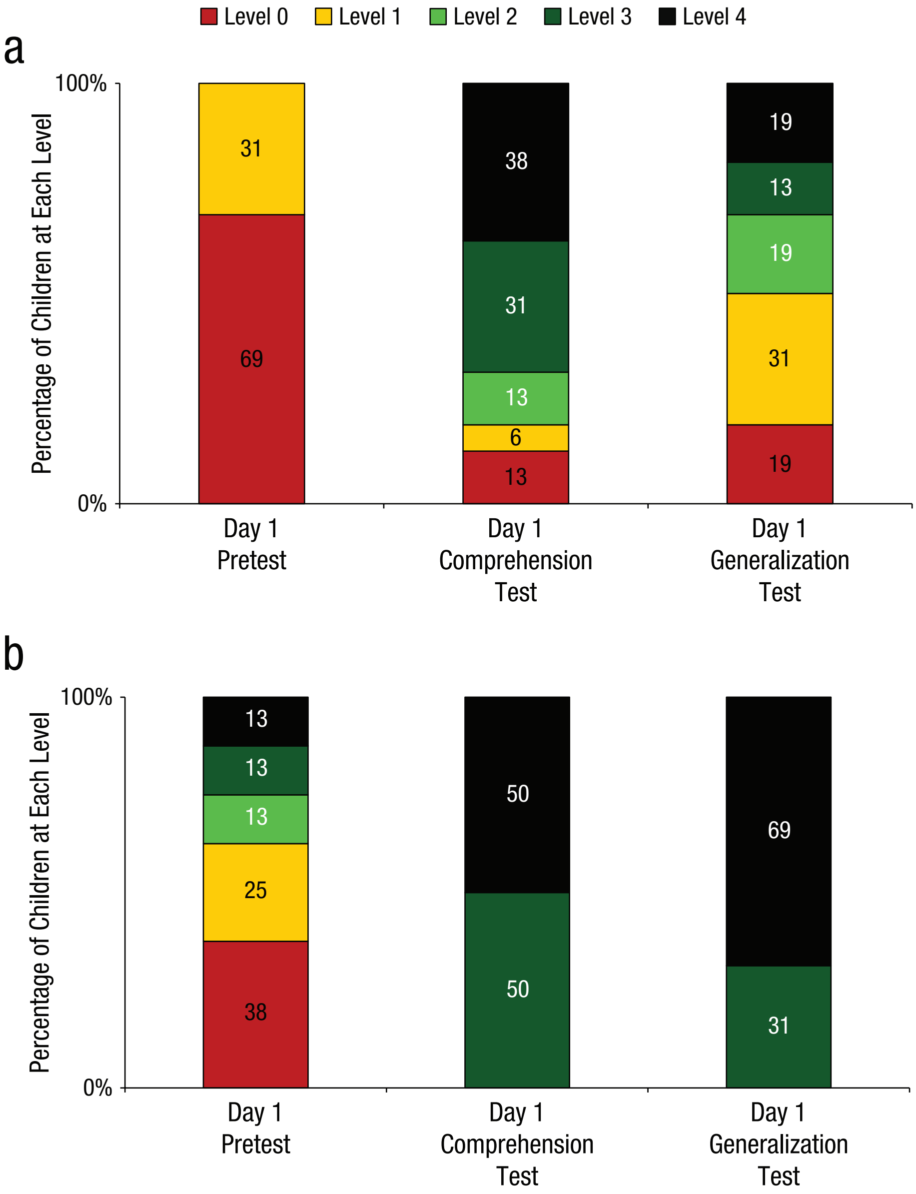

Fig. 2. Results from Experiment 2: percentages of (a) younger and (b) older children classified into the five levels of natural-selection understanding as a function of assessment. Because of rounding, percentages do not always add up to 100. Level 0 = no isolated facts; Level 1 = isolated facts but 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.

second storybook seemed to help older children transfer the process of adaptation.

General Discussion

The current findings demonstrate that, despite its complexity, the basic population-based logic of natural selection is within the reach of elementary school-age children. Young children demonstrated substantial learning of within-species adaptation as a result of a brief but comprehensive, theoretically motivated storybook intervention. Gains were particularly marked in Experiment 2, in which the intervention resulted in approximately 40-fold increases in children's odds of increasing their factual and theoretical understanding. Moreover, in both experiments, children generalized to novel cases despite the known difficulties of transfer. Both age groups learned a great deal, but as might be expected given their enhanced linguistic and processing capacities, 7- to 8-year-olds showed especially robust abilities to suppress any emergent competing commonsense ideas and master task demands, such that they could abstract and transfer the mechanism to markedly different species.

The present results suggest that comprehensive instruction about core evolutionary mechanisms can begin earlier than is currently recommended. Consistent with views of children as natural theory-builders, the young children in these experiments showed remarkable capacities to comprehend and abstract not only isolated facts but also mechanistically rich, novel scientific explanations when both the facts and the explanations were presented in a cohesive framework. Indeed, the children profited from mechanistic detail: Even those whose performance and knowledge of relevant individual facts was weak at pretest learned much transferable knowledge from the storybook intervention.

Collectively, such findings offer reasons for optimism regarding the ability to foster an accurate, generalizable, basic understanding of natural selection. They suggest that capitalizing on young children's drive for coherent explanation, factual knowledge, and interest in trait function, along with their affinity for picture storybooks, is a viable initial step toward overcoming conceptual pitfalls that can undermine later learning about adaptation. This conclusion, however, must be qualified in several ways. First, although the carefully designed intervention used here yielded substantial learning, it should be viewed as the beginning, not the end, of a learning process: This investigation focused on young children's capacities to accurately causally connect the essential components of within-species adaptation by natural selection. Despite the key relevance of this basic mechanism to understanding larger-scale evolutionary changes, teaching adult-level detail and promoting children's understanding or acceptance of speciation or common descent were not our goals. In consequence, this intervention should not be misconstrued as a panacea to all challenges faced by educators who are teaching a range of evolutionary concepts to older students (Rosengren et al., 2012).

Nevertheless, these findings constitute a promising first step. Repeated, spaced instruction on gradually scaled-up versions of the logic of natural selection could ultimately place students in a better position to suppress competing intuitive theoretical explanations such that they could elaborate a richer, more abstract, and broadly applicable knowledge of this process. Storybook interventions such as the ones reported here seem a promising start from which to promote scientific literacy in the longer term.

Author Contributions

D. Kelemen and P. A. Ganea developed the initial concept. D. Kelemen, R. Seston Schillaci, and P. A. Ganea contributed to the design of Experiment 1. R. Seston Schillaci performed data collection for that experiment, and R. Seston Schillaci, D. Kelemen, and N. A. Emmons conducted the analyses. N. A. Emmons, D. Kelemen, and R. Seston Schillaci contributed to the concept and design of Experiment 2. N. A. Emmons performed data collection for that experiment, and N. A. Emmons and R. Seston Schillaci conducted the analyses. D. Kelemen, N. A. Emmons, and R. Seston Schillaci drafted the manuscript, and P. A. Ganea provided revisions. All authors approved the final version of the manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

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Coding Procedure

Using transcriptions of video recordings, coders remained blind to participant age and whether an assessment was a pretest or generalization test (counterbalanced between subjects). Each assessment was assigned one of five overall levels of natural selection understanding (Levels 0-4). Levels were determined using a conceptual checklist and conservative coding rubric that considered all closed- and open-ended responses on a given assessment (see Table S3): Level 0, “No isolated facts,” was assigned when children failed to demonstrate sufficient factual knowledge assessed by the closed-ended questions. Level 1, “Isolated facts but no natural selection understanding,” was assigned when children demonstrated sufficient knowledge of isolated facts but no accurate population-based theory of natural selection. This occurred if children failed to correctly connect relevant conceptual components in their open-ended responses or if they demonstrated an active misconception in any portion of the test (e.g., claiming individuals acquired advantageous traits). Levels 2, 3, and 4 were assigned when children demonstrated sufficient factual knowledge in close-ended questions and an accurate population-based mechanism in their open-ended responses; however, the three levels differed in the degree of sophistication of the population-based logic. Level 2, “Foundation for natural selection understanding,” was assigned when open-ended responses accurately described adaptation occurring as a result of differential survival due to differential access to food; Level 3, “Natural selection understanding in one generation,” was assigned when children causally connected differential survival and differential reproduction in their open-ended responses to explain adaptation but limited their discussion to one generation; and Level 4, “Natural selection understanding in multiple generations,” was assigned when children extended a Level 3 understanding by also discussing differential reproduction occurring over multiple generations.

Coding Details. As Table S3 shows, children had to display sufficient knowledge of isolated facts relevant to natural selection to potentially be credited with an understanding of natural selection. Credit for each isolated fact required choosing a correct closed-ended answer option and correctly justifying that choice. “I don’t know” justifications were coded as inaccurate (see Table S1 for examples).

Open-ended questions probed children’s abilities to self-generate a causally-coherent population-based explanation of why the species changed over time. Responses were coded for causal reference to three processes: differential survival, differential reproduction in one generation, and differential reproduction in multiple generations. Credit for understanding differential survival was given if children correctly integrated health information with information about differential access to food (e.g., “the ones with wide trunks died because they couldn’t reach the food”). Credit for understanding differential reproduction was given if children either mentioned that animals with advantageous traits had more babies than those with disadvantageous traits (e.g., “the thinner trunks were healthy enough to have babies”) or that animals with disadvantageous traits had fewer babies than those with advantageous traits. Suggestions that animals with disadvantageous traits were equally or more healthy than animals with advantageous traits or that disadvantaged animals were equally or more fecund than animals with advantaged ones were coded inaccurate. Because the intervention never used them, if children mentioned terms like “evolve” or “adapt” when responding, they were prompted to explain the meaning. Credit for understanding that natural selection occurs via differential reproduction over multiple generations was given if children either mentioned that babies of animals with advantageous traits would grow up to have babies (e.g., “their children had children”) or that babies of animals with disadvantageous traits would grow up to have no or few babies. Because no assessment questions directly probed children’s awareness of natural selection occurring over multiple generations, children were given credit for this concept if it was mentioned during any part of the assessment. Reference to ideas demonstrating incorrect transformationist theories that individual members of a population acquired advantageous traits within their lifetimes were coded as misconceptions. These included suggestions that individuals acquired traits via development (e.g., “when they were a little older they could have some thinner trunks”), ingesting food (e.g., “[they got bigger] because they ate so much”), or functional need (e.g., “[the wider trunks changed because] they needed thinner trunks to reach the food”). Children displaying any misconception were automatically assigned to Level 0 or 1, receiving no credit for understanding natural selection.

This conservative coding scheme was enabled by an important feature of the design: In both experiments, the critical open-ended question asking children to explain species change was followed by follow-up questions (Experiments 1 and 2), and systematic prompts (Experiment 2) encouraged children to elaborate their underlying reasoning. This elicitation approach was adopted because participants were young and unsurprisingly reticent when asked challenging questions: their abbreviated initial responses could mask misconceptions (and conversely, competence). A Level 1 generalization test sample response from Experiment 2 highlights these points: Through prompting, the child reveals a misconception not unambiguously apparent in an initial open-ended response even as he clearly incorporates factual elements from the storybook. Note that prompting involved asking “why” and repeating back statements already issued by the child. Leading was avoided because experimenters never added new information.

> Experimenter: Many hundreds of years ago most of the grown-up Wilkies had shorter legs but now most of the grown-up Wilkies have longer legs. How do you think that happened?
>
> Child: Because they evolved with..um..longer legs because that's what they needed to be able to survive (*potential misconception*).

Experimenter: When you say evolve, what do you mean?

Child: Evolve means, um, turn into.

Experimenter: Turn into?

Child: Yeah, they turn into…all these wilkies turn into, um, ones with longer legs. (*misconception*)

Experimenter: What happened to wilkies with shorter legs?

Child: They died.

Experimenter: Why?

Child: Because, um, because they couldn't reach the yellow berries.

Experimenter: What happened to the wilkies with the longer legs?

Child: They lived a happy life because they could reach the berries.

Experimenter: Why?

Child: Because they had long legs so they could reach up.

Experimenter: What happened next after they lived a happy life and could reach the berries?

Child: They had kids and it went on and on and on and on and on and on and on… (shortened for length).

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Table S1. Closed-ended isolated fact questions for Experiment 1 and Experiment 2 with sample justifications.

	Experiment 1			**Experiment 2**		
Concept	**Question**	**Accurate Justification**	**Inaccurate Justification**	**Question**	**Accurate Justification**	**Inaccurate Justification**
Differential Survival	After the weather changed, which group of *okapis [long or short necks]* got more food? Why?	Long necks, because they can reach higher.	Long necks, because they had more room.	Nowadays, will a *wilkie with shorter legs* probably be healthy and live for a long time? Why?	No, because the berries got higher and they couldn't reach it.	No, because they are older.
	After the weather changed, which group of *passerines [big or small beaks]* were less healthy? Why?	Small beaks, because they got less food.	Small beaks, because there was no sun.	Nowadays, will a *rudoo with a longer neck* probably be healthy and live for a long time? Why?	Yes, because the red fruit are up on the top of the trees and it has a long neck.	I don't know.
Differential Reproduction	After the weather changed, which group of *pilosas [thin or wide trunks]* had more babies? Why?	Thin trunks, because they are more healthy.	Thin trunks, because they just got the babies.	Nowadays, will a *rudoo with a shorter neck* probably be healthy and live for a long time? Why?	No, because it had shorter necks so it didn't have enough to eat.	No, because it doesn't have room for the babies to fit in.
	When these baby *hemmies* grow up, which one *[long or short beak]* is more likely to have a baby? Why?	Long beak, because they are more healthy.	Long beaks, because all the other beaks will have the same beak as it.	Nowadays, will a *wilkie with longer legs* probably have lots of children? Why?	Yes, because they're healthy 'cause they eat the fruit from the trees.	Yes, because the appetite is way better because of the legs.
Trait Knowledge	See this *okapi* with a *short neck*? If this *okapi* had a baby, what kind of *neck [long or short]* would the baby have? Why?	Short neck, because usually the mother has the same thing as the baby.	Long neck, because they have to eat and they use their long neck.	These grown-up *wilkies* both have *shorter legs*. If these two *wilkies with shorter legs* had a child, what kind of *legs [longer or shorter]* would their child probably have? Why?	Shorter legs. Because the wilkie's parents had shorter legs.	Shorter legs. Because it's just a little child.
				See this young *rudoo*. It was born with *a longer neck*. When this *rudoo* grows up to be an adult, what kind of *neck* will it have *[longer or shorter]*?	Shorter neck. Because it already had a shorter neck when it was born so it should have a shorter neck when it's older.	Longer neck. When that one grows up, it would have to have a long neck to be able to survive.

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

Table S2. Open-ended questions for Experiment 1 and Experiment 2.

Experiment 1	**Experiment 2**
Pilosas had all different sized *trunks* a long time ago, but now *pilosas* only have *thin trunks*, why do you think that happened?	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 *thin trunks*?	What happened to *pilosas* with *thinner trunks*? Why? What happened next after…? [repeat child's response to previous question] Why? What happened next after…? [repeat child's response to previous question] Why?
What happened to *pilosas* with *wide trunks*?	What happened to *pilosas* with *wider trunks*? Why? What happened next after…? [repeat child's response to previous question] Why? What happened next after…? [repeat child's response to previous question] Why?
Hundreds of years after the weather changed, were there any families with *thin trunks* in the group? 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?
Hundreds of years after the weather changed, were there any families with *wide trunks* in the group? Why?	

Note. Italicized information differed depending on the animal species under consideration. Questions were in fixed order.

Table S3. Conceptual checklist of natural selection (NS) understanding with examples of open-ended responses in Experiments 1 and 2.

Level	Overall Category	Checklist	Open-ended Response Example
0	No isolated facts	Lacks sufficient knowledge of isolated facts as assessed by CE questions[1]	N/A
1	Isolated facts but no NS understanding	Has sufficient knowledge of isolated facts[1] but one, or more, of the following are also present: - Misconception in any portion of the test - No mention of differential survival advantage in response to OE questions - Inaccurate mention of any of the three key conceptual components: (a) differential survival advantage, (b) differential reproduction in one generation, (c) differential reproduction in multiple generations in response to OE questions	*Level 1 response: Misconception*[2] E: …now pilosas only have thin trunks. Why do you think that happened? P: All the wide trunks became small trunks so they could go into the holes. E: What happened to the pilosas with thin trunks? P: They just stayed the same and they kept eating E: What happened to the pilosas with wide trunks? P: They couldn't eat for a long time so they just waited until their trunks were small. *Level 1 response: No mention of differential survival*[2] E: …now passerines only have big beaks Why do you think that happened? P: They have small beaks and big beaks and it started to rain and the sun came out. E: What happened to the passerines with big beaks? P: They were scared of the rain. E: What happened to the passerines with small beaks? P: They don't cry.
2	Foundational NS understanding	All of the following are present: - Sufficient knowledge of isolated facts as assessed by CE questions - No misconception in any portion of the test - Accurate mention of differential survival advantage in response to OE questions	*Level 2 response: Differential survival, no differential reproduction*[2] E: …now pilosas only have thin trunks. Why do you think that happened? P: The wide trunks couldn't fit underground to get the milli bugs as well as the ones with thin trunks so when the weather changed they died out. E: So what happened to the pilosas with thin trunks? P: They survived. E: What happened to the pilosas with wide trunks? P: They died out.
3	NS understanding in one generation	All of the following are present: - Sufficient knowledge of isolated facts as assessed by CE questions - No misconception in any portion of the test - Accurate mention of differential survival advantage	*Level 3 response: Differential survival and differential reproduction*[3] E …now most of the grown-up rudoos have longer necks. How do you think that happened? P: I don't know. E: What's your best guess? P: The ones with the shorter necks all died out because they couldn't reach the fruit and then the ones with the longer necks could reach the fruit and had more babies so there were more ones with longer necks.

		in response to OE questions - Accurate mention of differential reproduction in one generation in response to OE questions	E: What happened to the rudoos with longer necks? P: I don't know. E: What's your best guess? P: They could reach the fruit so they had more babies so there were more and more and more of them. E: Why? P: Because the fruit was up high and the little ones couldn't reach it, the ones with the short necks couldn't reach it, and the ones with the longer necks could reach the fruit.
4	NS understanding in multiple generations	All of the following is present: - Sufficient knowledge of isolated facts as assessed by CE questions - No misconception in any portion of the test - Accurate mention of differential survival advantage in response to OE questions - Accurate mention of differential reproduction in one generation in response to OE questions - Accurate mention of differential reproduction in multiple generations in any portion of the test	*Level 4 response: Differential survival and reproduction in multiple generations*[2] E: …now okapis only have short necks. Why do you think that happened? P: The weather changed and the short neck okapis couldn't get any of the fruit that they need to live. E: What happened to the okapis with short necks? P: They probably died out. E: What happened to the okapis with long necks? P: They had babies and then these had babies and then they kept on having babies. *Level 4 response: Differential survival and reproduction in multiple generations*[3] E: …now most of the grown-up rudoos have longer necks. How do you think that happened? P: Um, you, these [points to shorter necks in past group] couldn't really eat a lot, and they died of starvation, and these [points to longer necks in past group] got a lot of, lot of things to eat, and had babies, and these [points to shorter necks in past group] mostly died out of starvation. E: What happened to rudoos with longer necks? P: Mmm, they live. E: And why do they live? P: Bec-c-… because they got enough food t-to eat. E: And so what happened next after they lived? P: …They had children and then died. E: And why is that? P: …because everything dies, and they ha-- they got children because they got a lot of, a lot of things to eat. E: And so what happened next after they had children and then died? P: Um, their children grew up to be grown-up rudoos, and then the same thing happened, like, they got old, they had children, and then they died. And the cycle…

Note. E = Experimenter; P = Participant; CE = closed-ended; OE = open-ended. [1]Sufficient knowledge of isolated facts was defined as accurately answering and justifying 4 of 5 closed-ended questions in Experiment 1 and 5 of 6 closed-ended questions in Experiment 2. [2] Full open-ended responses taken from Experiment 1. [3]Open-ended responses taken from Experiment 2 (edited for length).