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Psychological Science published online 6 February 2014

DOI: 10.1177/0956797613516009

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

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Psychological Science

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DOI: 10.1177/0956797613516009

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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

Received 6/6/13; Revision accepted 11/15/13

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

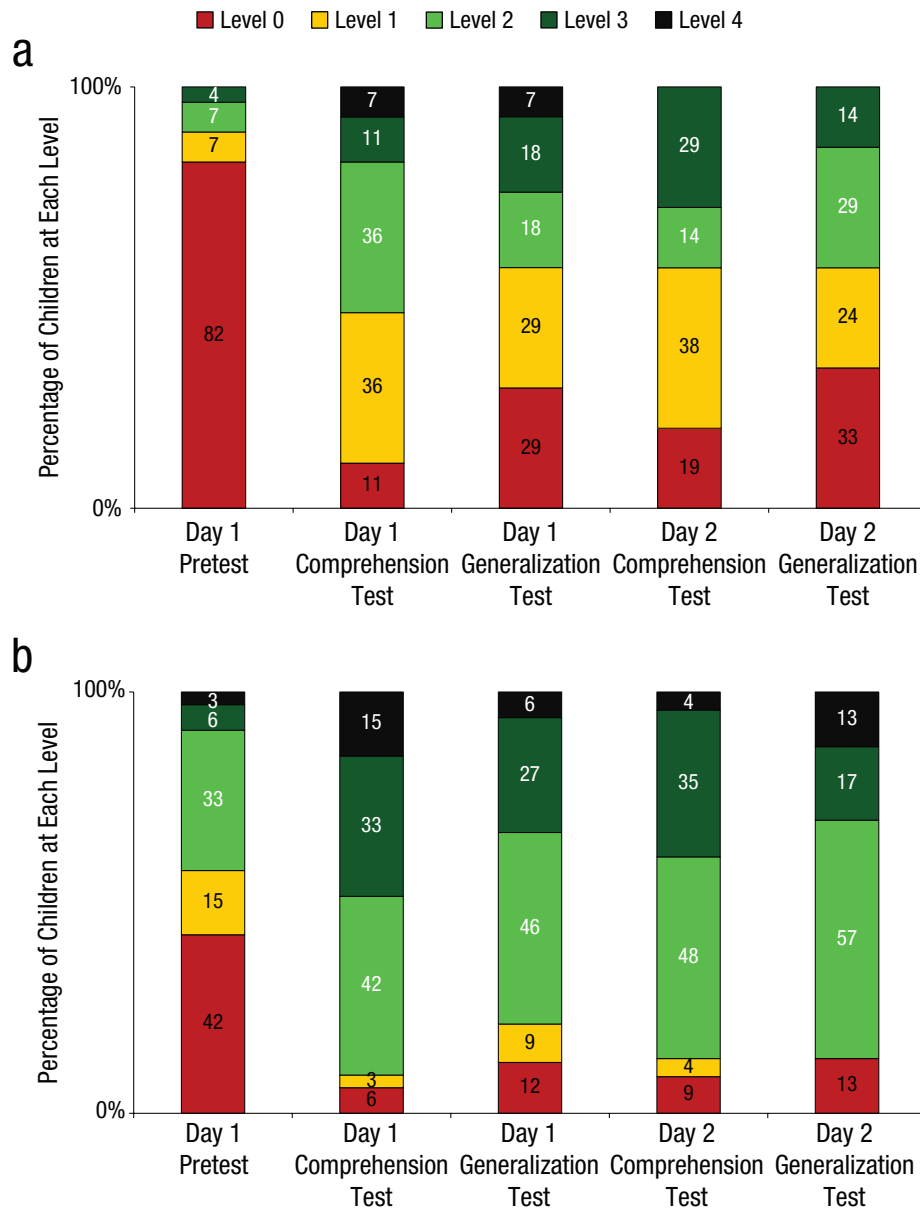


Fig. 1. Results from Experiment 1: percentages of (a) younger and (b) older children classified into the five levels of natural-selection understanding as a function of assessment. Because of rounding, percentages do not always add up to 100. Level 0 = no isolated facts; Level 1 = isolated facts but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

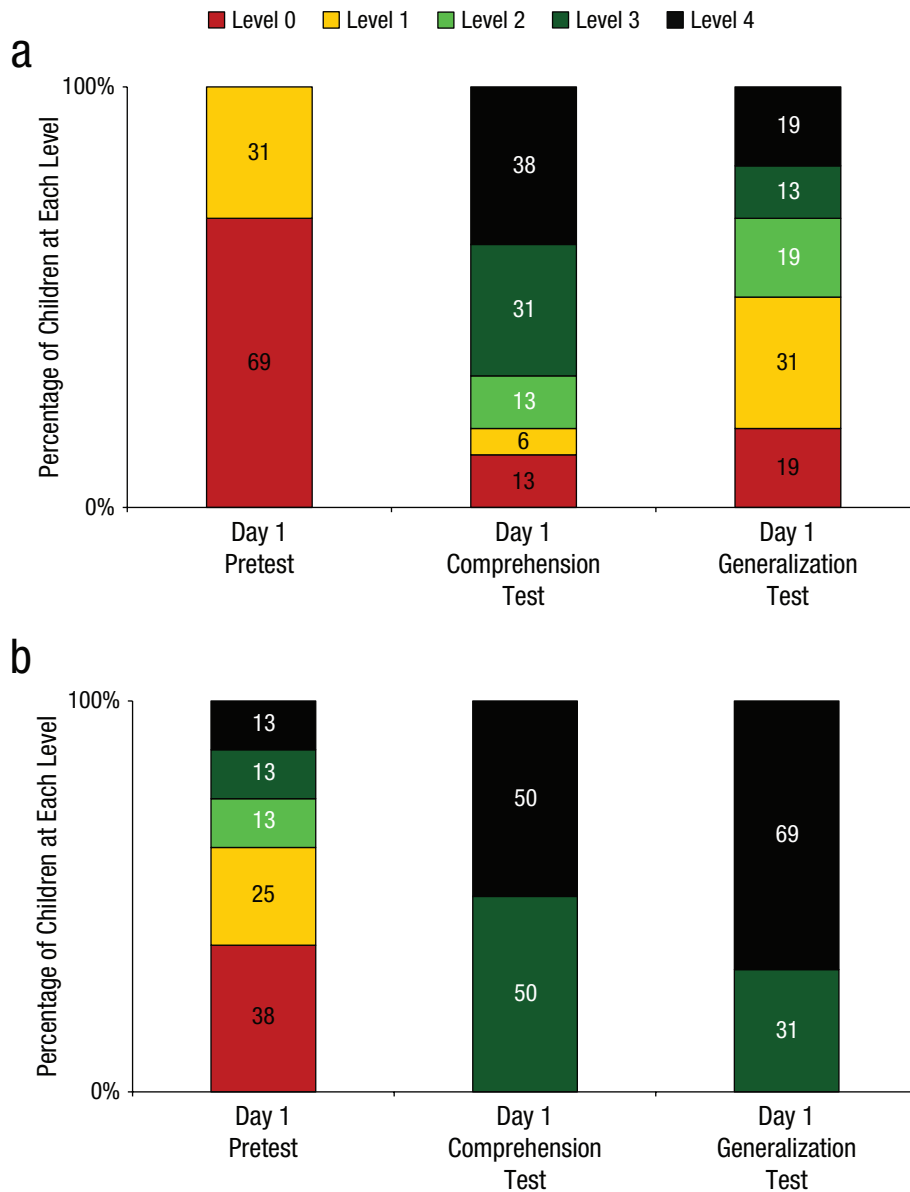


Fig. 2. Results from Experiment 2: percentages of (a) younger and (b) older children classified into the five levels of natural-selection understanding as a function of assessment. Because of rounding, percentages do not always add up to 100. Level 0 = no isolated facts; Level 1 = isolated facts but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

Acknowledgments

We thank James Traniello, Christopher Schneider, Timothy Heeren, Samantha Barry, Kristen Woo, Angel Lillard, Josh Rottman, and Hayley Smith.

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.

Funding

This work was supported by National Science Foundation (NSF) Research on Education and Learning Grant 0529599 (to D. Kelemen) and by NSF Research and Evaluation on Education in Science and Engineering Grant 1007984 (to D. Kelemen and P. A. Ganea).

Supplemental Material

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

References

- Achieve, Inc. (2013). *Next Generation Science Standards*. Retrieved from <http://www.nextgenscience.org/next-generation-science-standards/>
- American Association for the Advancement of Science. (2009). *Benchmarks for science literacy*. New York, NY: Oxford University Press.
- Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, 27, 415–427.
- Bjorklund, D. (2005). *Children's thinking: Cognitive development and individual differences*. Pacific Grove, CA: Wadsworth.
- Brown, A. L., Kane, M. J., & Long, C. (1989). Analogical transfer in young children: Analogies as tools for communication and exposition. *Applied Cognitive Psychology*, 3, 275–293.
- Browning, E., & Hohenstein, J. (2013). The use of narrative to promote primary school children's understanding of evolution. *Education 3-13: International Journal of Primary Elementary and Early Years Education*. Advance online publication. doi:10.1080/03004279.2013.837943

- Brumby, M. N. (1984). Misconceptions about the concept of natural selection by medical biology students. *Science Education*, 68, 493–503.
- Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.
- Coley, J. D., & Tanner, K. D. (2012). Common origins of diverse misconceptions: Cognitive principles and the development of biology thinking. *CBE-Life Sciences Education*, 11, 209–215.
- Evans, E. M. (2001). Cognitive and contextual factors in the emergence of diverse belief systems: Creation versus evolution. *Cognitive Psychology*, 42, 217–266.
- Ferrari, M., & Chi, M. T. H. (1998). The nature of naive explanations of natural selection. *International Journal of Scientific Education*, 20, 1231–1256.
- Friedman, W. J. (1977). The development of children's understanding of cyclic aspects of time. *Child Development*, 48, 1593–1599.
- Ganea, P. A., Ma, L., & DeLoache, J. S. (2011). Young children's learning and transfer of biological information from picture books to real animals. *Child Development*, 82, 1421–1433.
- Gelman, S. A. (2003). *The essential child: Origins of essentialism in everyday thought*. New York, NY: Oxford University Press.
- Gelman, S. A., & Wellman, H. M. (1991). Insides and essences: Early understandings of the non-obvious. *Cognition*, 38, 213–244.
- Gentner, D. (1989). *The mechanisms of analogical learning*. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 199–241). London, England: Cambridge University Press.
- Gopnik, A., & Meltzoff, A. N. (1997). *Words, thoughts, and theories*. Cambridge, MA: MIT Press.
- Gregory, T. R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education & Outreach*, 2, 156–175.
- Gripshover, S. J., & Markman, E. M. (2013). Teaching young children a theory of nutrition: Conceptual change and the potential for increased vegetable consumption. *Psychological Science*, 24, 1541–1553.
- Inagaki, K., & Hatano, G. (2002). *Young children's naive thinking about the biological world*. New York, NY: Psychology Press.
- Jaakkola, R. O., & Slaughter, V. (2002). Children's body knowledge: Understanding "life" as a biological goal. *British Journal of Developmental Psychology*, 20, 325–342.
- Jensen, M. S., & Finley, F. N. (1995). Teaching evolution using historical arguments in a conceptual change strategy. *Scientific Education*, 79, 147–166.
- Keil, F. C. (1995). *The growth of causal understandings of natural kinds*. In D. Sperber, D. Premack, & A. J. Premack (Eds.), *Causal cognition: A multi-disciplinary debate* (pp. 234–262). Oxford, England: Clarendon.
- Kelemen, D. (1999). Why are rocks pointy? Children's preference for teleological explanations of the natural world. *Developmental Psychology*, 35, 1440–1453.
- Kelemen, D. (2004). Are children "intuitive theists"? Reasoning about purpose and design in nature. *Psychological Science*, 15, 295–301.
- Kelemen, D., & DiYanni, C. (2005). Intuitions about origins: Purpose and intelligent design in children's reasoning about nature. *Journal of Cognitive Development*, 6, 3–31.
- Legare, C. H., Lane, J., & Evans, E. M. (2013). Anthropomorphizing science: How does it affect the development of evolutionary concepts? *Merrill-Palmer Quarterly*, 59, 168–197.
- Mayer, R., & Moreno, R. (2003). Nine ways to reduce cognitive load in multi-media learning. *Educational Psychologist*, 38, 43–52.
- National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.
- Nehm, R. H., Kim, S. Y., & Sheppard, K. (2009). Academic preparation in biology and advocacy for teaching evolution: Biology versus non-biology teachers. *Scientific Education*, 93, 1122–1146.
- Nehm, R. H., & Reilly, L. (2007). Biology majors' knowledge and misconceptions of natural selection. *Bioscience*, 57, 263–272.
- Nehm, R. H., & Schonfeld, I. (2007). Does increasing biology teacher knowledge about evolution and the nature of science lead to greater advocacy for teaching evolution in schools? *Journal of Science Teacher Education*, 18, 699–723.
- Rosengren, K. S., Brem, S. K., Evans, E. M., & Sinatra, G. M. (Eds.). (2012). *Evolution challenges: Integrating research and practice in teaching and learning about evolution*. New York, NY: Oxford University Press.
- Rosset, E., & Rottman, J. (2014). The big "whoops!" in the study of intentional behavior: An appeal for a new framework in understanding human actions. *Journal of Cognition and Culture*, 14, 27–39.
- Scott, E. (2012). *Foreword*. In K. S. Rosengren, S. K. Brem, E. M. Evans, & G. M. Sinatra (Eds.), *Evolution challenges: Integrating research and practice in teaching and learning about evolution* (pp. ix–xiii). New York, NY: Oxford University Press.
- Shtulman, A., & Schulz, L. (2008). The relation between essentialist beliefs and evolutionary reasoning. *Cognitive Science*, 32, 1049–1062.
- Solomon, G. E. A., Johnson, S. C., Zaitchik, D., & Carey, S. (1996). Like father, like son: Young children's understanding of how and why offspring resemble their parents. *Child Development*, 67, 151–171.
- Springer, K., & Keil, F. C. (1989). On the development of biologically specific beliefs: The case of inheritance. *Child Development*, 60, 637–648.
- Vlaardingerbroek, B., & Roederer, C. J. (1997). Evolution education in Papua New Guinea: Trainee teachers' views. *Educational Studies*, 23, 363–375.
- Wellman, H. M., & Gelman, S. A. (1992). Cognitive development: Foundational theories of core domains. *Annual Review of Psychology*, 43, 337–375.