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Is book reading always best? Children learn and transfer complex scientific explanations from books or animations

Samuel Ronfard[1*], Sarah A. Brown[2], Emma Pitt[2,3] and Deborah Kelemen[2]

Abstract

Background Storybooks are an effective tool for teaching complex scientific mechanisms to young children when presented in child-friendly, joint-attentional contexts like read-aloud sessions. However, static storybooks are limited in their ability to convey change across time and, relative to animated storybooks, are harder to disseminate to a wide audience. This study examined second graders' abilities to learn the deeply counterintuitive concepts of adaptation and speciation from multi-day interventions centered around two storybooks about natural selection that were either read-aloud (static) or watched on a screen (animated). The storybook sequence was progressive and first explained—in counter-essentialist and non-teleological terms—how the relative distribution of a terrestrial mammal's trait changed over time due to behavioral shifts in their primary food resource (adaptation, book 1). It then explained how–after a sub-population of this species became geographically isolated–they evolved into an entirely different aquatic species over many generations via selection on multiple foraging-relevant traits (speciation, book 2). The animated and static versions of the storybooks used the same text and illustrations, but while the animations lacked joint-attentional context, they more dynamically depicted successive reproductive generations. Storybook and animation presentations were interspersed with five parallel talk-aloud assessment interviews over three days.

Results Findings revealed substantial learning from the read-aloud static storybook sequence. They also revealed substantial learning from the animation condition with patterns suggesting that the dynamic representations of change over time particularly scaffolded acquisition of the deeply counterintuitive idea that a species can evolve into an entirely different category of species by natural selection.

Conclusions The results provide much-needed optimism in a context of increasing demands for scalable solutions to promote effective learning: animated storybooks are just as good (and may even be better) than static storybooks.

Keywords Explanation, Conceptual change, Science learning, Evolution, Video, Animation

Background

Natural selection is a foundational scientific concept. It provides an explanation for how members of a species evolve specialized traits (the process of adaptation) and how entirely new species evolve (the process of speciation). However, over thirty years of research has shown that natural selection is deeply counterintuitive and frequently misunderstood (Gregory 2009, for review). Natural selection is a population-based process that results from biological variation: individuals in a population who

*Correspondence:
Samuel Ronfard
samuel.ronfard@utoronto.ca
[1] University of Toronto, 3359 Mississauga Road, CCT Building, Room 4059, Mississauga, Toronto, ON L5L 1C6, Canada
[2] Boston University, Boston, USA
[3] Northeastern University, Boston, USA

happen to possess more environmentally advantageous traits tend to out-survive and out-reproduce individuals with less advantageous traits. Consequently, over successive generations, such individuals come to make up a greater proportion of the population, with selection on specific traits within a particular habitat leading a species to become ecologically specialized for that habitat (the process of adaptation). When sub-populations become geographically or reproductively isolated, selection on multiple traits can lead to evolutionary divergence and the emergence of entirely distinct species (the process of speciation). In shorthand terms, adaptation by natural selection can be characterized as a within-species or smaller scale evolutionary process and speciation can be characterized as a between-species or larger scale evolutionary process.

Regardless of the scale, the underlying mechanism of natural selection that leads to these evolutionary changes is hard to learn, running counter to people's intuitive understanding of biology. This is, in part, because understanding and retaining it requires inhibition of various early developing intuitive cognitive tendencies. For example, the teleological tendency to construe natural phenomena as existing to serve purposes (e.g., Coley and Tanner 2015; Kelemen 1999) promotes scientifically non-normative preconceptions that species gain beneficial specialized traits through invariant need-based transformations of all species members (e.g., giraffes evolved long necks because they needed to forage on tall trees). Likewise, the essentialist tendency to construe species' category membership and appearance as caused by an underlying core property (e.g., Gelman 2003) lessens appreciation that traits vary within populations (Emmons and Kelemen 2015; Shtulman and Schulz 2008) and strengthens preconceptions that species boundaries are fixed and immutable, thus changed only through transformational events (Coley and Tanner 2015; Gelman and Rhodes 2012; Ronfard et al. 2021; Shtulman 2006). For obvious reasons, these kinds of cognitive tendencies and their associated preconceptions make it conceptually difficult for individuals to represent the cumulative variation-based process that leads both adaptation and speciation to occur. Indeed, absent instruction, individuals develop intuitive theories of biological change that are internally consistent yet qualitatively different than a scientifically accurate understanding of evolution by natural selection (Bishop and Anderson 1990; Shtulman 2006; Sinatra et al. 2008). Over time (and without instruction to counteract them) these intuitive but incorrect theories have time to entrench, making later normative scientific learning and reasoning about evolution even more difficult (Kelemen et al. 2012, Kelemen 2019). Critically, rather than being revised-and-replaced during the learning process—as suggested by traditional models of conceptual change—such intuitive but inaccurate theories about the process of natural selection persist and coexist alongside formally learned theoretical understandings (e.g., Kelemen et al. 2012; Kelemen 2019; Shtulman and Lombrozo 2016). Consistent with this account, recent research with elementary school children has demonstrated that children's inhibition abilities predict their ability to acquire and express a scientifically accurate understanding of speciation (Ronfard et al. 2021). Elementary school children with greater scores on measures of inhibition (but not working memory) were more likely to acquire an accurate causal-mechanistic understanding of speciation presumably because their greater inhibition skills allowed them to set aside their intuitive but incorrect explanations for the evolution of new species. Moreover, of the children who did acquire this understanding, it was again those with greater inhibition scores who were able to ongoingly express this understanding rather than revert to explaining speciation using scientifically incorrect but intuitive explanations. These data suggest that early instruction may be key to helping individuals form robust representations of natural selection that can outcompete intuitive but scientifically incorrect conceptions of natural selection as need-based and occurring through transformational events. Thus, while instruction about the counterintuitive process of natural selection is typically delayed until high school, it can, and almost certainly should, be taught earlier (Kelemen 2019).

In the present research, we explore the effectiveness of a potentially scalable and accessible early educational response to the challenges of developing a normative population-based understanding of evolution by natural selection. Specifically, building on findings that elementary school children can understand—and transfer—the mechanisms of smaller- and larger evolutionary change when taught with interventions utilizing the joint attentional context of a traditional picture storybook "read aloud" (Brown et al. 2020; Emmons et al. 2016, 2017; Kelemen et al. 2014; Ronfard et al. 2021; Shtulman et al. 2016; see also Nadelson et al. 2009, Campos and Sá-Pinto 2013, Sá-Pinto et al. 2021), we explored whether children's learning and generalization is similar when taught via custom animations. Of note, this approach does not take the gradualist teaching approach associated with the alternative threshold concept approach which argues for a more sequenced, progressive rollout of concepts relevant to understanding natural selection (Meyer and Land 2005; Ross et al. 2010; Tibell and Harms 2017). We take the perspective that many of the constituent biological concepts of natural selection are best grasped when taught in relation to each other rather than decontextualized as independent facts about the world and that children possess enough of a rudimentary understanding of within-species variation (e.g., Emmons and Kelemen 2015), inheritance (e.g. Springer and Keil 1989; Solomon et al. 1996; Ware and Gelman 2014; Menendez et al. 2023) and other component concepts (see Kelemen et al. 2014) to begin to learn about evolution through natural selection. However, as we note in the discussion, a more complex understanding of evolution by natural selection of the kind generally taught to adults may require individuals to master threshold statistical and probabilistic concepts (Fiedler et al. 2018). In a spiraling sequence, the present kind of intervention could potentially provide a foundation for such elaborative teaching.

There are at least two reasons for investigating the impact of an animated storybook on children's learning relative to the impact of a traditional static storybook. First, static storybooks are limited in their ability to convey the process of population change across time. This raises the possibility that a more dynamic depiction of time and successive generations might yield stronger learning. Such dynamic representations may be particularly helpful for acquiring a population-based counter-essentialist understanding of speciation because an animated storybook would allow children to visualize how the selection process can breach category boundaries and lead one species to evolve into something entirely different. That is, animations may make it easier for children to see how the distribution of a trait or of a set of traits slowly spreads through a population over time, rather than the whole population shifting at once (see Tibell and Harms 2017 for a similar argument). While prior research has not examined the impact of animations on elementary school children's understanding, research with adolescents and adults suggests that dynamic visual representations of natural selection can improve participants' understanding of natural selection. For example, small groups of 13- to-14-year-old children who engaged with animations depicting how antibiotic resistance evolves through mutation and natural selection increased their understanding of this process: They were significantly more likely to describe differential survival and reproduction of randomly mutated bacteria as an explanation of antibiotic resistance after engaging with the animations than before doing so (Bohlin et al. 2018). Fiedler et al. (2018) also found evidence that animations can help 14- to 18-year-old children understand the role of random and probabilistic processes in evolution. Finally, animations have also shown promise in increasing undergraduate students' understanding of macroevolutionary timescales (Stenlund and Tibell 2019).

Second, there may be substantial logistical benefits associated with an animated storybook format. An animated storybook can be designed to have built-in attention cues (for example to highlight the passage of time) that would otherwise need to be taught to parents and teachers. These standardized time and referential cues made possible by an animated storybook might be highly beneficial to comprehension by ensuring standardization across children at a large scale. In addition, an intervention built around an animated version of a book is easier and cheaper to disseminate than its print counterpart. For example, it can be posted on YouTube and accessed all over the world for free. Thus, even if animated storybooks are equivalent to static versions in terms of learning outcomes, they may be preferred as an intervention mechanism due to their lower cost of implementation and the ease with which they can be disseminated.

Despite these benefits, there are reasons to believe that an animated storybook may be less effective at promoting learning and generalization of adaptation and speciation by natural selection than a print storybook (Mayer and Moreno 2003). Traditionally, storybooks are read by an adult in one-on-one settings or to a small group of children. In these contexts, storybook reading allows for joint attention, with the listeners able to follow the reader's eye gaze, gestures, and other nonverbal cues (Fletcher and Reese 2005; Strouse et al. 2013). A large body of research identifies the centrality of joint attention to young children's learning (e.g., Baldwin 1991; Tomasello and Farrar 1986), and may be one of the reasons that storybook reading is an effective tool for teaching a variety of complex scientific ideas (e.g., Kelemen et al. 2014; Venkadasalam and Ganea 2018). Thus, it is not clear that an animated storybook—even one that includes built-in attentional cues—will outperform or even perform at the same level as a static storybook. In general, because prior research on multimedia storybooks has primarily considered toddlers (e.g., Strouse and Ganea 2016), not elementary school children, and has also focused on the general literacy benefits of such books (e.g., vocabulary), not their benefits to learning of scientific explanations (Lee et al. 2013), a great deal remains unknown about potentially differential effects on learning.

The current study

The current study explores two questions: (1) does an animated storybook promote children's learning and generalization of smaller-scale evolution by natural selection (adaptation) to the same degree as a static print version? (2) Does an animated storybook promote children's learning and generalization of larger-scale evolution by natural selection (speciation) to the same degree as a static print version?

Our research focuses on 2nd grade children (7- to 8-year-old children). This is because, while prior research demonstrated that kindergarten students (5-to 6-year-old children) can learn to explain adaptation as resulting from natural selection, children at that earlier age found it harder than the older age group to far generalize their learning of natural selection from a storybook involving food access as the selection pressure to a scenario where the pressure was predation (Emmons et al. 2017). Given that the current intervention leverages children's ability to learn about smaller scale adaptation in service of learning about the larger scale evolutionary change of speciation (see Ronfard et al. 2021), it is most appropriate for an age group that can robustly learn and generalize natural selection across a variety of selection scenarios (see also Shtulman et al. 2016).

We tentatively predicted no difference in children's learning and generalization of small-scale evolutionary change (adaptation) when comparing a static and an animated storybook. This is because prior results suggest that, despite strong intuitive preconceptions, even 5- to 6-year-old children can acquire, generalize (to some degree), and retain an understanding of how differential survival and reproduction leads to trait adaptation within a population (Kelemen et al. 2014). In contrast, we predicted that an animated storybook designed to teach children about the more counterintuitive larger-scale concept of speciation would lead to greater learning and retention than a static storybook. Seven to eight-year-old children exposed to static storybook depictions of the process of speciation have difficulty with enduring retention of a population-based understanding of speciation and frequently revert to explaining this process in event-based terms, that is, as involving individuals spontaneously transforming into a new, more environmentally-suited species (Ronfard et al. 2021). Thus, we hypothesized that an animated storybook might be able to counteract this deeply rooted intuitive idea by making it clear—through a dynamic depiction of multiple cycles of differential survival and reproduction—that the process of speciation is a cyclic mechanism that takes place via selection over time rather than as a quick transformation when individuals encounter environmental challenges.

To test these hypotheses, we recruited 2nd grade students and randomly assigned them to two conditions: a static storybook condition ($N = 16$) and an animated storybook condition ($N = 17$). In both conditions, children were presented with two counter-essentialist and non-teleological storybooks used in prior research (Ronfard et al. 2021). The first storybook, "How the Piloses Evolved Skinny Noses" focused on adaptation. It introduced children to the piloses, a fictional anteater species. Individual piloses differed from one another across multiple traits including trunk width. The book chronicles how climate change leads to a change in the location of the piloses insect-like food source (from above ground into deep and narrow underground tunnels). This results in a change, over multiple generations, in the prevalence of piloses with skinny trunks: Initially rare, such piloses became more frequent over time as they are better able to catch insects than piloses with wider trunks and as a result live longer and out-reproduce them. The second storybook, "Meet the Miroungas" focuses on the process of speciation. It explains how a sub-population of piloses became reproductively isolated on an island and how, over many generations, the differential reproductive success of individuals with traits that are advantageous for aquatic foraging eventually results in a new, distinctive aquatic species–a species that is so different from the piloses (because members cannot have babies together), that scientists gave it a different name.

The animations used the same illustrations (and text) as the print storybooks and therefore adopted the same design principles (see Kelemen 2019). Both print and animated storybooks were designed to focus attention on the concepts being illustrated rather than the illustrations themselves. Therefore, the visuals in both were low key and minimalist, for example, they avoided the use of high levels of detail and bright colors. In consequence, the main difference between the static storybook and the animated storybook was the ability to better convey the passage of time via the animated storybook's dynamic depiction of offspring production, growth, and death over multiple successive generations, that is, to better convey the resulting gradual proportional take-over of individuals with advantageous traits.

Children's understanding of both adaptation and speciation was assessed using talk-aloud assessments that required children to apply what they had learned to novel scenarios immediately and after three months. We assessed children's understanding after a three-month delay to document the strength of children's learning over time. Assessing the robustness of children's learning over time is critical when evaluating the differential impact of the static versus animated storybook sequence because, consistent with dual processing accounts, prior evidence indicates that intuitive explanatory preconceptions about the process of natural selection are not replaced during the learning process. Rather they persist and coexist alongside the explicitly learned population-based account in both children (e.g., Ronfard et al. 2021) and adults (see Kelemen 2019; Shtulman and Lombrozo 2016). More robust learning is manifested in the form of fewer intrusions from coexistent intuitive preconceptions when reasoning about natural selection after a delay.

Methods

Participants

Our sample size was based on prior research (e.g., Kelemen et al. 2014; Emmons et al. 2017) using similar intervention designs that consistently yielded large effects (pre-to post-test Odds Ratios (OR) reflecting 12- to 100-fold increases in odds—these effect sizes are considered to be large and are equivalent to Cohen's d values between 1.37 and 2.54; Chen et al. 2010; Sánchez-Meca et al. 2003). Participants were 33 second graders (16 boys, 17 girls, *M* age = 7 years, 7 months, *SD* = 4 months). Children were drawn from two classes and children within each class were randomly assigned to one of the two conditions—the static versus the animated storybook intervention. Four experimenters completed data collection and were themselves randomly assigned to children in each condition for each testing session. Each experimenter received extensive training in reading of the print storybook and delivering the interview questions to ensure standardization across researchers. This training included multiple rounds of practice with corrective feedback until all experimenters read and delivered the materials and scripted assessments in the same manner. Because this research formed part of a larger project, we previously reported on the children assigned to the static storybook condition in context of answering different research questions (Ronfard et al. 2021). Both groups of children were randomly assigned to condition and tested during the same period. Classrooms represented relatively diverse racial, ethnic, and socioeconomic backgrounds: 66% of students at the school were identified as White, 11% Asian, 10% multi-race or non-Hispanic, 9% Hispanic, and 4% African American/Black, and 15% of students at the school were eligible for free or reduced lunch. This study was approved by the Ethics Committee of [blinded] ("[blinded]", # 2350E). Guardians of participants gave informed consent in writing before children participated in the study. Children gave verbal assent.

Materials and procedure

Intervention time table

Participants were tested individually. Table 1 provides a schematic of the intervention and indicates how it built from the theory of adaptation by natural selection to the process of speciation. As Table 1 shows, in *Session 1*, children received two pre-tests, each involving a different realistic but fictional novel species: one assessing their knowledge of adaptation, one assessing their knowledge of speciation. In *Session 2*, children were read (static condition) or watched (animation condition) the adaptation storybook, "*How the Piloses Evolved Skinny Noses*". Their understanding of natural selection in the context of adaptation was then evaluated in two adaptation post-tests: a comprehension post-test that focused on the piloses and evaluated their understanding of the adaptation book and a near generalization post-test that examined their ability to apply their learning to another novel species that underwent adaptation on a food-relevant trait. Note that the scenarios used for the adaptation pre-test and the adaptation generalization post-test were counterbalanced across children. In *Session 3*, children were read or watched the speciation storybook, "*Meet the Miroungas*". Their understanding of natural selection in the context of speciation was then evaluated twice: a comprehension post-test on the evolution of the miroungas that evaluated children's understanding of the speciation storybook and a near generalization post-test that examined their ability to apply their learning to another novel species that underwent speciation due to food-based selection pressures. Note that the scenarios used for the speciation pre-test and the speciation generalization post-test were also counterbalanced across children. *Session 4* took place after a three-month delay. Children completed two speciation assessments. They first completed a far generalization speciation post-test with a fictional novel species. In this scenario, the selection pressure derived from the arrival of predators rather than a change in climate: The advantaged individuals were the rare members of the population whose body color, longer claws and spikes afforded better camouflage and self-defense. Children then completed another far generalization speciation post-test with a familiar species. This scenario evaluated

Table 1 Participants heard (static print condition) or watched (animation condition) the adaptation storybook and the speciation storybook in a four-session sequence

Session 1 (pre-test)	Session 2 (adaptation)	Session 3 (speciation)	Session 4 (speciation after 3-month-delay)
Adaptation Pre-test Speciation Pre-test	Adaptation Storybook Reading Adaptation Comprehension Post-test Adaptation Generalization Post-test	Speciation Storybook Reading Speciation Comprehension Post-test Speciation Generalization Post-test	Speciation Delay Nove Speciation Delay Familiar

Book-readings were interspersed with talk-aloud assessments that required children to explain adaptation and speciation, applying them to novel scenarios immediately and after 3 months children's ability to apply the logic of natural selection to explain the evolution of moles from a mammalian ancestor. In this scenario, food-based selection pressure advantaged the rare individuals with larger claws, shorter tails, and bigger feet who could better dig for bugs.

Storybooks

The two static print storybooks and the animated versions of them used in the interventions were custom-made (see Kelemen and The Child Cognition Lab 2017, 2020; to learn about the design philosophy that informed these storybooks see Kelemen 2019 and Ronfard et al. 2021; see Menendez et al. 2022 for the effect of perceptual richness on learning outcomes). When reading the static storybooks, research assistants were trained to use the same scripted informative gestures to help children follow along when reading the book. In the animated versions of the storybooks, as each page is presented, parts of the image that are the focus of a gesture in a live presentation of the static print storybook are highlighted with some movement on the screen (e.g., individual piloses shaking slightly to draw children's attention when referenced in the narration).

Trait adaptation story

The first story ("*How the Piloses Evolved Skinny Noses*") coherently and comprehensively explained the population-based mechanism of adaptation. The anteater-like piloses undergo adaptation of their trunks when climate warming leads their "millibug" insect food to move into deep, thin underground tunnels. Piloses with wider trunks are initially more numerous but, because of their differential foraging advantage in the changed environment, the rare piloses with thinner trunks survive and reproduce more. Over many generations, piloses with thinner trunks come to predominate (see Fig. 1a).

Speciation story

The second story, "*Meet the Miroungas*" continued the story of the piloses. It explained how geographical isolation and selection on multiple traits—rather than just one as in the prior adaptation storybook—leads to the evolution of distinct new frog-like mammal ("miroungas"). Specifically, a group of predominantly thinner-trunked piloses is washed away to an island by a deluge of rain. Because the island doesn't have millibugs, the piloses start to forage for an alternative food, calibugs, that can only be found in the water. Because most calibugs swim in the deeper part of the ocean only piloses with shorter tails and trunks (that don't drag in the water) and big feet (that can push through more water) are able to catch enough calibugs to be healthy. Piloses without such traits are less healthy and reproduce less. As a result, over multiple generations, the animals on the island evolve into the entirely new frog-like species of miroungas (see Fig. 1b).

Assessments

Assessments of adaptation and speciation understanding involved different species but were conceptually parallel (see Orton et al., 2012 for a discussion of the role of mutual alignment for learning complex scientific concepts). The questions used in the adaptation assessments were identical to those in prior work (e.g., Emmons et al. 2016, 2017; Kelemen et al. 2014, Study 2). The questions used in the new speciation assessments were based on these adaptation questions and followed the same logic (see also Ronfard et al. 2021). For each type of assessment (adaptation and speciation), children were shown two pairs of images in succession. These two sets of images provided the introduction to the species that was the focus of the assessment and the setup for subsequent questions (see Fig. 2 for examples and description, for more examples see supplementary materials of Ronfard et al. 2021). Children were never told that the traits of interest had relevance to gaining access to food. They had to infer this relationship when prompted to explain the change in the population.

Following each setup, children answered six closed-ended questions that evaluated their knowledge of isolated facts relevant to understanding natural selection. These questions tapped four concepts: (i) differential survival (two questions e.g., "Nowadays, will a tardon with a stretchier/stumpier tail probably be healthy and live for a long time?"); (ii) differential reproduction (two questions, e.g., "Nowadays, will a tardon with a stretchier/stumpier tail probably have lots of children?"); (iii) constancy of traits over the lifespan (one question, e.g., "See this young tardon. It was born with a stumpier tail. When this tardon is fully-grown, will it be an adult with a stumpier tail or an adult with a stretchier tail?"), (iv) inherited family resemblance (one question, e.g., "These fully-grown tardons both have stumpier tails. If these two tardons had a child, what kind of tail would their child probably have?"). After giving their initial responses to these closed-ended questions, children were required to justify their answers. Children were only given credit if both their closed-ended answer and its justification were correct.

Following the six isolated fact questions, children were asked a global open-ended question (e.g., "How do you think that [change in trait frequency] happened?") to probe whether they could self-generate a correct explanation of population change in terms of natural selection. In the case of the adaptation scenario depicted in Fig. 2a, this initial open-ended question was: "Many hundreds of years ago most of the fully-grown tardons had stumpier

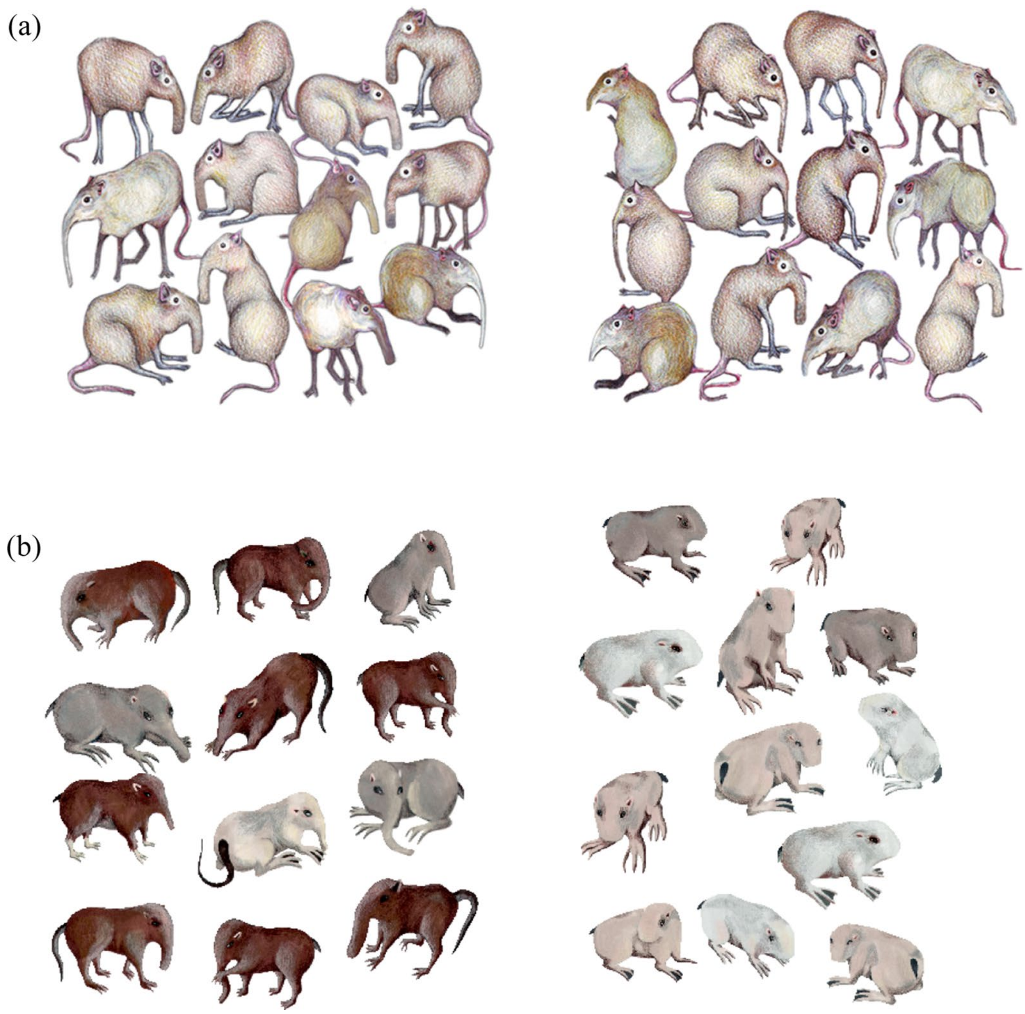

Fig. 1 Representation of (**a**) the populations of piloses before the change in the climate (left) and multiple generations after the change in climate (right, Story 1) (**b**) the initial group of piloses washed away to the island (left) and the group of animals now living on the island after multiple generations who are now called miroungas (right, Story 2). Note that these illustrations are from the research version of the storybooks. They were professionally redrawn for the trade publications

tails but now most of the fully-grown tardons have stretchier tails. How do you think that happened?". This was followed by prompts for elaboration. These prompts took the form of the experimenter repeating back what the child had already said (e.g., "What happened next after [child's previous response]?"). These prompts were necessary given children's tendency to truncate their answers. Moreover, given that the experimenter never provided new information or corrected children, these prompts made it possible to reveal preconceptions masked by children's unelaborated responses or, alternatively, to uncover their more sophisticated understanding of natural selection. Children also received two further open-ended questions that—with the prompting procedure described above—were designed to elicit further elaboration about the mechanism of change (e.g., "What happened to tardons with stumpier tails?"; "What happened to tardons with stretchier tails?").

For the speciation scenario depicted in Fig. 2b, the basic structure of the six closed-ended isolated fact questions was the same (e.g., "Nowadays, will an iggle with bigger legs, bigger claws, and a thinner tail/smaller legs, smaller claws, and a wider tail probably be healthy and live for a long time?"). The initial global open-ended question was also similar to that used in the adaptation scenario but made explicit mention of the fact that the present population was a different species by using a different name. This made the speciation assessment significantly harder given that the use of the different label for the present population could trigger children's essentialist thinking

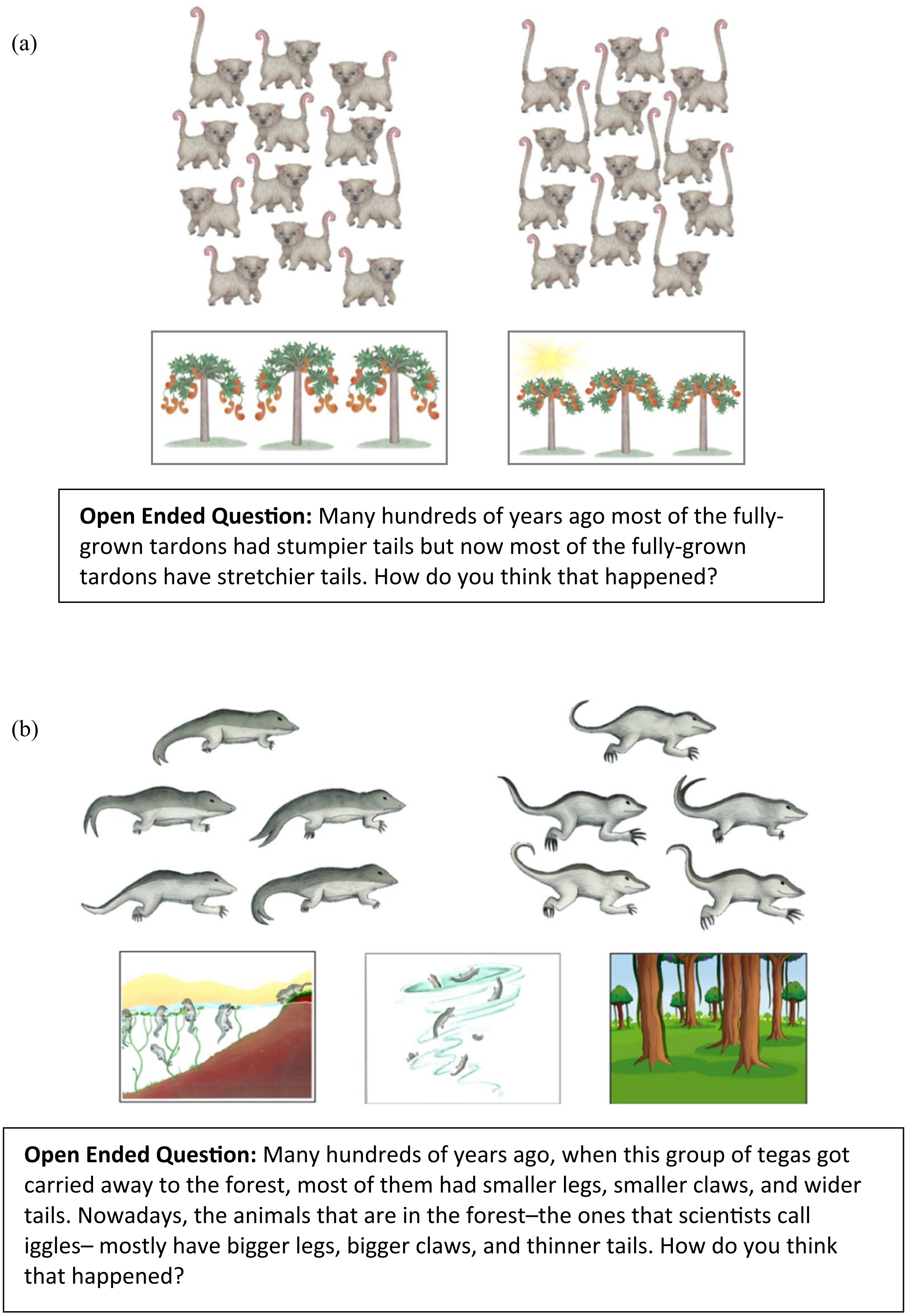

Fig. 2 Images used to provide the setup for the (**a**) adaptation and (**b**) speciation assessments. For each assessment species and for each type of assessment children were shown the past population (left) and the current population (right) as well as the change in habitat (depicted on the second row for each assessment type). Following six closed-ended questions, children were asked the open-ended questions above to assess whether they could self-generate a correct explanation of population change in terms of natural selection

about species: "Many hundreds of years ago, when this group of tegas got carried away to the forest, most of them had smaller legs, smaller claws, and wider tails. Nowadays, the animals that are in the forest–the ones that scientists call iggles– mostly have bigger legs, bigger claws, and thinner tails. How do you think that happened?" The same prompting for elaboration was used as in the adaptation assessments. Again, children got no feedback on the accuracy of their responses.

Coding

To facilitate comparisons with prior work, the coding scheme from earlier studies on children's learning of natural selection was used (e.g., Emmons et al. 2016, 2017; Kelemen et al. 2014, Study 2). For each assessment, children were assigned a global score that captured their natural selection understanding based on responses to all isolated fact and open-ended questions. Responses were coded based on a conceptual checklist that reflected a conservative coding rubric. For example, children displaying any evidence of a preconception were never credited with any level of normative population-based understanding of natural selection. We coded for four types of preconceptions. Table 2 displays these preconceptions along with definitions and examples.

Children's global understanding of natural selection was classified into one of five hierarchical levels. Their understanding was categorized as Level 1, "no isolated facts," when responses to the isolated fact questions demonstrated limited or no knowledge of the prerequisite facts needed to support an understanding of natural selection (i.e., fewer than five correct responses to the isolated fact questions). Understanding was categorized as Level 2, "isolated facts but no natural selection understanding," when children displayed robust factual knowledge (i.e., five or more correct responses to the isolated fact questions) but did not generate a correct explanation in response to the open-ended questions or when children displayed a preconception. The three highest levels of understanding (Levels 3–5) were only assigned when children demonstrated a robust understanding of the isolated facts (i.e., ≥ 5 five correct responses on the isolated fact questions) and self-generated a scientifically normative explanation based on the population-based logic of natural selection in response to the open-ended questions. To reiterate, a Level 3 or higher categorization was never assigned if there was any sign of a preconception at any point in the assessment. Children were assigned Level 3, "foundation for natural selection understanding," when their open-ended responses included the idea that species members with disadvantageous traits often died while those with advantageous traits tended to survive as a result of selection pressures (i.e., differential survival). They were assigned Level 4, "natural selection understanding in one generation," when they explained the species change in terms of both differential survival and differential reproduction. Finally, children were assigned Level 5, "natural selection understanding in multiple generations," when their open-ended explanations were expanded to explicitly reference the concept that adaptation/speciation occurs over multiple generations.

The assessments were coded based on transcripts from video recordings. Because pretest and generalization assessments were counterbalanced, coders were unaware of test phase from Session 1 to 3. However, because the delayed test assessments were only used in Session 4, coders may have had some awareness of test phase when coding these particular assessments. Nevertheless, given the number of assessments being coded, and the way coding was organized to keep coders unaware of each individual's learning progress across each test phase of the study (coders did not code each individual on all of their assessments in sequence but rather each assessment using a particular scenario was coded

Table 2 Preconception coding scheme with description and examples

Preconception type	Description	Examples
Developmental	The intuition that an individual member of a species will develop a given, generally beneficial, trait as it grows older	([The change] happened because) the shorter legs grew up/got older
Transformation	The intuition that one member/generation of a species is able to spontaneously acquire new generally beneficial traits	([The change] happened because) the shorter legs got longer / got stretchier (no clear mechanism given)
Explicitly Teleological	The intuition that members of a given species develop a trait *in response to a need* for that trait or because traits develop *in order to serve a purpose*	The wilkies needed longer legs so they got them. | The wilkies got longer legs so they could live. | The wilkies got longer legs because longer legs helped them get food
Other	Any other preconceptions	That's the way they were created | The one with the longer legs (lived longer) because he's bigger

Note that given the structure of the assessments, developmental and transformation preconceptions are potentially tacitly teleological even when lacking standard linguistic indicators of teleological explanation (e.g., "so that", "in order to"). Thus, we distinguish them from "explicitly" teleological explanations (see Brown et al. 2020 for discussion of this issue) across all individuals), it is unlikely that this aspect of the design was particularly salient during coding or that it influenced coding. All assessments were coded by two independent coders. Interrater reliability was excellent (Kappa = 0.90), and all disagreements were resolved through discussion.

Results

We evaluated the success of the intervention using two metrics: (1) whether the frequency of intuitive preconceptions was reduced following storybook instruction, i.e., whether we observed more intuitive preconceptions at pre-test than on the post-tests; (2) whether the global level of natural selection understanding increased following storybook instruction, i.e., whether the global level of natural selection understanding was greater on the post-tests than on the pre-test. In both cases, we confirmed that our data met the assumptions of our statistical tests. For example, we confirmed the Proportional Odds assumption for our repeated ordinal logistic regressions. We begin with the preconception analyses.

Are children's non-normative preconceptions about natural selection less frequent after instruction?

Below we report analyses of changes in children's expressions of intuitive preconceptions when explaining the process of adaptation and speciation by natural selection using repeated measures logistic regressions. Odds ratio statistics from these analyses indicate the magnitude of change in the odds that children expressed a scientifically non-normative idea or preconception at each different assessment time. Table 3 displays the change in the expression of preconceptions over time.

Preconceptions about adaptation before and after instruction

In our first model, we included the effect of Time, Condition, and the interaction between Time and Condition. Whether children expressed a preconception about adaptation before and after instruction did not differ as a function of whether children received instruction using the static storybook or the animated storybook. Indeed, inspection of Table 3 confirms a very similar pattern of results for children in the static and animated storybook conditions. The effect of Condition and the Condition X Time interactions were not statistically significant, χ^2 (3) = 2.79, $p = 0.43$. These terms were removed from the model. The model with only Time as a predictor explained a significant amount of variance, Wald χ^2 (2) = 11.00, $p = 0.004$. Whether static or animated, instruction significantly reduced the likelihood that children expressed an intuitive preconception. This was true when comparing the adaptation comprehension ($OR = 0.048$) and generalization ($OR = 0.032$) post-tests relative to pretest, $p = 0.003$, $p = 0.002$, respectively. Across conditions, a majority of children actively expressed an intuitive preconception during the adaptation pre-test (55%) rather than just evidencing a lack of isolated factual knowledge. The percentage of children displaying a preconception fell to 16% during the comprehension post-test and to 13% by the generalization post-test.

While not meeting criteria for a statistically significant difference, a contrast in the expression of preconceptions by children in the static and animated storybook is worth noting. While 25% of children in static storybook condition expressed preconceptions on the generalization post-test, none of the children in the animated storybook condition did so.

Table 3 Percentage of second graders in the static storybook ("Book", $N = 16$) and animated storybook ("Video", N = 17) condition who expressed each preconception during their individual interviews

	Any			Development		Transformation		Explicitly teleological		Other	
	Book	Video	Combined	Book	Video	Book	Video	Book	Video	Book	Video
Adaptation											
Pre-test	69	41	55	63	24	13	12	6	6	13	12
Comprehension	25	7	16	13	7	6	0	6	0	0	0
Post-test	25	0	13	19	0	0	0	6	0	0	0
Speciation											
Pre-test	88	94	91	56	35	44	59	38	29	13	18
Comprehension	19	29	24	13	6	6	18	0	6	0	0
Post-test	44	12	27	19	0	13	6	25	6	0	0
Delay novel	38	18	27	19	0	19	18	6	6	0	6
Delay familiar	63	35	48	13	0	38	24	13	18	6	0

Preconceptions about speciation before and after instruction

In our first model, we included the effect of Time, Condition, and the interaction between Time and Condition. This revealed that whether children expressed a preconception about speciation before and after instruction did not differ as a function of whether children received instruction using the static storybook or the animated storybook. The effect of Condition and the Condition X Time interactions were not statistically significant, Wald χ^2 (5) = 8.21, $p = 0.14$. These terms were removed from the model. The model with only Time as a predictor explained a significant amount of variance, Wald χ^2 (4) = 26.82, $p < 0.001$. Whether static or animated, instruction significantly reduced the likelihood that children expressed an intuitive preconception about speciation. Although most children expressed a preconception during the speciation pre-test (91%), the percentage of children who displayed a preconception was significantly lower relative to the pre-test, following instruction on both the speciation comprehension (24%, OR = 0.012) and generalization post-tests (27%, *OR* = 0.015), $p < 0.001$, $p < 0.001$, respectively. Moreover, children's ability to respond without stating a preconception remained visible after a three-month delay relative to the speciation pre-test on both the novel (27%, *OR* = 0.015) and familiar (48%, *OR* = 0.05) species assessments, $p < 0.001$, $p < 0.001$, respectively.

While not statistically different, the difference in the expression of preconceptions by children in the static and animated storybook is worth noting. Despite expressing more non-normative preconceptions during the pretest (94% vs. 88%), children exposed to the animated storybook expressed fewer preconceptions on the initial generalization posttest (12% vs. 44%) and this difference remained on the far generalization posttest after a three-month delay with children in the animated storybook condition expressing non-normative preconceptions at half the rate of children in the static storybook condition (35% vs. 63%).

Did instruction increase children's normative understanding of natural selection?

Below we report analyses of changes in children's global understanding of natural selection across assessments using repeated measures ordinal logistic regressions. These models examined how the distribution of children across the five hierarchical levels of natural selection understanding changed across time (which was nested within students to account for the non-independence of student scores across time). 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. Figure 3 displays the change in hierarchical levels of understanding over time.

Natural selection understanding in the context of adaptation

In our first model, we included the effect of Time, Condition, and the interaction between Time and Condition. Analyses revealed that changes in children's understanding of adaptation by natural selection did not differ as a function of whether children received instruction using the static storybook or the animated storybook. The effect of Condition and the Condition X Time interactions were not statistically significant, χ^2 (3) = 2.11, $p = 0.55$. Indeed, a visual comparison of Fig. 3a, b confirms a very similar pattern of results for children in the static and animated storybook conditions. These terms were removed from the model. The model with only Time as a predictor explained a significant amount of variance, Wald χ^2 (2) = 28.2, $p < 0.001$. Whether static or animated, instruction significantly increased children's scientific understanding of adaptation.

Relative to the adaptation pre-test, children across both conditions exhibited a higher level of understanding on the adaptation comprehension post-test following the storybook or video (*OR* = 315.17, $p < 0.001$) and successfully generalized the logic of adaptation by natural selection to an entirely new animal (*OR* = 182.50, $p < 0.001$). Specifically, before hearing the story, only 3% of children displayed a population-based logic (Level 3 or higher). In contrast, on the adaptation generalization post-test, 68% had integrated the facts into a normative population-based explanation that incorporated, at minimum, the concept of differential survival. Of note, and consistent with the results of preconception change analyses, greater learning occurred in the animated storybook condition than in the static storybook condition: 80% of children in the animated storybook condition displayed population-based logic on the generalization post-test while 57% of children did so in the static storybook condition.

Natural selection understanding in the context of speciation

In our first model, we included the effect of Time, Condition, and the interaction between Time and Condition. Analyses revealed that changes in children's understanding of speciation by natural selection did not differ as a function of whether children received book-based rather than animation-based instruction. The effect of Condition and the Condition X Time interactions were not statistically significant, χ^2 (5) = 10.25, $p = 0.07$. These terms were removed from the model. However, despite the lack of a statistically significant difference between the two conditions, a visual comparison of Fig. 3a, b reveals greater learning in the animated condition than in the static storybook

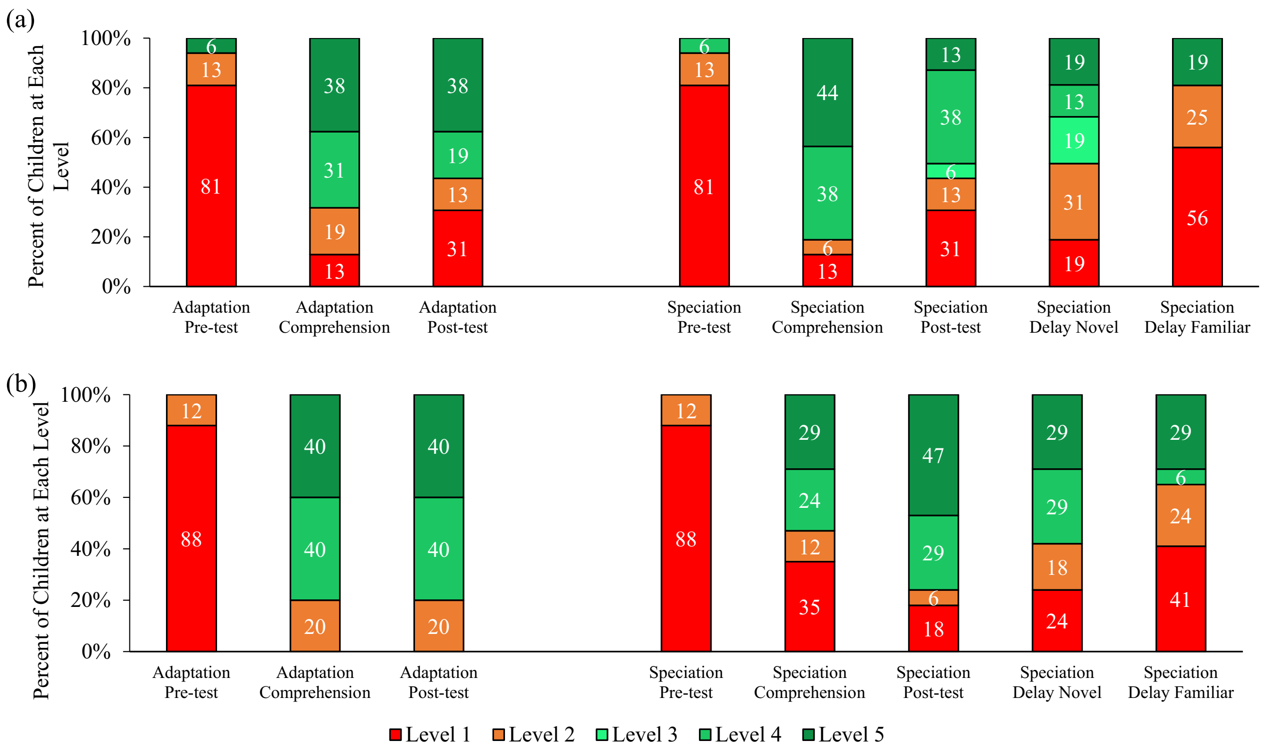

Fig. 3 Percentage of children who received (**a**) the static storybook intervention (*N* = 16) and the (**b**) animated storybook intervention (*N* = 17) classified into the five levels of natural selection understanding for each assessment. Level 1 = no isolated facts; Level 2 = isolated facts but no natural selection understanding; Level 3 = foundation for natural selection understanding; Level 4 = natural selection understanding in one generation; Level 5 = natural selection understanding for multiple generations

condition. Below, we first discuss changes in children's understanding across condition before describing the differences between conditions.

The model with only Time as a predictor explained a significant amount of variance, Wald χ^2 (5) = 25.57, $p < 0.001$ (see Fig. 3). Whether static or animated, instruction significantly increased children's scientific understanding of speciation. Relative to the speciation pre-test, children across both conditions exhibited a higher level of understanding on the speciation comprehension post-test following the storybook or animation ($OR = 126.26$, $p < 0.001$) and successfully generalized the logic of speciation by natural selection to an entirely new species ($OR = 22.76$, $p = 0.001$). While many children could learn and apply the logic of speciation, delayed generalization post-tests revealed that children's capacity for generalizing the theory only partially endured after 3 months: There was a significant difference in children's understanding of speciation when comparing performance on the speciation pre-test and delayed test about a novel species ($OR = 24.77$, $p < 0.001$) but not about a familiar species ($OR = 5.50$, $p = 0.059$).

While not statistically different, it is worth noting that more children reached the highest level of comprehension (Level 5) in the animated storybook condition than in the static storybook condition on all three speciation generalization posttests: immediate post-test, 47% vs. 13%; delayed post-test, 29% vs. 19%; delayed post-test with a familiar animal, 29% vs. 19%. To reach Level 5, children needed to explicitly mention the fact that the process of speciation occurs over multiple generations.

Discussion

This study examined children's ability to learn the counterintuitive concepts of adaptation and speciation from a read-aloud of a traditional print storybook versus a narrated, animated screen-based version. Results revealed substantial learning of natural selection from the storybooks. Furthermore, despite the absence of the joint attentional context—a factor known as highly relevant to children's learning–we found evidence that the animated version of the storybook is not worse than the static storybook. In fact, our results suggest that the animated version of the storybook is similar and may be potentially better than the static version. We had predicted that the animated storybook would boost children's learning relative to the static storybook for speciation but not adaptation. In fact, we found that the animated storybook condition generated statistical similar yet numerically greater learning of smaller scale *and* larger scale evolutionary change: (1) children in the animated storybook condition experienced greater and more sustained reductions in their preconceptions about the mechanism of evolutionary change than children in the static storybook condition on the adaption and speciation post-tests; (2) children in the animated storybook condition experienced greater and more sustained increases in their understanding of speciation as a process that takes place over multiple generations than children in the static storybook condition.

What explains these results? The animated and print storybooks used the same text and illustrations. However, the animated storybook allowed for a more dynamic depiction of successive generational cycles of birth, growth, and death than the static storybook. This more dynamic visualization helped make clear to children the non-goal-directed nature of change in adaptation as demonstrated by a greater and more sustained reduction in preconceptions. In so doing—because adaptation acts as a strong foundation to understanding of speciation (Ronfard et al. 2021)—it also helped children build a robust understanding of the evolution of species: a greater proportion of children in the animated storybook condition attained and sustained a Level 5 understanding indicating greater representational robustness of natural selection as a cyclic multi-generational mechanism.

These results are noteworthy for theoretical and practical reasons. Acquiring a normative scientific understanding of speciation is not easy. It requires that children overcome their essentialist and teleological biases (Kelemen 2019; Shtulman and Calabi 2012) and their difficulties with representing the passage of time (Friedman 2005; Levin 1992; Trend 1998). Critically, children must not only mobilize their executive functions to inhibit essentialist and teleological based preconceptions during the initial construction of the theory but also during the later expression of that normative scientific account of natural selection (see Ronfard et al. 2021). This is because rather than being replaced, children's preconceptions coexist with their normative scientific understanding of natural selection. As a result, as initially demonstrated by Ronfard et al. (2021), of the children who acquired a normative scientific understanding of natural selection from our storybooks, it was those with higher inhibition scores that were significantly more likely to retain and express such an understanding after a delay. The greater reemergence of intuitive preconception after a 3-month delay in the static storybook condition than in the animated storybook condition is consistent with this coexistence account: the increased representational robustness of natural selection as a cyclic mechanism engendered by the dynamic animations made it easier for children to deploy that understanding in the face of competing and coexisting preconceptions.

Natural selection is typically not taught until high school in part because of incorrect assumptions about the cognitive abilities of young children (see Kelemen 2019). The current study along with past work suggests that this is a mistake. By 7-years of age, children can benefit from coherent mechanistic explanations and acquire a normative scientific understanding of natural selection. By itself, this fact does not support its inclusion in the curriculum. However, evolution by natural selection is central to understanding the complexity, diversity, and functional specialization of living things. Given that it is a core concept of biology that is easily misunderstood, early instruction that is progressively revisited may be key to more successfully supporting its enduring acquisition and use (Kelemen 2019). However, adding new content to existing curricula is not easy especially when what is being added is difficult to teach and hard for adults to understand (Gregory 2009; Ha et al. 2019; Nehm and Reilly 2007). Thus, these results, along with recent curricula for teaching small- and large-scale evolution by natural selection (Kelemen et al. 2023) and for assessing children's classroom learning (Brown et al. 2020) provide much-needed optimism in a context of increasing demands for scalable solutions to promote effective learning. Animated storybooks are easily scalable, cost-effective, and can be made available to anyone with an internet connection. Their ability to generate similar and potentially greater learning to traditional read-aloud storybooks provides a potential solution for maintaining high quality instruction in future contexts where joint attentional contexts might be precluded, e.g., ongoing and future pandemics.

It will be important for future research to replicate and extend the current results with a larger sample size. Of both theoretical and practical interest would be the addition of an animated storybook condition that includes an avatar that narrates the storybooks and interacts with children (e.g., Blue's Clues or Dora the Explorer). Past research has shown that such animated and interactive educational programs can support children's learning (Calvert et al. 2007). An animated storybook with an interactive component may yield the best result as it would leverage the power of social interaction with the visualization of the cyclic process of natural selection.

It is also worth noting that, by design and necessity, the current study limited instruction to four key ideas: (1) species can change and entirely new species can evolve; (2) these changes are not goal-directed and do not occur in response to need; (3) these changes involve a mechanistic process and are not rapid event-based transformations; (4) and new species can evolve by the same process that leads to them to become specialized to their habitat. These key ideas provide a solid foundation for extending children's understanding to include a better understanding of the timescale of adaptation, of speciation, and of the details of genetic inheritance (see also Bruckermann et al., 2021 for a review of the evolutionary concepts children can learn and those they struggle to learn). Thus, one important question being explored in ongoing research is how far children's understanding can be pushed within the context of an extended curriculum that revisits and builds upon these four ideas by incorporating information about timescales and the kind of evidence (e.g., fossils) that supports scientific theory-building about the history of animal and plant species and the relatedness of disparate organisms to each other (Kelemen et al. 2023). Even if such expanded classroom interventions show learning benefits to elementary students, it is certainly possible that a more elaborated understanding of evolution by natural selection–one that incorporates an understanding of how variation-generating events (random mutation and recombination) lead to the individual variation that probabilistically influences fitness—requires additional cognitive maturity as well as instruction in key statistical concepts (Fielder et al. 2019).

Conclusion

In sum, second graders can learn the counterintuitive mechanism of speciation whether it is presented via a joint-attentional read-aloud of a static storybook or via the non-joint-attentional but more visually-dynamic medium of animation. Given recent demonstrations that acquiring and using a normative scientific understanding of natural selection requires inhibiting intuitive preconceptions (Ronfard et al. 2021), instruction about natural selection should not be delayed until high school. By then essentialist and teleologically based preconceptions will have entrenched themselves making instruction more difficult (Kelemen 2019). Moreover, our results fit within a broader literature on learning from multi-media sources (Danovitch 2019; Ganea et al. 2008; Richert et al. 2011; Richert and Schlesinger 2022). Storybooks whether animated or not support children's learning and transfer of hard-to-learn scientific concepts.

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Author contributions
SR, DK, SB, and EP designed the study and coding scheme. SR led the statistical analysis. SR and DK wrote the manuscript. SB and EP provided edits and comments. All authors read and approved the final manuscript.

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Availability of data and materials
The dataset supporting the conclusions of this article is available in the Open Science Framework repository, at https://osf.io/emrft/?view_only=8577def9510b427f8608051b0f104009. The adaptation and speciation assessments are openly available on the Evolving Minds project website (https://www.evolvingmindsproject.org/materials). The custom storybooks used in the intervention are available online or in bookstores (Kelemen and The Child Cognition Lab 2017; 2020). The animated versions of the storybooks can be found online: adaptation, https://youtu.be/b4yzh_HDu70; speciation, https://youtu.be/nxoErP_8Wt0.

Declarations

Competing interests
The authors declare that they have no competing interests.

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