



Qualitative differences between naïve and scientific theories of evolution

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Abstract

Philosophers of biology have long argued that Darwin's theory of evolution was qualitatively different from all earlier theories of evolution. Whereas Darwin's predecessors and contemporaries explained adaptation as the transformation of a species' "essence," Darwin explained adaptation as the selective propagation of randomly occurring mutations within a population. The present study explored the possibility of a parallel between early "transformational" theories of evolution and modern naïve theories. Forty-two high school and college students and three evolutionary biologists were tested on their understanding of six evolutionary phenomena: variation, inheritance, adaptation, domestication, speciation, and extinction. As predicted, a plurality of participants demonstrated transformational reasoning inconsistent with natural selection. Correlational analyses revealed that participants who demonstrated transformational reasoning were as internally consistent as participants who demonstrated an understanding of natural selection, with the exception of one group of participants who appeared to have assimilated two heuristics—"survival of the fittest" and "acquired traits are not inherited"—into an otherwise transformational framework. These findings suggest that the widespread and early-developing tendency to essentialize biological kinds precludes students from conceptualizing species as populations of individuals differentially affected by the environment.

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1. Introduction

The question of why organisms are adapted to the environment in which they live was first formulated by Greek philosophers as early as the seventh century BC (Mayr, 1982), yet it remained unsolved until Darwin published *The Origin of Species* in 1859. Darwin's solution was inspired by three empirical phenomena: (1) superfecundity, or the fact that organisms often produce more offspring than the environment can support, (2) variation, or the fact that offspring are never exact replicas of their parents, and (3) inheritance, or the fact that at least some of this variation is passed down from one generation to the next. From these facts, Darwin inferred the principle of *natural selection*: only those organisms most adapted to the environment will survive to reproduce, thereby increasing the proportion of adaptive traits to non-adaptive traits in future generations of the same species.

Even though Darwin's theory of evolution by natural selection offers a scientific solution to the problems of speciation and species adaptation, it remains a source of controversy and confusion to the public at large. A recent national survey found that only 35% of Americans believe that Darwin's theory of evolution has been well supported by evidence (Newport, 2004). Among Americans with postgraduate degrees, this percentage rises to only 65%. Interestingly, those who do not endorse the claim that Darwin's theory of evolution has been well supported by evidence tend to endorse the alternative claim (i.e., that Darwin's theory of evolution has *not* been well supported by evidence) rather than plead ignorance.

Many biologists have interpreted evolution's lack of popularity and frequent misrepresentation (e.g., as a ladder, chain, or hierarchy) as signs that natural selection is not well understood by the general public. Dawkins (1987), for example, surmises that natural selection is a concept everyone thinks they understand but few actually do. "How can such a powerful idea go still largely unabsorbed into popular consciousness?" he asks. "It is almost as if the human brain were specifically designed to misunderstand Darwinism and to find it hard to believe" (p. xi). Though Dawkins' speculation was most likely made in jest, there is at least one reason to take this speculation seriously: human beings tend to essentialize biological kinds and essentialism is incompatible with natural selection.

To be more specific, a growing body of psychological research suggests that individuals of all ages and cultures assume that a species' outward appearance and behavior are determined by a kind of hidden causal power or "essence" (see Gelman, 2003; Medin & Atran, 2004). Evidence of biological essentialism has been found in children as young as four. Like adults, children of this age believe that species members share both observable and non-observable traits (Gelman & Markman, 1986); that species members possess an innate potential to develop the same traits (Gelman & Wellman, 1991); and that species identity remains constant across both temporary, artificial transformations (Keil, 1989) and permanent, natural transformations (Rosengren, Gelman, Kalish, & McCormick, 1991). Beliefs of this nature have been observed not only in American children but also in Yucatek Maya children (Atran et al., 2001) and Brazilian children (Sousa, Atran, & Medin, 2002). As a framework for understanding the reproduction and inheritance of individual organisms, biological essentialism appears to become entrenched throughout development and is not easily abandoned.

Applied to the study of biological adaptation, essentialism led early evolutionary theorists to commit what Gould (1996) calls the "fallacy of reified variation," or the tendency "to abstract a single ideal or average as the essence of a system and to devalue or ignore variation among the individuals that constitute the full population" (p. 40). These theorists

construed evolution as the process by which a species' essence is transformed over time, and they proposed a variety of essence-transformation mechanisms, including the inheritance of acquired traits (Lamarck, 1809), the unfolding of a preprogrammed design (Chambers, 1844), the recapitulation of ontogeny (Haeckel, 1876), the acceleration of growth (Cope, 1896), the chemical structure of protoplasm (Berg, 1926), the lawful properties of organic matter (Eimer, 1898), the intentional properties of intelligent systems (Butler, 1916), and an *élan vital* (Bergson, 1911).

Unlike the other biologists of his day, Darwin focused on individual differences among members of the same (and closely related) species, which lead him to devise what Mayr (2001) calls a “variational” theory of evolution, as opposed to the “transformational” theories of his predecessors and contemporaries. Fig. 1 depicts the fundamental conceptual differences between variationism and transformationism in the context of the evolution of the peppered moth, *Biston betularia* (which may or may not have evolved darker coloration in response to the pollution produced by the Industrial Revolution; see Hooper, 2002). The four rows of moths displayed in each panel of Fig. 1 represent an observable instance of evolution that variationists and transformationists would explain differently. Whereas variationists would explain this change in terms of two processes (mutation and selection)

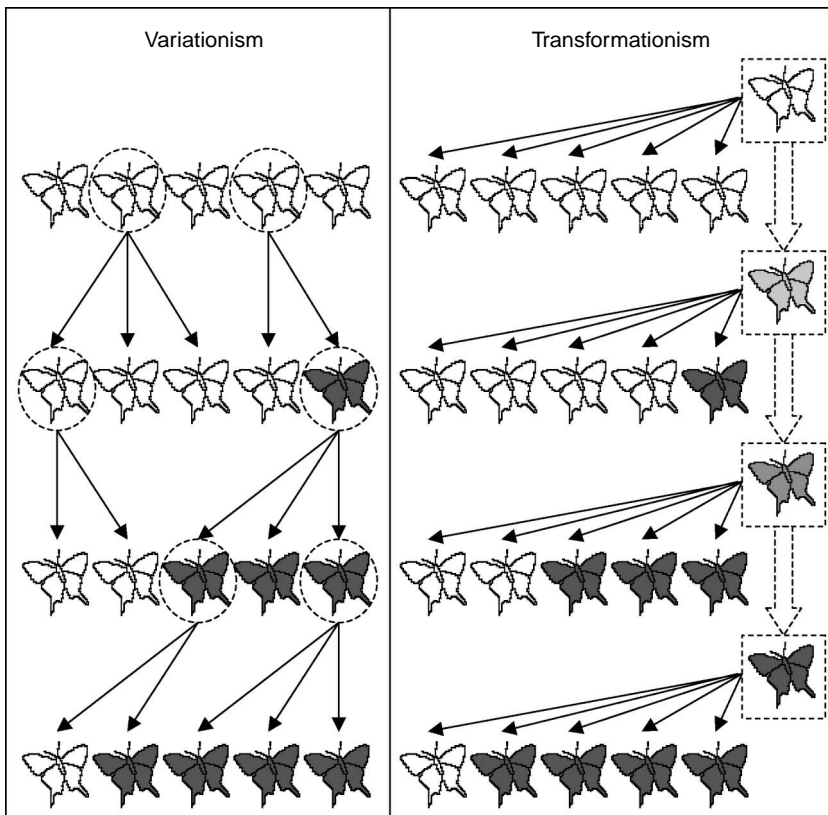


Fig. 1. Illustration of the conceptual differences between variational and transformational theories of evolution (in the context of moth evolution). Dashed lines represent mechanisms of adaptation and arrows represent pathways of inheritance. Moth coloration is treated as a dichotomous trait (white vs. gray) for simplicity's sake.

operating on a population of individuals, transformationists would explain this change in terms of a single process operating on the species' "essence."

Put differently, variationists treat adaptation as a two-step process. First, chance mutations and sexual recombinations create individual differences among members of the same species (depicted in the lefthand panel of Fig. 1 as arrows between parents and offspring of different colors). Second, some of these individual differences are retained and others are eliminated on the basis of their utility to survival and reproduction (depicted by circles around the few organisms that produce offspring). Transformationists, on the other hand, conflate these two processes into one. Organisms are believed to bear offspring that are better adapted to the environment than they were themselves because the essence common to all members of that species (depicted in the righthand panel of Fig. 1 as the "average moth") is continually transformed from one generation to the next. This process of "essence transformation" entails a secondary process in which changes to a species' essence are transmitted to the species members themselves (depicted by arrows from the former to the latter). Note that this particular example, involving the evolution of a single, dichotomous trait, makes the practice of "reifying the mean" appear more irrational than it might otherwise have appeared in the context of real organisms with multiple, continuous traits.

In summary, individuals are predisposed to essentialize species, which, in turn, predisposed early evolutionary theorists to construe evolution as the transformation of a species' essence. Are modern day students of evolution also predisposed to construe evolution as the transformation of a species' essence? The plausibility of this hypothesis is supported by various studies showing that cognitive development within the individual often parallels theory development in the history of science. Domains in which students' naïve theories have been shown to resemble earlier theories in science include mechanics (McCloskey, 1983), thermodynamics (Wiser, 1988), acoustics (Mazens & Lautrey, 2003), physical chemistry (Smith, Carey, & Wiser, 1985), and cosmology (Vosniadou & Brewer, 1992). What about the domain of evolution?

To date, researchers interested in evolution education have documented a variety of misconceptions in a variety of populations (Bishop & Anderson, 1990; Brumby, 1984; Demastes, Settlage, & Good, 1995; Greene, 1990; Jensen & Finley, 1995, 1996; Lawson & Thompson, 1988; Settlage, 1994; Southerland, Abrams, Cummins, & Anzelmo, 2001). However, with respect to the question of whether the average adult's understanding of evolution is transformational in nature, these findings are largely inconclusive for two reasons. First, many of these studies were conducted at a level of analysis too broad to capture the theoretically meaningful differences between variationism and transformationism described above. For instance, many researchers have examined students' verbal responses for evidence of teleological language, yet even Darwin used teleological language to describe natural selection (Ruse, 2003) and it would be a mistake to classify Darwin as a non-Darwinist. Second, studies that have analyzed students' misconceptions at the level of individual concepts have not looked for within-participant consistency across multiple concepts or within-group consistency across multiple participants. Without these measures, it is unclear whether errors in reasoning exhibited by a group reflect the existence of an alternative theory or merely a handful of isolated misconceptions.

What is needed to establish the existence of an alternative theory is not the number of errors made by a group but the pattern of errors made by individuals. To this end, participants in the present study were tested on their understanding of six evolutionary phenomena: variation, inheritance, adaptation, domestication, speciation, and extinction. It was hypothesized that some participants would interpret each and every phenomenon within a variational framework (like Darwin) and others would interpret each and every phenomenon within a

transformational framework (like Darwin's predecessors and contemporaries). It was further hypothesized that participants who demonstrated transformational reasoning would do so as consistently as participants who demonstrated variational reasoning, with the possible exception of participants in the midst of theory change.

2. Methods

2.1. Participants

Forty-five students were recruited from the Harvard Summer School study pool and were given class credit as reimbursement for their participation. Three of these students did not complete the survey in its entirety and were dropped from the sample. Of the remaining 42, 29 were high school students from across the United States and 13 were college undergraduates from a variety of universities (only two attended Harvard). The average number of biology classes taken by this group of participants was 1.5 (range = 0 to 4), and 76% of participants claimed to be familiar with Darwin's theory of evolution. Ninety-five percent agreed with the statement "species have changed over time;" 69% agreed with the statement "natural selection is the best explanation for how a species adapts to its environment;" and 62% disagreed with the statement "the origin of human beings requires a different explanation than the origin of other species." Thus, the sample included two anti-evolutionists (most likely creationists) and at least thirteen students skeptical of natural selection.

Three individuals with doctorates in biology were also asked to participate in the study in order to validate the test measures. Two of these individuals held faculty positions at major research universities, and the other taught college-level biology courses at a high school. As expected, all three agreed with the statements "species have changed over time" and "natural selection is the best explanation for how a species adapts to its environment" and disagreed with the statement "the origin of human beings requires a different explanation than the origin of other species."

2.2. Materials

Participants' evolutionary reasoning was assessed with a thirty-question test, reproduced (with slight modifications) in Appendix A. This test was designed to elicit different variational and transformational interpretations of the same six evolutionary phenomena: variation, inheritance, adaptation, domestication, speciation, and extinction. These differences are summarized in Table 1 and elaborated below. Note that the test in Appendix A was *not* designed to elicit different evolutionist and creationist interpretations of the same phenomena (e.g., interpreting fossils as the remains of ancestral species vs. the remains of animals who died in the flood described in Genesis), for participants were asked to answer each question in accordance with Darwin's theory of evolution by natural selection regardless of whether they believed this theory to be valid. Readers interested in differences between creationist and evolutionist reasoning should see Samarapungavan and Wiers (1997) or Evans (2001).

2.2.1. Variation

Variationists and transformationists would agree that members of the same species are not identical. Only variationists, however, would interpret such differences as relevant to

Table 1
Variational (V) and transformational (T) interpretations of the same evolutionary phenomena

Phenomenon	Theory	Interpretation
Variation	V	Individual differences are fodder for selection
	T	Individual differences are minor and non-adaptive
Inheritance	V	A trait's heritability depends upon its origin
	T	A trait's heritability depends upon its adaptive value
Adaptation	V	Differential survival/reproduction produces adaptation
	T	Differential survival/reproduction is irrelevant to adaptation
Domestication	V	Species are domesticated via selective breeding
	T	Species are domesticated via changes to individual organisms
Speciation	V	All species share a common ancestor
	T	Closely related species share a common essence
Extinction	V	Extinction is more common than adaptation
	T	Adaptation is more common than extinction

evolution (i.e., as fodder for selection). Transformationists, on the other hand, would interpret individual differences as non-adaptive, or maladaptive, deviations from a species' essence, thereby underestimating their frequency.

2.2.2. *Inheritance*

Transformationists, like variationists, know that offspring resemble their parents. However, only transformationists would interpret this resemblance as mediated by the species' essence. As such, organisms are believed to inherit any trait that would be adaptive to the species as a whole, regardless of whether that trait was exhibited by the organism's parents. Variationists, on the other hand, believe that organisms inherit the traits of their parents, regardless of the traits' adaptive value (a belief that Springer and Keil (1989) found to be counterintuitive to most preschool children).

2.2.3. *Adaptation*

Variationists and transformationists would agree that many organisms die prior to reproductive maturity. Only variationists, however, would deem this fact relevant to adaptation. Transformationists, on the other hand, believe that all members of a species, fit or unfit, share a common essence, and would therefore devalue the role of selection in species adaptation, if not deny the role of selection altogether.

2.2.4. *Domestication*

Evidence of humankind's ability to alter the evolution of other species can be found in every pet store and grocery store in the country. However, because transformationists allow no role for selection—natural *or* artificial—in the process of evolution, they are likely to attribute these changes to the manipulation of individual organisms over the course of multiple generations. Consequently, transformationists should underestimate the extent to which humans can modify (and have modified) other species.

2.2.5. *Speciation*

According to variationists, speciation occurs when prolonged geographic isolation or non-random mating causes two groups of organisms to become so genetically diverse as to preclude the creation of fertile offspring. Because transformationists believe that all

members of the same species share a common essence, they cannot account for speciation in terms of reproductive isolation and must instead interpret instances of cladogenesis, or branching evolution, as instances of anagenesis, or linear evolution (e.g., interpreting chimpanzees as a parent species, not a sister species, to humans). Moreover, transformationists should deny that morphologically distinct species share any common ancestors whatsoever.

2.2.6. *Extinction*

Instances of extinction can be ordered along a continuum by how quickly a species' death rate surpasses its birth rate. At one end of the continuum are instances of "mass extinction," or situations in which all members of a species die simultaneously at the hands of a drastic environmental change (e.g., a flood). At the other end of the continuum are instances of "background extinction," or situations in which species slowly decrease in size over multiple generations. To variationists, background extinction is just an extreme form of natural selection in which selection pressures overwhelm within-species variation. Transformationists, on the other hand, believe that species are always able to adapt to their environment (see Poling & Evans, 2004a) and should therefore underestimate the frequency of extinction, particularly background extinction.

2.3. *Coding*

All test questions were scored on a scale between -1 and $+1$. Responses consistent with variationism received $+1$ points, and responses consistent with transformationism received -1 points. Fourteen of the 30 questions included an open-ended component for which participants' verbal responses were occasionally consistent with both conceptual frameworks. These "ambiguous" responses received 0 points. On the whole, participants provided theoretically interpretable responses nearly four times as often as they provided ambiguous responses ($M = 2.9$ vs. $M = 11.1$), and no participant provided ambiguous responses to more than half of the open-ended questions. Exact coding schemas for the open-ended questions can be found in Appendix A. Although each schema was created prior to testing, some schemas were expanded to include unanticipated, yet theoretically interpretable, responses. The reliability of these schemas was verified by comparing the classifications of two independent coders (the author and an undergraduate with extensive knowledge in evolutionary biology). Overall agreement was 92%, and all disagreements were resolved via discussion.

The decision to treat variational responses and transformational responses as two ends of a continuum, rather than as discrete categories, was motivated by the desire to sum participants' question scores within a section and compare those scores across sections. As a result, participants' section scores are less intrinsically meaningful than their question scores, and their overall test scores are even less intrinsically meaningful. Qualitative differences in reasoning were therefore investigated at the level of question scores and section scores but not at the level of overall test scores.

3. Results

3.1. *An overview of the test*

As mentioned previously, the six-section, 30-question test used to assess participants' evolutionary reasoning can be found in Appendix A, and the number of participants who

received -1 , 0 , or $+1$ points for each question are listed in Appendix B. A few questions from each section are discussed below in order to give the reader a flavor for the test as a whole.

3.1.1. Variation

The evolution of the peppered moth, *Biston betularia*, was used as a vehicle for eliciting participants' beliefs regarding the prevalence and importance of within-species variation. On one task, participants were shown a table containing 25 moth outlines—five rows of five moths each—and asked to shade each row to reflect the coloration they would expect to find in five random samples of *Biston betularia* collected over the course of the nineteenth century. Shading was accomplished by selecting one of five grayscale values for each and every moth. Depicted in Fig. 2 are ideal variational and transformational shading patterns. Whereas the variational pattern depicts an adaptation spreading through a population, the transformational pattern depicts a population uniformly adapting. Twenty-two percent of participants produced shading patterns similar enough to the variational pattern to receive a positive score; 47% produced shading patterns similar enough to the transformational pattern to receive a negative score; and 31% produced ambiguous shading patterns that received an overall score of zero.

3.1.2. Inheritance

A fictitious species of woodpeckers was used as a vehicle for eliciting participants' beliefs regarding the heritability of various traits. On question 1, participants were told that these woodpeckers have beaks that are, on average, one inch long and that their only food source is a tree-dwelling insect that lives, on average, one-and-a-half inches under the tree bark. Participants were then asked to decide whether the offspring of any two woodpeckers would develop a longer beak than its parents, a shorter beak than its parents, or either of the two features, neither being more likely. Consistent with variationism, 42% of participants claimed that neither outcome was more likely and justified their response by referencing the randomness of mutations. Consistent with transformationism, 36% of

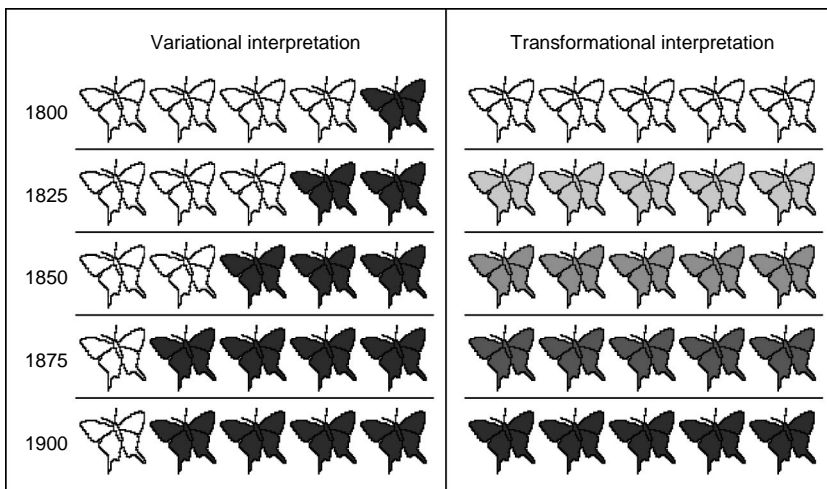


Fig. 2. Ideal variational and transformational shading patterns for variation questions 2–5.

participants claimed that the woodpecker would develop a longer beak than its parents and justified their response by referencing the necessity of longer beaks for survival. The remaining participants justified their forced-choice selections ambiguously and received zero points for that particular question.

3.1.3. *Adaptation*

Five analogical-reasoning questions were used to assess participants' interpretation of the mechanisms of adaptation. On each question, participants were shown four explanations for why a group of individuals had improved their performance along some dimension and asked to select the explanation that was most analogous to Darwin's explanation for the adaptation of species. Each explanation exemplified one of four analogies: a selection analogy, a force analogy, a growth analogy, and an intention analogy. Whereas the selection analogy attributed the group's improvement to changes in group membership, the other three analogies attributed the group's improvement to changes in the group members themselves. For example, on question 1, participants were shown the following four explanations for why a youth basketball team had won more games in one season than in another: (a) each returning team member grew taller over the summer; (b) any athlete who participates in a sport for more than one season will improve at that sport; (c) more people tried out for the same number of spots this season; or (d) each team member practiced harder this season than he did last season. Consistent with variationism, 49% of participants chose (c), the selection analogy. Consistent with transformationism, 22% of participants chose (a), the growth analogy; 16% chose (b), the force analogy; and 13% chose (d), the intention analogy.

3.1.4. *Domestication*

The domestication of corn from Teosinte, a wild grass native to Central America, was used as a vehicle for eliciting participants' beliefs regarding the manner in which a species can be modified by human intervention. On one task, participants were informed of the artificial origins of corn and were then asked to rank, in order of relevance, six factors that may have been involved in the domestication of this species: (a) the degree of similarity among plants of the same generation, (b) the average amount of time each plant was exposed to direct sunlight, (c) the preferences of those who decided which kernels to plant, (d) the fertility of the soil in which the kernels were planted, (e) the average rainfall per year, and (f) the percentage of each crop used to breed the next generation. Whereas factors (a), (c), and (f) are relevant to the modification of an entire species, factors (b), (d), and (e) are relevant only to the modification of individual plants. Consistent with variationism, 31% of participants ranked factors (a), (c), and (e) higher than they ranked factors (b), (d), and (f). Consistent with transformationism, 33% of participants ranked one of the irrelevant factors (b, d, or f) higher than one of the relevant factors (a, c, or f); 16% ranked two of the irrelevant factors higher than two of the relevant factors; and 20% ranked all three irrelevant factors higher than all three relevant factors.

3.1.5. *Speciation*

Primate evolution was used as a vehicle for eliciting participants' beliefs regarding common ancestry and species individuation. On question 1, participants were shown a list of nine species—lemurs, elephants, salamanders, sparrows, bees, jellyfish, algae, daffodils, and brontosaurus—and asked to place a check next to each species that shares a common ancestor with humans. Only 38% of participants claimed that humans share a common

ancestor with all nine species. The rest claimed that humans do *not* share a common ancestor with at least two or more of the species. In particular, 13% of participants claimed that humans share a common ancestor with only two of the species (typically lemurs and elephants), and 18% claimed that humans share a common ancestor with only one of the species (typically lemurs). This finding is consistent with Poling and Evans' (2004b) finding that students often deny that morphologically dissimilar species (e.g., rats, whales, and zebras) share a common ancestor.

3.1.6. Extinction

The evolution of bacteria was used as a vehicle for eliciting participants' beliefs regarding the frequency and causes of extinction. On one task, participants were asked to arrange the fossils of eight kinds of bacteria into a "family tree" (see Fig. 3). One fossil was identified as a living specimen and the remaining seven were labeled with unique dates of origin. Participants were told that the living specimen was definitely a descendent of the oldest fossil and asked to place the remaining six fossils into the same lineage or different lineages depending upon their visual similarity. Half were designed to fit most parsimoniously into the surviving lineage, and half were designed to fit most parsimoniously into extinct lineages. Consistent with transformationism, 40% of participants overlooked the possibility of creating extinct lineages and placed fossils only into the surviving lineage, if they placed them into any lineage at all. Consistent with variationism, 20% of participants produced the fossil arrangement displayed in the top panel of Fig. 3. The remaining participants produced fossil arrangements intermediate between these two extremes.

3.1.7. Overall test scores

A frequency distribution of participants' overall test scores are displayed in Fig. 4. These scores ranged from -22 to 30 and averaged -0.5 ($SD = 16.40$). At the far right of

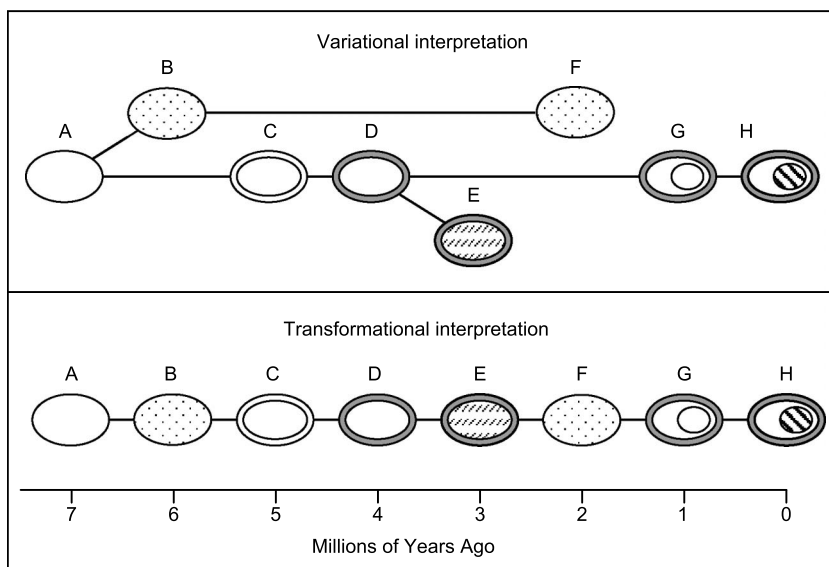


Fig. 3. Ideal variational and transformational fossil arrangements for extinction questions 3–5.

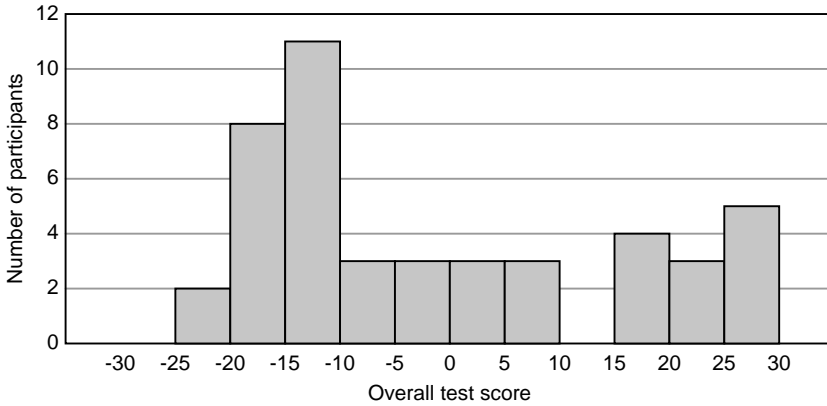


Fig. 4. A frequency distribution of participants' overall test scores. Each bar is inclusive of the test score to its right.

this distribution were the three individuals with doctorates in biology, who each scored between 28 and 30 points. Broken down by section, participants scored an average of -0.7 points on the variation questions ($SD = 3.1$), 0.5 points on the inheritance questions ($SD = 3.4$), -0.2 points on the adaptation questions ($SD = 4.5$), 0.6 points on the domestication questions ($SD = 3.0$), -0.4 points on the speciation questions ($SD = 3.3$), and -0.4 points on the extinction questions ($SD = 3.1$). A repeated-measures ANOVA revealed a significant effect of question type, $F(5,220) = 2.42$, $p < 0.05$. However, post hoc comparisons of the individual sections revealed no significant differences, implying that each section elicited approximately the same amount of transformational reasoning.

3.2. Within-participant consistency

Participants' scores on individual questions within each section were summed for the sake of comparison. In terms of sign alone, 31% of participants earned scores of the same sign on all six sections; 40% earned scores of the same sign on five of the six sections; and 18% earned scores of the same sign on four of the six sections. Thus, 89% of participants demonstrated one form of reasoning (i.e., variational reasoning or transformational reasoning) on at least twice as many sections as they demonstrated the other. In terms of actual magnitude, participants' section scores ranged from -5 to 5 . Correlations among these scores are displayed in Table 2. Each section score was significantly correlated with every other section score, and the majority of these correlations (10 of 15) exceeded a magnitude of $r = 0.50$. A principal component analysis was used to assess the dimensionality of this correlation matrix. It was predicted that variance in participants' responses would be best explained by a single dimension rather than by a handful of orthogonal dimensions (e.g., microevolutionary reasoning vs. macroevolutionary reasoning). This prediction was confirmed in three respects.

First, only the first principal component had an eigenvalue greater than one, indicating that the remaining five components accounted for less variance in the dataset than did any individual variable. Second, the first principal component accounted for the majority of variance in participants' responses (65%) and more than five times as much variance as accounted for by the second principal component (12%). Third, all but one of the six factor

Table 2
Correlations between participants' section scores and the first principal component of all six measures

Section	VAR	INH	ADA	DOM	SPE	EXT	Factor
Variation (VAR)	1.00	.45**	.75**	.54**	.68**	.66**	.68
Inheritance (INH)		1.00	.44**	.54**	.55**	.41**	.85
Adaptation (ADA)			1.00	.56**	.64**	.50**	.81
Domestication (DOM)				1.00	.68**	.50**	.79
Speciation (SPE)					1.00	.76**	.90
Extinction (EXT)						1.00	.80

* $p < .05$.

** $p < .01$.

loadings on the first principal component was stronger than the strongest correlation among the individual variables ($r = 0.76$). Thus, variation in participants' interpretations of the six separate phenomena was best explained by a single factor, which is perhaps best interpreted as "theoretical orientation."

3.3. Between-participant consistency

The above analyses suggest that participants' reasoning was coherent, but did the participants who produced mainly transformational responses reason as coherently as the participants who produced mainly variational responses? To answer this question, participants' scores on all 30 questions were subjected to a cluster analysis using Ward's method as the clustering algorithm and squared Euclidean distances as the proximity measure (see Fig. 5). Contrary to expectation, this analysis split participants into three major clusters rather than two. The anticipated clusters consisted of participants who earned overall test scores between 16 and 30 (henceforth referred to as "variationists") and participants who earned overall test scores between -22 and -5 (henceforth referred to as "transformationists"). The unanticipated cluster consisted of participants who earned overall test scores near zero and who shall henceforth be referred to as "pre-variationists." The term "pre-variationist" was chosen to reflect the fact that although most of these participants provided transformational responses more often than they provided variational ones, they nevertheless provided enough variational responses to merit their own cluster.

How did the pre-variationists differ from the transformationists? This question was investigated using one-way ANOVAs to test the effect of cluster membership on participants' section scores. The results of these analyses are summarized in Table 3. Not surprisingly, participants' section scores differed significantly as a function of cluster membership for all six sections. However, post hoc comparisons of the individual clusters revealed that the pre-variationists differed significantly from the transformationists on only two: inheritance and adaptation. Because the pre-variationists produced fewer ambiguous responses than the transformationists did ($M = 2.9$ vs. $M = 3.8$), these differences cannot be attributed to confusion or laziness on the part of the pre-variationists. Rather, they suggest that the pre-variationists held two variational beliefs that the transformationists did not: (1) that organisms inherit the traits of their parents regardless of their adaptive value and (2) that differential survival is relevant to species adaptation.

Differences between the pre-variationists and the transformationists regarding the interpretation of species adaptation were particularly profound. Whereas 11 of the 15

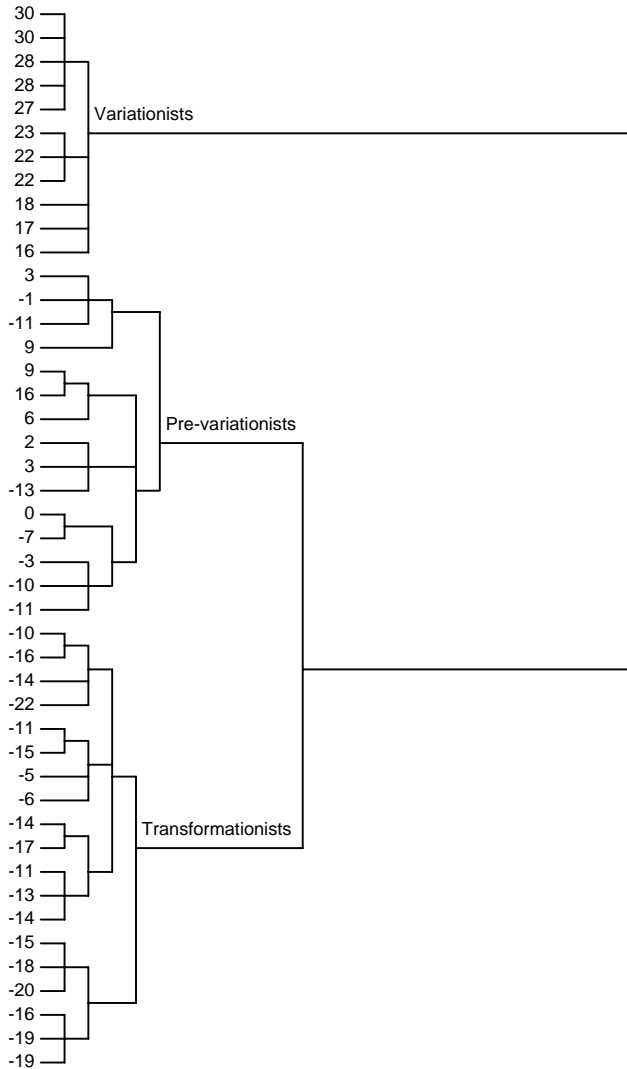


Fig. 5. Cluster analysis of participants' responses to all 30 questions using Ward's method as the clustering algorithm and squared Euclidean distances as the proximity measure. Participants are labeled by their overall test score and the three main clusters are labeled in accordance with those scores.

pre-variationists judged the selection analogy “most analogous” to species adaptation on three or more of the adaptation questions (i.e., the analogical-reasoning questions), none of the transformationists judged the selection analogy “most analogous” to species adaptation on more than a single question. The relative popularity of the other analogies was explored in a series of one-way ANOVAs testing the effect of cluster membership on the analogies judged “most analogous” to species adaptation, as well as the analogies judged “least analogous” to species adaptation (note that participants' “least analogous” classifications were not used to score this section). The results of these analyses are summarized in Table 4. Participants' judgments differed significantly by cluster membership for all four

Table 3

Post hoc comparisons of the variationists' (V), pre-variationists' (P), and transformationists' (T) mean section scores (range = -5 to 5)

Section	Mean score			<i>F</i> value	Comparisons
	V	P	T		
Variation	2.8	-1.7	-1.8	88.45**	V > P, P = T
Inheritance	2.5	1.4	-2.4	44.08**	V > P, P > T
Adaptation	5.0	1.4	-4.5	74.56**	V > P, P > T
Domestication	4.0	0.0	-0.9	16.28**	V > P, P = T
Speciation	4.4	-1.3	-2.6	72.19**	V > P, P = T
Extinction	3.1	-0.5	-2.3	19.26**	V > P, P = T

* $p < .05$.

** $p < .01$.

Table 4

Post hoc comparisons of the variationists' (V), pre-variationists' (P), and transformationists' (T) analogy classifications (range = 0 to 5)

Classification	Analogy	Mean classifications			<i>F</i> value	Comparisons
		V	P	T		
Most analogous	Selection	5.0	3.1	0.3	71.86**	V > P, P > T
	Force	0.0	0.3	2.0	25.71**	V = P, P < T
	Growth	0.0	1.0	1.7	10.15**	V = P, P = T
	Intention	0.0	0.7	1.0	3.73*	V = P, P = T
Least analogous	Selection	0.0	1.1	2.4	16.39**	V < P, P < T
	Force	0.9	1.0	0.6	0.53	V = P, P = T
	Growth	1.2	1.0	0.6	1.25	V = P, P = T
	Intention	2.9	1.9	1.3	5.25**	V = P, P = T

* $p < .05$.

** $p < .01$.

“most analogous” classifications and for two of the four “least analogous” classifications (selection and intention. Post hoc comparisons of the individual clusters revealed that the pre-variationists were significantly more likely than the transformationists to judge the selection analogy “most analogous” to species adaptation and significantly less likely than the transformationists to judge the selection analogy “least analogous” to species adaptation.

3.4. Belief and education

After completing the test, participants were asked to rate their endorsement of the nine statements of belief listed in Table 5. As mentioned previously, most participants endorsed the factuality of evolution and the validity of Darwin's theory of evolution, and their endorsement ratings did not differ significantly by cluster membership (as assessed with one-way ANOVAs). The statements of belief for which participants' endorsement ratings *did* differ significantly by cluster membership were “I have taken a class or read a book that sufficiently explained natural selection,” “I understand the concept of natural selection,” and “I believe in the existence of God.” Post hoc comparisons of the individual clusters revealed that the variationists were significantly more likely than transformationists to

Table 5

The average degree to which the variationists' (V), pre-variationists' (P), and transformationists' (T) endorsed nine statements of belief (5 = strongly agree, 1 = strongly disagree)

Statement	V	P	T	F value
Species have changed over time	4.6	4.5	4.4	0.31
The species in existence today have not always existed	4.6	4.3	4.1	0.74
Natural selection explains species adaptation	4.5	3.7	3.6	2.56
Natural selection explains the origin of nonhuman species	4.0	3.1	3.5	1.78
Natural selection explains the origin of humans	3.4	2.5	2.6	1.62
I have taken a class or read a book explaining natural selection	4.6	3.6	2.8	11.57**
I understand the concept of natural selection	4.5	4.0	3.4	6.31**
I believe in the existence of God	2.3	3.2	3.9	5.34**
I believe in the existence of souls	2.7	3.5	3.9	2.96

* $p < .05$.

** $p < .01$.

endorse the first two statements but significantly less likely than the transformationists to endorse the third. The pre-variationists, on the other hand, did not differ significantly from either the variationists or the transformationists on any of the three statements. Interestingly, only 9 of the 19 transformationists disagreed with the statement “I have taken a class or read a book that sufficiently explained natural selection,” suggesting that exposure to the concept of natural selection is necessary, but not sufficient, for learning that concept.

4. Discussion

Prior to Darwin, evolutionary theorists conceptualized evolution as the transformation of a species' essence. Although transformational theories fell out of favor within the scientific community nearly a century ago (Bowler, 1983), a plurality of participants in the present study appeared to reason about evolution on the basis of such a theory. These participants were not only consistent across multiple phenomena but were also consistent with one another. Even participants who demonstrated a mixture of variational and transformational reasoning deviated from pure transformationism in similar ways. Such consistency is striking when one considers that, prior to participation, few participants were likely to have pondered the phenomena they were asked to interpret, and none could have received explicit instruction in transformationism.

These findings contribute to a growing literature on the existence of qualitative changes in conceptual development. Such changes have been previously analyzed in a variety of ways, including the differentiation and coalescence of preexisting concepts (Carey, 1991), the reassignment of concepts between two branches of an ontological hierarchy (Chi, Slotta, & de Leeuw, 1994; Thagard, 1992), the replacement of inaccurate presuppositions (Vosniadou & Brewer, 1992), and the reordering of a causal chain (Ahn, Gelman, Amsterdam, Hohenstein, & Kalish, 2000). Because these analyses are not mutually exclusive, all four could be applied fruitfully to the findings of this study (for an example, see Ferrari & Chi, 1998). Thus, rather than focus on minor differences among preexisting models of conceptual change, I shall focus on the question of whether naïve theories of evolution should, in fact, be considered theories at all.

This question has been well debated in the aforementioned literature on evolution education. Southerland et al. (2001), for example, argue that the average student's understand-

ing of evolution is less like a theory and more like a heuristic, namely “need as a rationale for change.” Consistent with this claim is the finding that students of all ages prefer teleological explanations of biological change to mechanistic ones. Indeed, this finding was replicated in the present study in the sense that the transformationists used the phrases “need to,” “have to,” “in order to,” or “must” three times as often as the variationists did. Moreover, the transformationists rarely favored one, and only one, type of analogy on the analogical-reasoning questions, suggesting that they had not thought much about the mechanism responsible for species adaptation prior to participation. Indeed, the fact that evolution is simply not evident from one’s interaction with a seemingly static biological world suggests that few students would have contemplated the problem of biological adaptation prior to taking a biology class, and even fewer students would have devised their own solution to this problem.

Thus, if the term “theory” is taken to mean an explicit and highly integrated network of causal-explanatory beliefs, then it may be inappropriate to apply such a term to the average student’s understanding of evolution. If, on the other hand, this term is taken to mean *any* self-consistent network of causal-explanatory beliefs—explicit or implicit, dense or sparse—then the kinds of beliefs elicited in the present study should indeed be considered a theory. Without doubt, none of the participants in this study held a transformational theory of evolution as well-developed or as well-articulated as those proposed by Lamarck, Cope, or Haeckel. Nevertheless, many participants did appear to hold the same assumptions that led these biologists astray—namely, that species have essences and that these essences are transformed over time. More importantly, they did *not* appear to hold the same assumptions that led Darwin to infer the principle of natural selection—namely, that the individuals within a species vary and that only some of this variation is retained across generations.

The discovery of the “pre-variationists” provides further evidence of the robustness and generativity of students’ naïve transformational assumptions. Whereas the pre-variationists agreed with the variationists in their interpretation of two evolutionary phenomena (adaptation and inheritance), they agreed with the transformationists in their interpretation of the remaining four (variation, domestication, speciation, and extinction). These students’ understanding of evolution might best be interpreted as what Vosniadou and Brewer (1992) call a “synthetic” framework, or a fundamentally non-scientific framework into which certain scientific principles have been assimilated. In particular, these students appeared to have assimilated the principles “survival of the fittest” and “acquired traits are not inherited” into an otherwise transformational framework. Although such heuristics might have allowed transformationists to respond like variationists on sections of the test in which their use was transparent, only the abandonment of biological essentialism could have allowed them to respond like variationists on all six sections.

To conclude, I shall consider three implications of these findings for the practice and preservation of evolution education. First, science educators should be aware that their students are likely to misunderstand any mode of discourse amenable to a transformational interpretation. The word “adaptation,” for example, can be interpreted either as changes to group membership or as changes to the group members themselves (see Jimenez, 1994). Similarly, design-based explanations can be interpreted either as reverse engineering or as attributing foresight to evolution, and phylogenetic trees can be interpreted either as depictions of common ancestry or as depictions of linear evolution. Although ambiguous modes of discourse are unlikely to be the cause of evolutionary misconceptions, they facilitate the persistence of such misconceptions nonetheless.

Second, science educators should be aware that their students are likely to analogize the adaptation of species to the adaptation of individuals, as evidenced by the analogical-reasoning questions in the adaptation section. One strategy for ridding students of such essence-based analogies would be to contrast them with population-based analogies, like those that originally inspired Darwin (see Gruber, 1974). Indeed, Darwin (1859) himself introduced the concept of natural selection by analogy to selective breeding, a practice familiar to his Victorian audience. Although this particular analogy is unlikely to be effective with modern day students, analogy has been shown to be an effective tool for teaching unfamiliar scientific concepts more generally (see Gentner & Gentner, 1983; Kurtz, Miao, & Gentner, 2001; Smith & Unger, 1997). Exactly which analogies would be most effective for teaching evolution remains an empirical question.

Third, the concept of natural selection is unlikely to garner popular support anytime soon. Beginning with the Scopes trial of 1925, evolution's place in the biology curriculum of American high schools has been hotly debated. In the 1980s, for example, legislation mandating that "creation science" be taught alongside natural selection was introduced in more than 30 states, and in 1999 the Kansas Board of Education dropped evolution from the science curriculum (a decision later appealed and overturned). Currently, school boards across the country are considering the permissibility of teaching "intelligent design" as an alternative to evolution.

Devout atheists like Dawkins (1987) speculate that disbelief in evolution stems from a misunderstanding of Darwin's theory, for anyone who grasps the explanatory power of natural selection cannot help but affirm its validity. However, studies that have measured both participants' belief in natural selection and participants' understanding of natural selection (e.g., Demastes et al., 1995; Lawson & Worsnop, 1992; Sinatra, Southerland, McConaughy, & Demastes, 2003) have found no significant correlation between the two. Consistent with these studies, participants in the present study were no more likely to endorse the statement "natural selection is the best explanation for how a species adapts to its environment" if they understood natural selection than if they did not. Indeed, 12 of the 19 transformationists endorsed the validity of Darwin's theory of evolution, and 1 of the 11 variationists denied the factuality of evolution altogether. If participants in the present study are at all representative of participants in the evolutionist-creationist debates waged in local courtrooms, newspapers, and school board meetings, one must wonder which theory of evolution—variationism or transformationism—is actually being debated.

Appendix A

A.1. Variation

Question 1. "During the 19th century, England underwent an Industrial Revolution that resulted in the unfortunate side effect of covering the English countryside in soot and ash. During this same period of time, the members of England's native moth species *Biston betularia* became, on average, darker in color. Assuming that darker coloration was adaptive, how might a change in the moths' environment brought about a change in the moths' color?" Variational responses (scored +1): scenarios that referenced individual differences (e.g., "If the environment became darker, the moths with darker color would be better camouflaged against predators and be more likely to reproduce"). Transformational responses

(scored -1): scenarios that referenced the needs of the population as a whole (e.g., “In order to blend in with their surroundings, the moths had to become darker in color”).

Questions 2–5. “Imagine you are a nineteenth-century biologist who ventures into the English countryside every 25 years and gathers a random sample of *Biston betularia*. What range of colorations would you expect to find at each point in time? To depict your answer, shade each moth in the graph below by picking one of five grayscale values between white and dark gray” (see Fig. 2. Question 2 consisted of the comparison of rows “1800” and “1825”; question 3 was consisted of the comparison of rows “1825” and “1850”; question 4 consisted of the comparison of rows “1850” and “1875”; question 5 consisted of the comparison of rows “1875” and “1900”. Variational response (scored $+1$): shading a pair of rows such that the darkest moth in the second row was no darker than the darkest moth in the first row. Transformational response (scored -1): shading a pair of rows such that the darkest moth in the second row was darker than the darkest moth in the first row.

A.2. Inheritance

Question 1. “Imagine that biologists discover a new species of woodpecker that lives in isolation on some secluded island. These woodpeckers have, on average, a one inch beak, and their only food source is a tree-dwelling insect that lives, on average, one-and-a-half inches under the tree bark. Compared to its parents, the offspring of any two woodpeckers should develop which of the following features? (a) A longer beak; (b) a shorter beak; (c) either a longer beak or a shorter beak; neither feature is more likely. Please explain your answer”. Variational responses (scored $+1$): choice (c) because offspring vary randomly from their parents; choice (c) because the environment does not influence the direction of mutations. Transformational responses (scored -1): choice (a) because a longer beak is necessary for survival; choice (a) because the birds will adapt to their environment; choice (c) because one generation is not enough time for longer beaks to evolve.

Question 2. “The biologists clip the wing feathers of some of the birds, rendering them unable to fly. Compared to the offspring of other woodpeckers, the offspring of those with clipped wings should have which of the following features? (a) Shorter wing feathers; (b) longer wing feathers; (c) either shorter wing feathers or longer wing feathers; neither feature is more likely. Please explain your answer”. Variational responses (scored $+1$): choice (c) because traits acquired during one’s lifetime cannot be passed on; choice (c) because the change is not genetic; choice (c) because offspring vary randomly from their parents. Transformational responses (scored -1): choice (a) because the biologists introduced a new trait; choice (c) because the change is detrimental to survival; choice (c) because one generation is not enough time for the change to set in.

Question 3. “Suppose that a pair of woodpeckers migrates to a different island with fewer trees and more wind. As a consequence of flying in a windier environment, both woodpeckers develop stronger wing muscles. Compared to the offspring of the woodpeckers on the original island, the offspring of these two woodpeckers should have which of the following features? (a) Stronger wing muscles; (b) weaker wing muscles; (c) either stronger wing muscles or weaker wing muscles; neither feature is more likely. Please explain your answer”. Variational responses (scored $+1$): choice (c) because traits acquired during one’s lifetime cannot be passed on; choice (c) because the change is not genetic; choice (c) because offspring vary randomly from their parents. Transformational responses (scored

–1): choice (a) because stronger wings are necessary for survival; choice (a) because the birds are adapting to their new environment; choice (c) because one generation is not enough time for stronger wings to evolve.

Question 4. “In studying the birds, the biologists notice that only a small percentage reproduce each year. Compared to populations in which the majority of birds reproduce each year, this population should adapt to its environment in which of the following ways? (a) Faster; (b) slower; (c) either faster or slower; neither outcome is more likely. Please explain your answer.” Variational responses (scored +1): choice (a) because only the best adapted birds will reproduce; choice (b) because there will be fewer mutations and therefore less variation; choice (c) because the variation in each population is not known. Transformational responses (scored –1): choice (b) because the birds will have fewer opportunities to adapt; choice (b) because the birds are not able to adapt; choice (c) there is no relationship between reproduction and adaptation.

Question 5. “Imagine that biologists re-measure the birds’ beaks in 2100 and discover that the average beak length has increased from one inch to one-and-a-half inches over the last hundred years. Nevertheless, some of the birds still have beaks that are shorter than one-and-a-half inches. These birds most likely descended from which of the following groups of birds alive one hundred years ago? (a) Birds with shorter-than-average beaks; (b) birds with longer-than-average beaks; (c) birds with either shorter-than-average beaks or longer-than average beaks; neither possibility is more likely. Please explain your answer.” Variational response (scored +1): choice (b) because the birds with longer-than-average beaks were more likely to reproduce; choice (b) because the birds with shorter-than-average beaks were more likely to die without offspring. Transformational responses (scored –1): choice (a) because birds with shorter-than-average beaks passed on their trait; choice (c), because evolution is random; choice (c) because longer beaks would be beneficial to both groups.

A.3. Adaptation

Question 1. “A youth basketball team scores more points per game this season than they did the previous season. Which explanation for this change is most analogous to Darwin’s explanation for the adaptation of species? (a) Each returning team member grew taller over the summer; (b) any athlete who participates in a sport for more than one season will improve at that sport; (c) more people tried out for the same number of spots this year; (d) on average, each team member practiced harder this season.” Variational response (scored +1): choice (c), the selection analogy. Transformational responses (scored –1): choice (a) the growth analogy; choice (b) the force analogy; choice (d) the intention analogy.

Question 2. “A magazine attains a wider circulation than it did last year. Which explanation for this change is most analogous to Darwin’s explanation for the adaptation of species? (a) The magazine maintained the same number of writers but decreased the number of articles it published; (b) the length and complexity of a writer’s sentences will increase the longer he/she writes; (c) the magazine’s staff vowed to work harder this year; (d) the style of each staff writer gradually matured throughout the year.” Variational response (scored +1): choice (a) the selection analogy. Transformational responses (scored –1): choice (b) the force analogy; choice (c) the intention analogy; choice (d) the growth analogy.

Question 3. “Within a year the average SAT score at a private high school increased by thirty points. Which explanation for this change is most analogous to Darwin’s explanation for the adaptation of species? (a) Every student was offered a \$100 reward for increasing their SAT score; (b) the school recently amended its admissions policy, holding legacies to the same standards as non-legacies; (c) since the last test, each returning student had grown more knowledgeable; (d) a student’s score will increase with every test he / she takes.” Variational response (scored +1): choice (b) the selection analogy. Transformational responses (scored –1): choice (a) the intention analogy; choice (c) the growth analogy; choice (d) the force analogy.

Question 4. “A symphony orchestra received more critical acclaim this season than they did last season. Which explanation for this change is most analogous to Darwin’s explanation for the adaptation of species? (a) A musician’s speed and accuracy will increase the longer he / she plays an instrument; (b) over the course of the previous season, each player’s sense of pitch became more precise; (c) the orchestra filled many vacant seats with principal players from a recently defunct orchestra; (d) outside of rehearsals, each player practiced twice as long this year.” Variational response (scored +1): choice (c) the selection analogy. Transformational responses (scored –1): choice (a) the force analogy; choice (b) the growth analogy; choice (d) the intention analogy.

Question 5. “A toy company conducted a longitudinal study on the speed at which children complete jigsaw puzzles and discovered that, within a year, the child participants were able to complete the puzzles twice as fast as they had been able to at the beginning of the study. Which explanation for this change is most analogous to Darwin’s explanation for the adaptation of species? (a) Each child’s brain continued to grow and develop throughout the study; (b) the children became more interested in the task and were thus more motivated to complete it; (c) the speed at which a person completes a puzzle will increase each time he/she attempts one; (d) children who disliked the task tended to drop out of the study.” Variational response (scored +1): choice (d) the selection analogy. Transformational response (scored –1): choice (a) the growth analogy; choice (b) the intention analogy; choice (c) the force analogy.

A.4. Domestication

Questions 1–3. “Corn is an entirely artificial food. Over a period of thousands of years, Native Americans purposefully transformed maize through special cultivation techniques, modifying corn from a wild grass (Teosinte) which grew in Central America 7000 years ago. In contrast to modern maize, which yields hundreds of plump kernels per cob, each Teosinte plant yielded a handful of small, hard kernels. Below are six factors that may or may not have been relevant to the domestication of corn. Please rank these factors according to their estimated relevance (1 = most relevant, 6 = least relevant): (a) the degree of similarity among plants of the same generation; (b) the average amount of time each plant was exposed to direct sunlight; (c) the preferences of those who decided which kernels to plant; (d) The fertility of the soil in which the kernels were planted; (e) the average rainfall per year; (f) the percentage of each crop used to breed the next generation.” Question 1 consisted of the ranking of factor (b); question 2 consisted of the ranking of factor (d); question 3 consisted of the ranking of factor (e). Variational response (scored +1): ranking these factors 4th, 5th, or 6th. Transformational response (scored –1): ranking these factors 1st, 2nd, or 3rd.

Question 4. “Would it be possible to change corn back into a plant like Teosinte? Why or why not?” Variational responses (scored +1): “yes” because one can selectively breed the corn that is most similar to Teosinte; “no” because domestication eliminated all of Teosinte’s undesired traits. Transformational responses (scored –1): “no” because it is impossible to reverse evolution; “no” because adaptations are permanent; “yes” because one can use advanced technology (as opposed to selective breeding).

Question 5. “Select the ‘odd man out’ and describe what makes that item different from the others: (a) corn selectively bred to produce purple kernels; (b) corn genetically engineered to produce purple kernels; (c) corn grown in a special soil to produce purple kernels.” Variational responses (scored +1): choice (c) because that corn is the only corn whose genes have not been altered; choice (c) because that corn’s offspring will not have purple kernels. Transformational responses (scored –1): choice (b) because that corn is the only corn whose genes have been altered; choice (b) because that corn is the least natural; choice (c) because that corn is the most natural.

A.5. Speciation

Question 1. “Indicate which of the following organisms share a common ancestor with humans: elephants, lemurs, salamanders, sparrows, bees, jellyfish, algae, daffodils, brontosaurus.” Variational response (scored +1): all nine species attributed common ancestry. Transformational response (scored –1): all nine species *not* attributed common ancestry.

Question 2. “Humans and chimpanzees share a common ancestor. This ancient primate was more similar to which of the following species? (a) Modern day humans; (b) modern day chimpanzees; (c) either modern day humans or modern day chimpanzees; neither species is necessarily more similar. Please explain your answer.” Variational responses (scored +1): choice (c) because each species changed in response to unique selection pressures; choice (c) because both species continued to evolve after they diverged; choice (c) because we do not know how many of the LCA’s traits were retained by each species. Transformational responses (scored –1): choice (b) because chimpanzees are less evolved than humans; choice (b) because only humans continued to evolve after they diverged from chimpanzees; choice (a) because chimpanzees descended from the least humanlike proto-humans.

Question 3. “The last common ancestor between humans and chimpanzees was more similar to which of the following species? (a) Modern day humans; (b) modern day gorillas; (c) please explain your answer either modern day humans or modern day gorillas; neither species is more likely.” Variational responses (scored +1): choice (a) because humans are a direct descendent of the human-chimpanzee LCA but gorillas are not; choice (a) because humans diverged from gorillas earlier than they diverged from chimpanzees. Transformational responses (scored –1): choice (b) because gorillas are less evolved than humans; choice (a) because humans are more evolved than gorillas; choice (c) because both humans and gorillas evolved from this primate.

Question 4. “As chimpanzees continue to evolve, they will become which of the following? (a) More similar to modern day humans; (b) less similar to modern day humans; (c) either more or less similar to modern day humans; neither outcome is more likely. Please explain your answer.” Variational responses (scored +1): choice (b) because humans and chimpanzees live in very different environments; choice (c) because either species’ environ-

ment might change. Transformational responses (scored -1): choice (a) because chimpanzees will eventually evolve into humans; choice (a) because human traits would be beneficial to any species; choice (b) because chimpanzees are following a different evolutionary path; choice (c) because evolution is random.

Question 5. “If chimpanzees and humans could produce fertile offspring (i.e., offspring that could eventually produce offspring of its own), should they still be considered separate species? Why or why not?” Variational responses (scored $+1$): “no” because the definition of a species entails reproductive isolation; “no” because interbreeding would gradually eradicate existing morphological differences. Transformational responses (scored -1): “yes” because humans and chimpanzees are morphologically distinct; “no” because humans and chimpanzees are both primates.

A.6. Extinction

Question 1. “Compared to the number of living bacteria species, the number of extinct bacteria species is which of the following? (a) Greater; (b) smaller; (c) either greater or smaller; neither situation is more likely. Please explain your answer.” Variational responses (scored $+1$): choice (a) because bacteria has existed for billions of years; choice (a) because there are more ways to go extinct than to adapt. Transformational responses (scored -1): choice (b) because each extinct species gave rise to many new species; choice (b) because species usually adapt; choice (c) because evolution is random.

Question 2. “Compared to the number of bacteria species in existence today, the number of bacteria species in existence ten million years from now will be which of the following? (a) Greater; (b) smaller; (c) either greater or smaller; neither situation is more likely. Please explain your answer.” Variational responses (scored $+1$): choice (c) because extinction depends upon the availability of resources; choice (c) because new species will fill any ecological niches made available by extinct species. Transformational responses (scored -1): choice (a) because many new species will come into being; choice (b) because human beings will kill off most of the existing species.

Questions 3–5. “Imagine scientists discover a new species of bacteria (specimen A in Fig. 3) and eight fossils similar in appearance to the newly discovered species (specimens B–H in Fig. 3). Various methods of fossil dating reveal the timeline depicted below in which a picture of each fossil is displayed next to its date of origin and a picture of the living species is displayed at the top. Assuming the living species is a direct descendant of the species represented by the oldest fossil, arrange the remaining fossils into a sensible evolutionary “family tree.” Variational response for question 3 (scored $+1$): specimen A is depicted as the most immediate ancestor of specimen C. Transformational response for question 3 (scored -1): specimen A is *not* depicted as the most immediate ancestor of specimen C. Variational response for question 4 (scored $+1$): specimen D is depicted as the most immediate ancestor of specimen G. Transformational response for question 4 (scored -1): specimen D is *not* depicted as the most immediate ancestor of specimen G. Variational response for question 5 (scored $+1$): specimen B is depicted as the most immediate ancestor of specimen F. Transformational response for question 5 (scored -1): specimen B is *not* depicted as the most immediate ancestor of specimen F.

Appendix B

The scoring distribution and mean score for each survey question

Section	No.	Content	–1	0	+1	Mean
Variation	1	Peppered moth evolution	22	5	18	–0.09
	2	Population in 1800 vs. 1825	29	NA	16	–0.29
	3	Population in 1825 vs. 1850	25	NA	20	–0.11
	4	Population in 1850 vs. 1875	23	NA	22	–0.02
	5	Population in 1875 vs. 1900	26	NA	19	–0.16
Inheritance	1	Heritability of beak length	19	11	15	–0.09
	2	Heritability of clipped feathers	10	6	29	0.42
	3	Heritability of stronger muscles	17	6	22	0.11
	4	Differential reproduction	17	7	21	0.09
	5	Line of descent	16	13	16	0.00
Adaptation	1	Basketball team analogy	22	NA	23	0.02
	2	Magazine staff analogy	27	NA	18	–0.20
	3	Private school analogy	23	NA	22	–0.02
	4	Symphony orchestra analogy	22	NA	23	0.02
	5	Psychology study analogy	23	NA	22	–0.02
Domestication	1	Relevance of direct sunlight	16	NA	29	0.29
	2	Relevance of soil fertility	22	NA	23	0.02
	3	Relevance of average rainfall	18	NA	27	0.20
	4	Changing corn to Teosinte	15	11	19	0.09
	5	Purple-kernelled corn	19	7	19	0.00
Speciation	1	Common ancestry	28	NA	17	–0.24
	2	Human-chimp LCA vs. chimps	15	12	18	0.07
	3	Human-chimp LCA vs. gorillas	16	15	14	–0.04
	4	Chimpanzee evolution	21	14	10	–0.24
	5	Species definition	17	7	21	0.09
Extinction	1	No. of extinct bacteria species	13	8	24	0.24
	2	No. of future bacteria species	19	8	18	–0.02
	3	Ancestry of specimen C	21	NA	24	0.07
	4	Ancestry of specimen G	31	NA	14	–0.38
	5	Ancestry of specimen F	29	NA	16	–0.29

References

- Ahn, W., Gelman, S. A., Amsterlaw, J. A., Hohenstein, J., & Kalish, C. W. (2000). Causal status effect in children's categorization. *Cognition*, 76, B35–B43.
- Atran, S., Medin, D., Lynch, E., Vapnarsky, V., Ucan Ek', E., & Sousa, P. (2001). Folkbiology doesn't come from folkpsychology: Evidence from Yukatek Maya in cross-cultural perspective. *Journal of Cognition and Culture*, 1(1), 3–42.
- Berg, L.S., 1926/1969. *Nomogenesis or evolution determined by law* (J.M. Rostovtsov, Trans.). Cambridge, MA: The MIT Press.
- Bergson, H., 1911/1928. *Creative evolution* (A. Mitchell, Trans.). London: Macmillan.
- Bishop, B., & Anderson, C. A. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, 27, 415–427.
- Bowler, P. J. (1983). *The eclipse of Darwinism: Anti-Darwinian theories in the decades around 1900*. Baltimore: John Hopkins University Press.
- Brumby, M. N. (1984). Misconceptions about the concept of natural selection by medical biology students. *Science Education*, 68(4), 493–503.
- Butler, S. (1916). *Life and habit*. London: A.C. Fifield.

- Carey, S. (1991). Knowledge acquisition: enrichment or conceptual change. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays in biology and cognition* (pp. 257–291). Hillsdale, NJ: Lawrence Erlbaum.
- Chambers, R. (1844). *Vestiges of the natural history of creation*. London: John Churchill.
- Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction*, 4, 27–43.
- Cope, E. D. (1896). *The primary factors of organic evolution*. Chicago: Open Court.
- Darwin, C. R. (1859). *The origin of species*. London: J. Murray.
- Dawkins, R. (1987). *The blind watchmaker*. New York: W.W. Norton.
- Demastes, S. S., Settlage, J., & Good, R. J. (1995). Students' conceptions of natural selection and its role in evolution: Cases of replication and comparison. *Journal of Research in Science Teaching*, 32, 535–550.
- Eimer, G.H.T., 1898. *On orthogenesis and the importance of natural selection in species formations* (T.J. McCormack, Trans.). Chicago: Open Court.
- 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 naïve explanations of natural selection. *International Journal of Science Education*, 20(10), 1231–1256.
- Gelman, S. A. (2003). *The essential child*. Oxford, UK: Oxford University Press.
- Gelman, S. A., & Markman, E. M. (1986). Categories and induction in young children. *Cognition*, 23, 183–209.
- Gelman, S. A., & Wellman, H. M. (1991). Insides and essences: Early understanding of the nonobvious. *Cognition*, 38, 213–244.
- Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Lawrence Erlbaum.
- Gould, S. J. (1996). *Full house: The spread of excellence from Plato to Darwin*. New York: Three Rivers Press.
- Greene, E. D. (1990). The logic of university students' misunderstanding of natural selection. *Journal of Research in Science Teaching*, 27(9), 875–885.
- Gruber, H. (1974). *Darwin on man: A psychological study of scientific creativity*. London: Wildwood House.
- Haeckel, E. (1876). *The history of creation: or the development of the earth and its inhabitants by the action of natural causes*. New York: Appleton.
- Hooper, J. (2002). *Of moths and men, an evolutionary tale: The untold story of science and the peppered moth*. New York: Norton.
- Jensen, M. S., & Finley, F. N. (1995). Teaching evolution using historical arguments in a conceptual change strategy. *Science Education*, 79(2), 147–166.
- Jensen, M. S., & Finley, F. N. (1996). Change in students' understanding of evolution resulting from different curricular and instructional strategies. *Journal of Research in Science Teaching*, 33(8), 879–900.
- Jimenez, A. M. P. (1994). Teaching evolution and natural selection: A look at textbooks and teachers. *Journal of Research in Science Teaching*, 31(5), 519–535.
- Keil, F. C. (1989). *Concepts, kinds, and cognitive development*. Cambridge, MA: MIT Press.
- Kurtz, K. J., Miao, C., & Gentner, D. (2001). Learning by analogical bootstrapping. *Journal of the Learning Sciences*, 10(4), 417–446.
- Lamarck, J.B., 1809/1963. *Philosophie zoologique* (H. Elliot, Trans.). New York: Haffner.
- Lawson, A. E., & Thompson, L. D. (1988). Formal reasoning ability and misconceptions concerning genetics and natural selection. *Journal of Research in Science Teaching*, 25(9), 733–746.
- Lawson, A. E., & Worsnop, W. A. (1992). Learning about evolution and rejecting a belief in special creation: Effects of reasoning skill, prior knowledge, prior belief and religious commitment. *Journal of Research in Science Teaching*, 29(2), 143–166.
- Mazens, K., & Lautrey, J. (2003). Conceptual change in physics: children's naïve representations of sound. *Cognitive Development*, 18, 159–176.
- Mayr, E. (1982). *The growth of biological thought: Diversity, evolution, and inheritance*. Cambridge, MA: Harvard University Press.
- Mayr, E. (2001). *What evolution is*. New York: Basic Books.
- McCloskey, M. (1983). Naïve theories of motion. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Lawrence Erlbaum.
- Medin, D., & Atran, S. (2004). The native mind: Biological categorization and reasoning in development and across cultures. *Psychological Review*, 111(4), 960–983.
- Newport, F. (2004). *Third of Americans say evidence has supported Darwin's evolution theory*. Princeton, NJ: The Gallup Organization.

- Poling, D. A., & Evans, E. M. (2004a). Are dinosaurs the rule or the exception. Developing concepts of death and extinction. *Cognitive Development*, *19*, 363–383.
- Poling, D. A., & Evans, E. M. (2004b). Religious belief, scientific expertise, and folk ecology. *Journal of Cognition and Culture*, *4*(3), 485–524.
- Rosengren, K., Gelman, S. A., Kalish, C., & McCormick, M. (1991). As time goes by: Children's early understanding of biological growth. *Child Development*, *62*, 1302–1320.
- Ruse, M. (2003). *Darwin and design: Does evolution have a purpose*. Cambridge, MA: Harvard University Press.
- Samarapungavan, A., & Wiers, R. W. (1997). Children's thoughts on the origin of species: A study of explanatory coherence. *Cognitive Science*, *21*(2), 147–177.
- Settlage, J. (1994). Conceptions of natural selection: A snapshot of the sense-making process. *Journal of Research in Science Teaching*, *31*(5), 449–457.
- Sinatra, G. M., Southerland, S. A., McConaughy, F., & Demastes, J. W. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. *Journal of Research in Science Teaching*, *40*(5), 510–528.
- Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition*, *21*, 177–237.
- Smith, C., & Unger, C. (1997). What's in dots-per-box? Conceptual bootstrapping with stripped-down visual analogues. *The Journal of the Learning Sciences*, *6*(2), 143–181.
- Sousa, P., Atran, S., & Medin, D. (2002). Essentialism and folkbiology: Evidence from Brazil. *Journal of Cognition and Culture*, *2*(3), 195–223.
- Springer, K., & Keil, F. C. (1989). On the development of biologically specific beliefs: The case of inheritance. *Child Development*, *60*, 637–648.
- Southerland, S. A., Abrams, E., Cummins, C. L., & Anzelmo, J. (2001). Understanding students' explanations of biological phenomena: Conceptual frameworks or p-prims? *Science Education*, *85*, 328–348.
- Thagard, P. (1992). *Conceptual revolutions*. Princeton, NJ: Princeton University Press.
- Wiser, M. (1988). The differentiation of heat and temperature: History of science and novice-expert shift. In S. Strauss (Ed.), *Ontogeny, phylogeny, and historical development*. Norwood, NJ: Ablex.
- Vosniadou, S., & Brewer, W. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*, 535–585.