Authentic Science with Live Organisms Can Improve Evolution Education

RECOMMENDED FOR AP Biology

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Abstract

Evolution education in the United States remains controversial and challenging. This is in part due to the difficulty educators face when trying to overcome students' preexisting beliefs about evolution, which can bias assimilation of information and inhibit learning. We propose that the most effective way to overcome such belief persistence is through an engaging, hands-on inquiry approach that mimics the scientific process used to study evolution. Although this teaching approach, known as authentic science, has gained recognition for its effectiveness in the classroom, it has not been widely applied to teach evolution. We describe how an authentic science approach can be used to teach evolution by natural selection, and provide a formula for the development of such programs. Following this blueprint, we developed a program using Trinidadian guppies and implemented it in 7th grade classrooms in Colorado. Pre- and post-program assessments revealed significant increases in both the understanding and acceptance of evolution among participants. Authentic science experiments using locally adapted populations of live organisms may be able to overcome belief persistence and improve student understanding of evolution.

Key Words: *evolution; education; authentic science; middle school; belief persistence; inquiry teaching.*

○ Introduction

Evolutionary approaches are becoming increasingly important in solving the world's most pressing problems, such as improving global food security, preventing and treating diseases, coping with climate change, and preserving ecosystems (Losos et al., 2013). However, despite a large body of research on evolution education in the United States and extensive reform (reviewed in Glaze & Goldston, 2015), we continue to fall short in our efforts to increase acceptance and understanding of evolutionary principles (Rice et al., 2011).

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Students in the United States are not typically exposed to evolution through formal teaching until they reach middle school (Wagler, 2012). Although it is recognized that knowledge must be constructed based on existing knowledge (Ausubel et al., 1978; Bransford et al., 2000), evolution educators must also facilitate construction of knowledge in the face of preset beliefs that students develop from experiences in primary school, at home, and from religious influences (Alters & Nelson, 2002; Bloom & Weisberg, 2007; Williams, 2009). Preexisting beliefs have been shown to bias assimilation of information and inhibit learning (Lord et al., 1979; Anderson et al., 1980; Bloom & Weisberg, 2007; Kahan, 2010), and for evolution education, religious beliefs can have a particular influence on learning (McKeachie et al., 2002; Glaze & Goldston, 2015).

Belief persistence may be overcome by maximizing student engagement (Dole & Sinatra, 1998; Nelson, 2008), exposing students to causal evidence (Slusher & Anderson, 1996; Nelson, 2008; Kampourakis & Zogza, 2009; Winslow et al., 2011), and by holding students accountable for conclusions based on evidence (Tetlock, 1983). Thus, an effective teaching approach would be modeled after the scientific process in which students ask fundamental questions, collect data, and draw conclusions based on their results. Such a teaching approach is referred to as *authentic science*, and it is a style of inquiry teaching in which students engage in the scientific process as if they were practicing scientists (Chinn & Malhotra, 2002; Buxton, 2006). It has been suggested that an inquiry approach should be used to teach evolution (Scharmann, 1994; Farber, 2003; Scharmann, 2005; Robbins & Roy, 2007) since it may increase both knowledge and acceptance of evolution (Robbins & Roy, 2007).

Although there have been calls to design programs that specifically attempt to overcome preset beliefs associated with evolution

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(Kampourakis & Zogza, 2009), few authentic science programs have been developed for teaching evolution by natural selection (but see Bordenstein et al., 2010). Several case study inquiry programs have been developed (Farber, 2003; Passmore et al., 2005; Desantis, 2009), but they do not involve hands-on authentic science experiences, which should allow student input and control at all stages of the scientific process (Chinn & Malhotra, 2002).

Unlike other foundational scientific principles that can be demonstrated in the classroom, an authentic science approach to teaching evolution is complicated by the problem of how to demonstrate a process that typically occurs over long timescales. How can students ask evolutionary questions, collect data on evolutionary processes, and draw their own conclusions about evolution during a typical one-week lesson? This may be accomplished using fast-growing organisms like bacteria or viruses (Bordenstein et al., 2010) or through simulations like computer games (e.g., "Sex and the Single Guppy," www.pbs.org/wgbh/evolution/sex/guppy). Although it has been argued that computer simulations may mimic the scientific process and facilitate conceptual change (Smetana & Bell, 2012), experiences with living organisms are more engaging (Allen, 2004). Here we propose an authentic science method to teach evolution by natural selection using live animals, and then provide an example of its effective use in 7th-grade classrooms in Colorado. We adapted this 7th-grade program into a self-guided kit and provide teaching tools and resources (Kane et al., 2018, this Issue).

○ Methods

General Program Design and Overview

Rather than trying to observe ongoing evolutionary change in the classroom (e.g., Bordenstein et al., 2010), students can instead investigate adaptively divergent populations of organisms that represent the outcome of past evolutionary change, much like the examples used by Charles Darwin in presenting his case for evolution by natural selection (Darwin, 1872). Populations of living organisms that differ from each other in obvious ways, because they have become locally adapted to divergent environments, provide a powerful empirical framework to explore the conditions necessary for natural selection to occur. In particular, by quantifying variation within and between populations, with foundational knowledge of inheritance, locally adapted divergent populations can be used to illustrate four important concepts that students must grasp to understand evolution by natural selection: (1) variation exists within and among populations; (2) much of that variation is inherited through genes; (3) selection determines which individuals pass on their genes to the next generation; and (4) over time this leads to genetic changes in a population, or evolution. These concepts are often reduced to four words—Variation, Inheritance, Selection, and Time—and are commonly represented by the abbreviation VIST (www.evolution.berkeley.edu). An authentic science approach allows students to make observations and conduct experiments to discover ideas 1–3, and can conclude with thought exercises about outcomes over time, idea 4, and how this leads to the observed differences among the populations before them.

The first objective of the program is to engage the students in the scientific process, which begins with observation. Before introducing students to the terms "evolution" or "natural selection," they can be engaged by making observations of a plant or animal system and noting differences within and among populations. Live organisms are particularly engaging (Allen, 2004), and it is important to maximize engagement in order to overcome belief persistence (Dole & Sinatra, 1998; Nelson, 2008). Almost any plant or animal system can be used as long as there are obvious, quantifiable phenotypic differences that can be intuitively connected to a source of natural selection (Figure 1). Whenever possible, it is helpful to use a familiar or local species, or to even use domesticated organisms, since students are more likely to engage if they feel a connection to the content because of past experiences (Dole & Sinatra, 1998).

Once students are familiarized with the contrasting environments where the organisms live (e.g., sunny vs. shady, with and without predators; Figure 1), they can begin to ask questions and propose explanations for why differences might exist among the populations. They can then design observational or experimental studies to test their hypotheses. These studies should quantify the variation in traits of interest within and among populations (Figure 1a), explore the evidence for inheritance (Figure 1b), and demonstrate how selection acts on variation via differential survival or reproduction in response to environmental variation (Figure 1c).

At this stage, students have engaged in authentic science by generating hypotheses and predictions for why populations might differ in traits of interest, and have observed and collected data on how traits vary within and between populations. Students can then use their own data and observations to test their own hypotheses within the VIST framework:

- Students can explore the concept of *variation* (V) by examining plots of their data (e.g., frequency distributions of measured traits like plant height or fish coloration) and visualizing that *there is variation both among individuals within a population and between populations* (Figure 1a). Sources of genetic and environmental variation can also be introduced and discussed (e.g., Broder et al., 2016). More generally, discussions of the observed results should emphasize that variation within and between populations is commonly found in almost all organisms, and this can be illustrated with familiar visual examples of other plants and animals.
- Students can then apply their knowledge of *inheritance* (I) by focusing on *heritable variation* (Figure 1b) using traits from the system being studied as well as familiar examples (e.g., domestic animals). A review of Mendelian genetics is important since an emphasis on genetics in evolution programs can promote conceptual change (Kampourakis & Zogza, 2009).
- Students can then be introduced to the idea of *selection* (S), that *not all individuals are equally likely to survive and reproduce depending on the environment*. If students have carried out experiments in class, they can discuss how certain traits increase or decrease the likelihood of surviving and reproducing in various environments. For example, students might explore how variation in light shapes leaf size or survival in low-light conditions in plants, or how predation regime influences color patterns in fish (e.g., background matching may provide a selective advantage to prey fish if predators are present; Figure 1c). However, if such experiments are not possible, then students can discuss familiar examples of natural selection in the wild (disease, drought, etc.).
- Finally, students can consider the consequences of these findings over *time* (T), that *this variation in survival and reproduction leads*

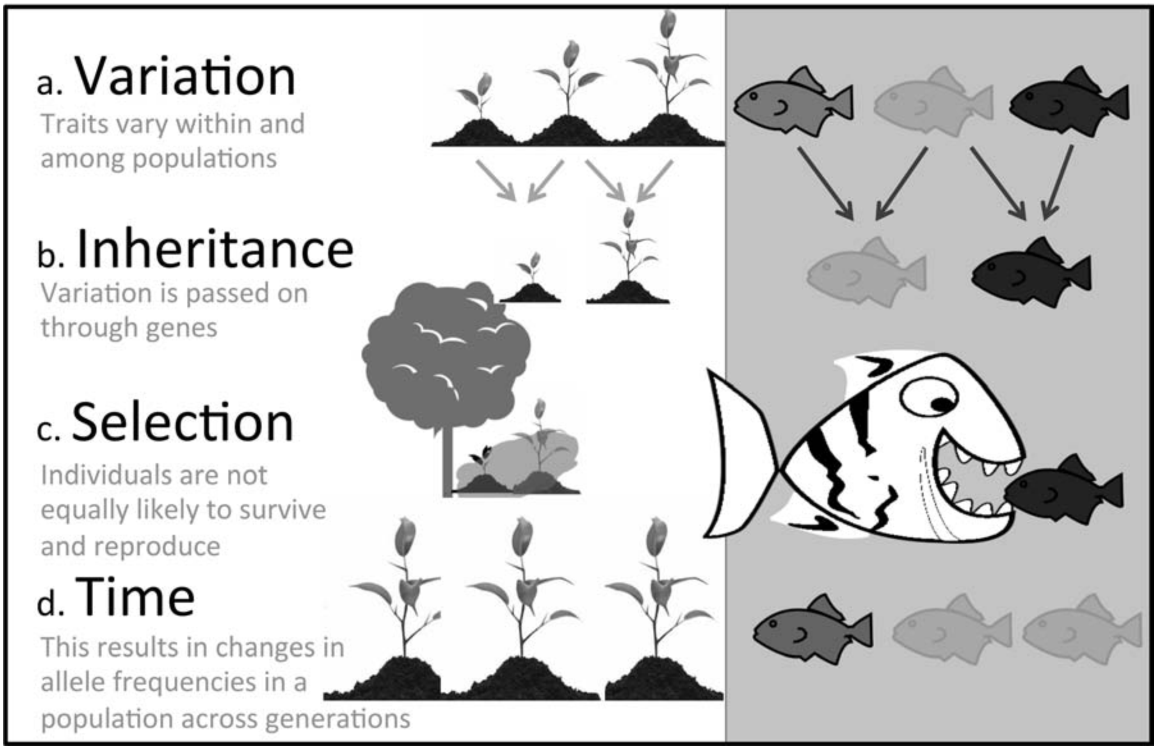

Figure 1. Schematic showing how VIST can be applied to a hypothetical plant and animal system.

to changes in allele frequencies across generations (Figure 1d). There are many ways to make this last point, including online tools, computer simulations, and thought exercises. The main conclusion the students should draw is that genetic change over time is an inevitable outcome when selection acts on heritable variation.

Following a discussion of variation, inheritance, selection, and time, the final step is to describe this process as evolution by natural selection. By defining the process of evolution as a change in allele frequencies within a population over time—an idea that students just discovered during the VIST activities—students must reconcile their preconceived ideas of evolution with the conclusions they reached examining their own results. We feel this point is critical. Students are more likely to overcome preset beliefs through asking their own questions and engaging in the scientific process (Nelson, 2008), collecting their own data (Slusher & Anderson, 1996), and drawing and defending their own conclusions (Tetlock, 1983) about evolution before learning the definition from instructors. This approach should lead to increased acceptance and understanding of evolution.

This formula for teaching evolution aligns with the Next Generation Science Standards for middle school. Specifically, this program teaches middle school disciplinary core ideas LS4.B (natural selection) and LS4.C (adaptation) while allowing students to accomplish MS-LS4-4, "Construct an explanation based on evidence that describes how genetic variations of traits in a population increase some individuals' probability of surviving and reproducing in a specific environment" (NGSS Lead States, 2013). Additionally, the final step of our program asks students to predict how different scenarios would affect the frequencies of alleles and consequently the frequency of traits in a population, supporting MS-LS4-6, where students should "use mathematical representations to support explanations of how natural selection may lead to increases and decreases of specific traits in populations over time" (NGSS Lead States, 2013).

Specific Program Details

We developed and implemented a program based on the above framework for 7th grade students at Windsor Middle School in Windsor, Colorado, and Severance Middle School in Severance, Colorado. Evolution by natural selection was illustrated using live Trinidadian guppies (*Poecilia reticulata*). Guppies are a model system in evolutionary biology for studying natural selection in the wild (Reznick et al., 1990; 1997), and are familiar to many students via the pet trade. We used guppies sourced from three populations: (1) wild guppies collected from a stream where predation from larger fish is very high, and individuals exhibit a suite of genetically based morphological traits (e.g., reduced male coloration) and behavioral traits (e.g., faster escape responses) known to reduce predation risk; (2) wild guppies collected from a stream where most predators are absent, and individuals exhibit traits that reflect reduced predation risk (e.g., increased male coloration, more courtship displays, slower escape responses); and (3) domesticated guppies from a local pet store that exhibit exaggerated traits (e.g., ornate colors, elongated fins and tails, naive behaviors toward predators) that have been artificially selected. Students generated hypotheses to explain differences they observed among guppy populations (e.g., male body coloration) and designed two experiments: (1) observations of mating behavior to test that male color provided a mating advantage, and (2) a predator encounter experiment to test if dull colored males were less visible to predators.

We strived to make the experience as authentic as possible based on Chinn & Malhotra's distinction between simple versus authentic science (2002). We guided the students' questions and experiments toward reproduction and survival because of our content goals, but allowed students to design details. For example, we encouraged students to allow guppies to interact with a predator to learn something about antipredator behavior and survival. They chose to place three male guppies (one from each of the three populations) in a tank with a predator, allowed an acclimation time before removing a barrier, and decided which antipredator behaviors to record. Students could have designed this experiment differently (e.g., used females instead of males or allowed one guppy to interact with the predator at a time). Students also helped design data sheets and came to a consensus on the operational definitions of behaviors. For example, in the mating trials, students observed videos of mating behavior, and agreed on definitions of a courtship display and a forced copulation attempt. Students then divided into pairs and observed mating behavior of one male and one female guppy from the same population. Though each pair of students collected data on a single mating pair, they also switched tanks with classmates to observe pairs of guppies from the other two populations. We compiled the data from the entire class, and each student made figures summarizing both experiments and evaluated the results in light of their hypotheses. We did not know the outcomes of the experiments in advance, and students often had to justify anomalous results—an important part of the authentic science experience (Chinn & Malhotra, 2002).

We followed the student experiments with discussions of their data and experiences to introduce our four concepts:

1. *Variation*: The coloration and number of courtship displays performed by male guppies was variable both within and among populations.
2. *Inheritance*: A Mendelian Punnett-square approach illustrated how genes for bright coloration and high rates of courtship are passed on to offspring (Kane et al., 2018, this Issue).
3. *Selection*: Results from the predator encounter experiment, where domestic guppies were six times more likely to be depredated than males from the two wild populations, illustrated a mechanism of natural selection. Results from the mating experiments, where females were more interested in bright males, demonstrated a mechanism of sexual selection. We also discussed how selective breeding for the pet trade produced the exaggerated coloration of domestic guppies, to explain artificial selection. Finally, we discussed how particular traits should affect fitness in the three environments.
4. *Time*: A thought exercise, where students imagined that males could have alleles that code for bright (**A**) or dull (**a**) coloration, allowed them to predict how the ratio of **A** to **a** alleles might change over time in the population under different scenarios (see Kane et al., 2018, this Issue, for details).

Assessment

We implemented this program in April 2012 and April 2013 at Severance and Winsor Middle Schools. All participants were 7th grade students associated with two teachers (SW and KDK), and the guppy program described above replaced their regular unit on evolution by natural selection. We administered pre- and post-program assessments in 2013 to five of KDK's classes at Severance and four of SW's classes at Windsor (n = 204 total students). To estimate knowledge of evolution by natural and artificial selection, we used the seven-question, multiple-choice test administered each year to Windsor Middle School 7th grade students (Appendix). These questions were written by one of the teachers (SW) based on the suggested learning outcomes for microevolution education in the Colorado Academic Standards (2009). The presenters of the program (EDB, CKG, and LMA) did not alter these questions, ensuring that the questions were not influenced by the program. We were unable to supplement this with a published assessment, because of a lack of tools in the literature appropriate for this age group at the time of this study. Other assessments exist for high school and college students, including "The Knowledge of Evolution Exam" (Moore et al., 2009) and the "Measure of Understanding of Macroevolution" (Nadelson & Southerland, 2010), but they were deemed inappropriate given their Flesch-Kincaid grade-level scores of 8.9 and 9.3, respectively (Flesch, 1948).

To measure acceptance of evolution, we selected four questions from the MATE Instrument, which uses a Likert scale to indicate agreement with various statements (Rutledge & Sadler, 2007; Appendix). We recognize the limitations of using only a subset of the MATE Instrument, and our results cannot be compared to other studies that used the full MATE instrument. We had to exclude questions that mentioned religion or beliefs because the teachers (SW and KDK) felt that it was a violation of their teaching agreement to include such questions. This assessment was granted exemption by the Colorado State University Human Subjects Approval Board (IRB ID 038-14H).

To analyze the results, we performed two repeated measures ANOVAs; the first used the average scores from the seven multiple-choice questions (knowledge), and the second used the average scores from the four Likert scale questions (acceptance). In both analyses, the test (pre- or post-) was a fixed effect. We also included random effects of individual student (n = 204) nested within classroom (n = 9) nested within teacher (n = 2). We excluded students who did not have both a pre- and post-program assessment.

○ Results

Students who participated in our program increased both their knowledge (Figure 2a) and acceptance (Figure 2b) of evolution based on their pre- and post-program scores. Evolution knowledge test scores increased from 65.8 ± 1.4 (x ± SE) on the pre-test to 79.7 ± 1.4 on the post-test out of 100 possible points ($F_{1,203} = 87.00$, $p < 0.0001$). The least-squared means accounting for random effects increased from 66.0 ± 1.4 to 79.7 ± 1.4 (Figure 2a). The acceptance of evolution scores, which could range from 1 to 5, increased from an average of 3.07 ± 0.04 (x ± SE) on the pre-test to 3.21 ± 0.05 on the post-test ($F_{1,197} = 7.49$, $p = 0.007$). The least-squared means accounting for random effects increased from 3.07 ± 0.04 to 3.20 ± 0.04 (Figure 2b). Though there was variation among classrooms and schools, the observed patterns did not

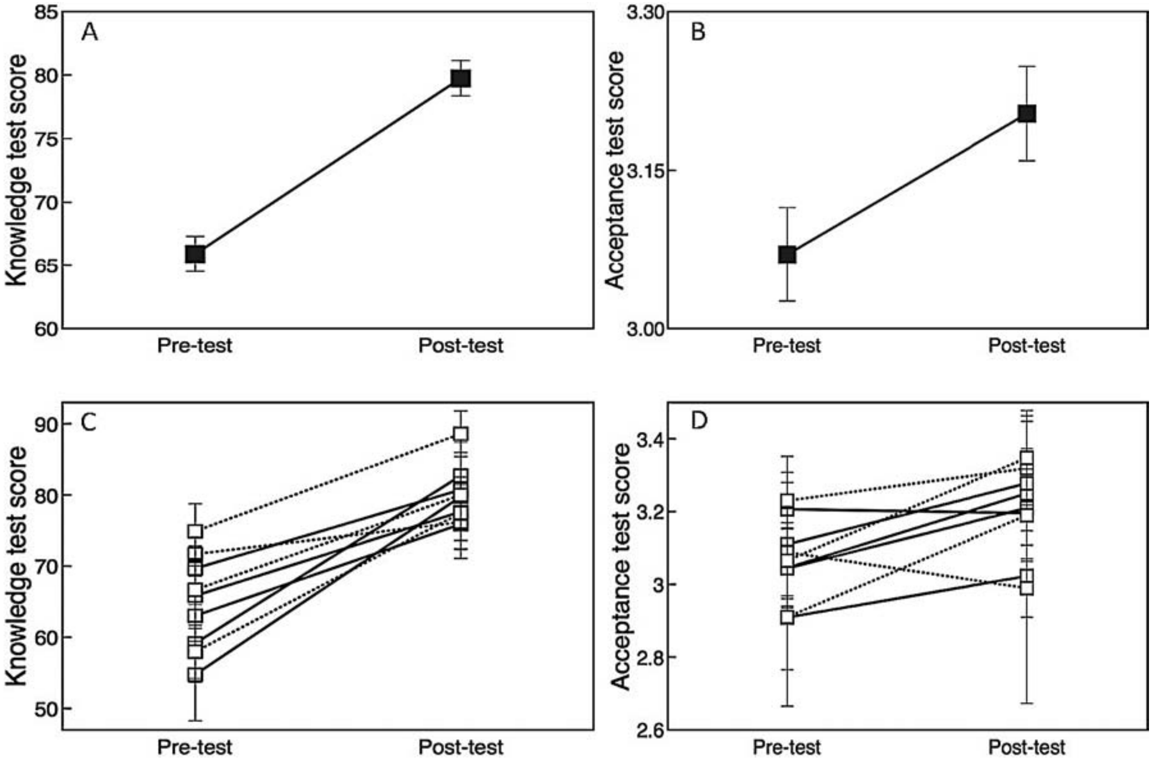

Figure 2. Assessment results: least squared means ± SE are shown for both analyses (repeated measures ANOVAs) comparing pre- and post-program test scores for program participants for **(A)** a measure of evolution knowledge, and **(B)** a measure of acceptance of evolution. The raw means are shown separately for the five classes from Windsor Middle School (solid lines) and the four classes from Severance Middle School (grey dashed lines) for the knowledge test scores **(C)** and the acceptance test scores **(D)**.

appear to be influenced by just one classroom or school, as most of the nine participating classrooms showed similar increases in scores on the knowledge assessment (Figure 2c) and the acceptance assessment (Figure 2d).

○ Conclusions

The persistent rejection of evolution by a significant portion of the United States population in the face of educational reforms has been called the "single greatest failure of science education in the history of the U.S." (Rice et al., 2011). We present an authentic science approach that is flexible in its structure, but shares the common elements of VIST to teach evolution by natural selection using populations adapted to different environments. With this program as a guide, we created a self-guided kit and provide all teaching resources (Kane et al., 2018, this Issue).

Our use of this approach resulted in positive outcomes, as students appeared to overcome belief persistence by indicating a greater acceptance of evolution and exhibiting increased knowledge of evolution by natural selection. For comparison, a teacher at Windsor Middle School administered our pre- and post-assessments, but did not participate in the program, teaching the same material at the same time using traditional approaches like readings, hands-on activities, and interactive worksheets. Those three classrooms of students (*n* = 59 students) showed no change in knowledge test scores (x ± SE; 61.4 ± 3.1 pre-test and 61.5 ± 3.2 post-test) or acceptance scores (x ± SE; 3.0 ± 0.07 pre-test and 2.9 ± 0.07 post-test). Though this cannot be considered a control group since it was only one teacher who may or may not have been enthusiastic about teaching evolution, this example supports claims that traditional teaching methods are ineffective at teaching evolution (Alters & Nelson, 2002).

It is important to note that we cannot isolate any one factor as being responsible for the differences in student performance or acceptance. It is likely a combination of the authentic science approach, the VIST framework, the use of live animals, and the presence of scientists in the classroom. Nevertheless, such results suggest that similar approaches can be a highly effective means for teaching evolution. In addition to potentially increasing knowledge and acceptance of evolution, an authentic science approach has the benefit of increasing student understanding of the nature of science more broadly, which is positively associated with the acceptance of evolution (Lombrozo et al., 2008). As funding agencies push for broader impact, we encourage scientists to consider the significant impact on knowledge and acceptance of evolution that might be made through collaborations with K-12 educators to teach evolution and develop authentic science programs more generally.

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APPENDIX

ASSESSMENT

Thank you for participating in this short quiz. Remember that you will not be graded on this quiz. But please do your best to answer the questions.

1. Which of the following is NOT an example of an adaptation?
   a. Desert foxes have very large ears to release extra body heat.
   b. Guppy males display their colors to attract females for mating.
   c. Polar bears have a layer of fat under their fur to keep them warm in icy waters.
   d. Chimpanzees prefer oranges over apples because they like the flavor.
2. Which is NOT needed for natural selection to take place?
   a. Some animals must die or fail to reproduce based on their environment.
   b. There must be human impact on the environment.
   c. There must be variation (differences).
   d. Traits must be inherited (passed to offspring).
3. There are many breeds of dogs today, from the Chihuahua to the Labrador. These were developed through which process?
   a. Artificial selection
   b. Extinction
   c. Natural selection
   d. Speciation
4. In ARTIFICIAL selection, how are animals selected to pass on their genes?
   a. By the breeder
   b. By wild predators
   c. By female choice
   d. Both b and c, depending on the environment
5. In NATURAL selection, how are animals selected to pass on their genes?
   a. By the breeder
   b. By wild predators
   c. By female choice
   d. Both b and c, depending on the environment
6. If only the tallest animals on an island can reach the treetops and get enough food to survive, what will be true of the next generation of animals?
   a. There will be more TALL individuals.
   b. They will be more SHORT individuals.
   c. They will be THE SAME as the previous generation.
   d. No prediction can be made, genes are just random.

7. If female birds on an island prefer birds with bright feathers, what will be true of the next generation of birds?
   a. There will be more BRIGHT feathered males.
   b. There will be more DULL feathered males.
   c. They will be THE SAME as the previous generation.
   d. No prediction can be made, genes are just random
8. On this question there is no right or wrong answer. We are asking your opinion about several statements. Please fill in the circle indicating if you agree or disagree with the each statement.

	Strongly disagree	**Disagree**	**Undecided**	**Agreed**	**Strongly agree**
The theory of evolution cannot be tested scientifically	○	○	○	○	○
Evolution is a scientifically valid theory	○	○	○	○	○
Current evolutionary theory is the result of sound scientific research	○	○	○	○	○
The available data are unclear as to whether evolution actually occurs	○	○	○	○	○