AN INVESTIGATION OF STUDENT UNDERSTANDING AND ACCEPTANCE OF EVOLUTION

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Evolution is central to biology education and yet, it is often one of the most misunderstood and controversial topics that biology educators must teach. Research spanning the last four decades has shown that students continue to struggle, even with direct instruction, to understand the process of evolution by natural selection. In my first chapter, I found that students enrolled in non-majors geology course did not increase in their understanding of evolution, even after instruction. This followed similar findings from research occurring over 30 years in the past. Discipline-based education researchers have theorized that students' persistent difficulties understanding evolution may stem from the conceptual challenges inherent to complex biological systems. To meet the needs of biology instructors, I developed a new teaching tool, a rapid response rubric (3R: Evolution), to provide more opportunities for formative assessment and feedback in large-enrollment courses. I found the 3R: Evolution provided direct and actionable feedback, allowing students to modify their understanding of evolution in large-enrollment courses and exhibit large increases in their knowledge from pre- to post-assessment. However, knowledge of evolution is not the only challenge to biology education: students must also accept evolution. A lack of evolution acceptance can emerge from various social, cultural, and epistemological factors including religiosity and regional impacts, knowledge of the nature of science, openness to experience, and evolution exposure. In this work, I present a path analysis to illuminate the direct causal relationships from these individual factors to evolution acceptance. I found that while religiosity was the largest casual predictor of acceptance, the other chosen factors, including knowledge of evolution, were all significant predictors of evolution acceptance. Even though evolution remains a difficult topic, this work shows that students can increase both their understanding and acceptance of evolution, using new curriculum and increasing exposure to evolution content across their school career.

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DEDICATION

This dissertation is dedicated to my grandfather, Robert Seely, who started me on the path to loving research by helping me (doing) my 5th grade science fair project. I'm still fascinated by bubbles.

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INTRODUCTION

Two years before his death, renowned evolutionary biologist Theodosius Dobzhansky submitted an essay to The American Biology Teacher entitled, “Nothing in Biology Makes Sense except in the Light of Evolution” in which he argued that evolution is the underlying framework for all aspects of biology and that, without an understanding of evolution, biology would never be more than a collection of disjointed facts (Dobzhansky, 1973). Cited nearly 4,000 times in the 45 years since its publication, this phrase has become a mantra for biology educators, emphasizing the centrality of evolution in the biology curriculum. Recent national education reform initiatives, spearheaded by the National Science Foundation (NSF) and the American Association for the Advancement of Science (AAAS), identified evolution as the first of five core concepts for biological literacy in the 21st century (AAAS Vision and Change, 2011). As such, evolution is a ubiquitous component of undergraduate introductory biology sequences nationally. In spite of its importance, research over the last three decades has shown that students struggle, even after direct instruction, to understand how evolution by natural selection causes a population of organisms to change over time (Bishop and Anderson, 1990; Ferrari and Chi, 1998; Anderson et al., 2002; Nehm and Schonfeld, 2008; Harding et al., 2020). While a systematic review of the undergraduate evolution education literature has revealed more than 300 publications attempting to remedy this problem (Ziadie and Andrews, 2018), the biology education research community has failed to produce instructional resources that consistently promote robust conceptual understanding, particularly in large-enrollment courses.

Education researchers have theorized that students’ persistent difficulties understanding evolution arise from conceptual challenges inherent to biological systems. Complex systems are characterized by emergence, a property where macro-level patterns are caused by interactions of system components at the micro-level (Chi et al., 2012). Thinking about systems in biology requires reasoning across biological scales, and this is especially true of evolutionary processes (Catley, 2006; Dauer et al., 2013; Petrosino et al., 2015; Dauer and Dauer, 2016). Evolution can be considered a complex biological process in which macroevolutionary changes occurring across geologic time are the result of compounded effects of selection on populations. In turn, selection at the population level is driven by interactions among organisms with variable phenotypes and their environment resulting in differential survival and reproduction. Phenotypic variation acted on by selection is the result of genetic level variation that arises through mutation.

Reasoning about systems is a core competency of biology (AAAS Vision and Change, 2011), and yet research has shown that undergraduate students lack or struggle with systems thinking skills (Dauer et al., 2013; Reinagel and Bray Speth, 2016). Chi and colleagues have forwarded the hypothesis that students may form incorrect ideas about natural selection if they conceive of natural selection as an event rather than an emergent equilibration process (Ferrari and Chi, 1998; Chi et al., 2012). In the absence of correct emergent causal schema (Chi et al., 2012), intuitive reasoning patterns such as teleology may interfere with thinking scientifically about how evolutionary processes occur (Tamir and Zohar, 1991; Coley and Tanner, 2015; Barnes et al., 2017), leading to many of the misconceptions that have been documented by evolution education researchers (Sinatra et al., 2003; Nehm and Reilly, 2007; Nehm and Schonfeld, 2008). Such misconceptions about how evolution occurs have been shown to persist even after direct instruction (Bishop and Anderson, 1990; Nehm and Reilly, 2007; Yates and Marek, 2014). Achieving robust conceptual understanding of evolution by natural selection therefore requires curriculum that effectively supports reasoning about evolution as a system and helps students integrate ideas across biological scales.

However, conceptual challenges are not the only barrier to learning evolution. This became quite apparent during my experiences as a student teacher in a 10th grade biology classroom in Waynesville, North Carolina — a rural community nestled in the foothills of the Appalachian Mountains. Waynesville is located within a highly conservative county and was ranked number three on the list of “[T]he 10 Most Bible Thumping Cities in North Carolina” (James, 2016). Having just completed the Collaborations in Discipline-Based Education Research (CiDER) REU program the summer before, I decided to apply my newfound research skills to better gauge what students actually learned about evolution in my class. For many of my students, this class would be the last time that they learned about evolution, as most Tuscola High School graduates directly enter the workforce or trade school rather than go on to college. I gave my students the Bishop and Anderson diagnostic instrument (1990) pre- and post-instruction to assess the level of understanding they would take with them. We found that students performed poorly both pre- and post-instruction. One student’s response in particular stands out. In large letters at the top of his post-instruction survey he wrote, “Colossians 2:8 NLT”, which reads, “Don’t let anyone capture you with empty philosophies and high-sounding nonsense that come from human thinking and from the spiritual powers of this world, rather than from Christ.” Other students annotated questions asking about their knowledge of macroevolution with statements like, “I don’t believe it” and “According to Evolutionist beliefs.” It is notable that these responses came from children of community leaders including school administrators. Even though these students did gain some understanding of evolution by natural selection, their responses indicate that it is unlikely that they would rely on this knowledge in their everyday lives after leaving my classroom.

Despite the possible challenges of reconciling student religious beliefs with evolutionary theory, evolution acceptance is a critical outcome for evolution educators (Dunk et al., 2019). Evolution acceptance is correlated with an increased understanding of evolution (Nadelson and Southerland, 2010), but acceptance also has impacts on a student’s ability to interact with the current scientific landscape. Evolution acceptance is one component of public trust in science, which is essential for developing policies that use science to advance the public good. Cultivating trust in science and an understanding of the nature of science allows students to grasp various biological phenomena including antibiotic resistance, the uses of genetically modified crops, and the trust needed to take new vaccines (Dobzhansky, 1973; Nadelson and Hardy, 2015; Dunk et al., 2017). Solving the pressing biological problems of our time requires correct applications of evolutionary theory. For example, evolution provides the background for scientists and researchers to determine the origin of antibiotics resistance, use phylogeny to track the evolution of HIV and Zika virus strains, and predict the effects of climate change on the spread of diseases, range of organisms, and overall impacts on biodiversity. By working towards an increased level of evolution acceptance, educators can heighten the use of evolutionary theory to solve current biological problems. These examples illustrate the need for a comprehensive understanding of what impacts evolution acceptance. Research has shown that a lack of evolution acceptance emerges from various social, cultural, and epistemological factors including religiosity and regional impacts (Hawley et al., 2011), knowledge of the nature of science (Dunk et al., 2017), openness to experience (Short and Hawley, 2012; Dunk et al. 2017), teleology (Barnes et al., 2017) and even celebrity opinion (Arnocky et al., 2018). Researchers agree that many things impact evolution acceptance, but a clear direct causal relationship from any of these individual factors to evolution acceptance is unclear and requires more examination.

Research on evolution education is widespread and spans the educational career of students from middle school classrooms (Beardsley, 2004), to high school classrooms (e.g. Demastes et. al, 1995; Spindler and Doherty, 2009; and Nieswandt and Bellomo, 2009) and to undergraduate classrooms (e.g. Bishop and Anderson, 1990; Anderson et al., 2002; Nehm & Reilly, 2007; Nehm & Schonfeld, 2008, Barnes et al., 2017). However, the non-cognitive and socioculutural aspects of evolution education, assessment, and acceptance have dominated the policy decisions in the field of evolution education research over the last several decades. Educational policy is heavily influenced by combatants of evolution. For example, the phrase 'just a theory' was used to negotiate the inclusion of creationism in high school biology textbooks and to debate the necessity of evolution instruction at all levels of education (Alters and Alters, 2001; Miller, 1998). At the same time, there has also been widespread reform aimed to improve evolution education at the middle school and high school level through the Next Generation Science Standards (Next Generation Science Standards Lead States, 2013) and at the college level through Vision and Change in Undergraduate Biology Education: A Call to Action (American Association for the Advancement of Science, 2011). Even with these reform efforts, there are still many questions about what individual instructors can do in their own classrooms, especially at the undergraduate level where instructors have much more autonomy, to increase acceptance and understanding of evolution.

Dobzhansky made the argument 45 years ago that evolution is an essential element in any biology curriculum. Since that time thousands of researchers have assessed student understanding of evolution, generating new curriculum, new understanding and questions about the relationship between knowledge and acceptance, leading to drastic policy and educational reform across the country. Even with all this research, the United States still ranks almost last in acceptance of evolution (Miller, 2004) and instructors in parts of the country are still hesitant to include evolution curriculum in the biology classroom (Lerner, 2000; Glaze and Goldston, 2015). This dissertation targets three of the current needs in evolution education: 1) to evaluate students' level of understanding of evolution by natural selection after completing a non-majors course, 2) uncover non-cognitive and sociocultural factors that affect evolution acceptance for our students at NDSU, and 3) create quality instruction that helps students overcome inherent conceptual difficulties and that meets students where they are in their knowledge of evolution.

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CHAPTER 1. WHAT DO STUDENTS KNOW ABOUT EVOLUTION BY NATURAL SELECTION AFTER A NON-MAJORS GEOLOGY COURSE? AN ANALYSIS OF STUDENT RESPONSES TO OPEN-ENDED QUESTIONS[1]

Abstract

Most of the research on student understanding of evolution by natural selection has focused on undergraduate biology courses for science majors. However, the majority of undergraduates in the United States will not enroll in a biology course for majors. In this study, we identify the extent of natural selection understanding that students acquire through an undergraduate, non-majors geology course. Using a pre/post assessment model, we administered open-response items from the Bishop and Anderson Diagnostic Instrument and a religiosity scale. Student responses were coded for inclusion and correctness of five key principles of natural selection: variation in a population, origin of variation, inheritance, fitness, and change in a population over time. The majority of students included few, if any, key principles of natural selection in their responses prior to instruction, and improvement after direct instruction in their geology course was minimal (cheetah: mean pre 1.01, mean post 1.37; salamander: mean pre 0.79, mean post 1.15). In most cases, students' self-reported religiosity was unrelated to their knowledge of natural selection. Together, our results demonstrate that in spite of instruction, non-majors geology students struggle to describe the process of natural selection using foundational principles. We encourage the continued development of cross-disciplinary educational resources for this important population to help all students, regardless of major or career path, gain a more robust understanding of evolution by natural selection.

Introduction

Evolution is recognized as a core concept of biological and geological literacy (American Association for the Advancement of Science, 2011; Wysession, 2012; Next Generation Science Standards Lead States, 2013; St. John, 2018). Evolution understanding is essential not only to twenty-first century biologists and geologists, but also to science teachers, medical professionals, government

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[1] The material in this chapter was co-authored by Rachel Harding, Kurt Williams, Frank Forcino, Jonathan Dees, Madelyn Pennaz, and Jennifer Momsen. Rachel Harding had primary responsibility for data collection and analysis. Rachel Harding was the primary developer of the conclusions that are presented here. Rachel Harding also drafted and revised all versions of this chapter. Jennifer Momsen served as proofreader and reviewer throughout the manuscript revision process.

officials, and all citizens who help determine policy (Funk & Goo, 2015; Funk & Rainie, 2015). Citizens need to understand evolution to make sense of how bacteria develop drug resistance (microevolution) and how Earth has transformed from an uninhabitable rock to a home for millions of diverse species (macroevolution) (Miller, 1998). Several reports, including The Future of Undergraduate Geoscience Education (Mosher et al., 2014), Vision and Change in Undergraduate Biology Education (AAAS, 2011), and A Community Framework for Geoscience Education Research (St. John, 2018) emphasize the critical roles that geosciences and biology educators should play in helping students develop a deep and meaningful understanding of the evolutionary character of Earth's systems and history. Efforts are especially needed considering the socially controversial status of evolution and climate change among science topics.

Historically, many U.S. states have deprioritized evolution as a core component of biology and earth science curricula at the high school level (Lerner, 2000), though the development of the Next Generation Science Standards (NGSS) has re-centered evolution as a cross-cutting theme in secondary science education (Next Generation Science Standards Lead States, 2013; Thompson, 2019). However, robust standards at the state level may not be reflected in how high school instructors interpret the standards or use them in their classrooms (Moore, 2002). For example, Bandoli (2008) compared two bordering states, one receiving a grade of "A" and the other receiving an "F" in Lerner's (2000) analysis of evolution state standards. Undergraduate students in both states completed retrospective surveys that asked them to reflect on their high school biology evolution instruction. They reported receiving essentially the same content and amount of instruction, regardless of differences in state standards. Thus, even when evolution is explicitly taught, it is unclear how much of the evolutionary mindset students actually achieve. Systematic assessment of student understanding of evolution is needed to determine the extent to which these reforms have been successful.

Over the last two decades, biology education researchers have conducted several studies assessing the depth of understanding students attain about evolution by natural selection in high school (e.g., Demastes et. al, 1995; Spindler and Doherty, 2009; and Nieswandt and Bellomo, 2009) and undergraduate biology classrooms (e.g., Nehm & Reilly, 2007; Nehm & Schonfeld, 2008). Most of the recent empirical research has occurred in undergraduate biology courses for science majors (e.g., Opfer et al., 2012; Kalinowski et al., 2016). However, most people—and most college students—do not take majors biology courses; for instance, in the 2017-2018 academic year, only 6% of the two million bachelor's degrees conferred were in biological and biomedical sciences (National Center for Education Statistics (NCES), 2020). Analogous studies that focus on students enrolled in non-majors science courses, including geology, are limited (e.g., Anderson et al., 2002; Rankey, 2003; Catley & Novick, 2009). Dominant research agendas thus allow many students to fall through the cracks of research on evolution instruction and assessment (Glaze & Goldston, 2015).

Student understanding of evolution

A basic understanding of evolution by natural selection includes a synthesis of Darwin's postulates and geologic time (Darwin, 1859; Bishop & Anderson, 1990; Zen, 2001; Jensen & Finley, 1996; Anderson et al., 2002; Petrosino et al., 2015). Previous work by Bishop and Anderson (1990) explored how students enrolled in a non-majors biology course reasoned about natural selection using Darwin's postulates. Student responses describe evolution by natural selection with five key principles: variation in a population, origin of variation, inheritance, fitness, and change in a population over time (Bishop & Anderson, 1990; Bray-Speth et al., 2009). Evolutionary processes operate over spatial and temporal scales, from the instantaneous (e.g., mutation) to deep time (e.g., evolutionary radiation). A complete understanding of evolution by natural selection therefore must incorporate both microevolutionary and macroevolutionary time (Bray-Speth et al., 2009; Petrosino et al., 2015).

Although natural selection is not a particularly complex process (Ferrari & Chi, 1998; Coyne, 2009; Kalinowski et al., 2016), students struggle to understand how natural selection results in a population of organisms changing over time. Students may have misconceptions (i.e., deep-seated beliefs about how evolution occurs) or an incomplete understanding of how the principles of evolution by natural selection fit together (Nehm & Reilly, 2007; Gregory, 2009; Heddy & Sinatra, 2013; Yates & Marek, 2014). For example, students often suggest that an organism changes within its own lifetime, or that all organisms in a population gradually change over time (Anderson et al., 2002; Nehm & Reilly, 2007). Student responses may also contain non-normative scientific ideas or naïve conceptions (Ferrari & Chi, 1998; Ha & Nehm, 2016; Heredia et al., 2016). For example, a student response may indicate that an organism needs to change to survive in its particular environment or that lack of use of a particular trait causes it to disappear from the organism, without including temporal context of these processes (Ha & Nehm, 2016).

Along with the complex nature of evolution by natural selection, students must also contend with the political and cultural debates that surround this topic. Student understanding of evolution and student acceptance of evolution may be intertwined, but the relationship is unclear (Bishop and Anderson, 1990; Brem et al., 2003; Ingram and Nelson, 2006; Rice et al., 2011; Barnes et al., 2017; Dunk et al., 2019). Dunk et al. (2017) reported that student acceptance of evolution is most strongly predicted by their understanding of the nature of science, but also by their religiosity. The interplay between religiosity, acceptance of evolution, understanding of evolution, and other knowledge factors, including the nature of science and teleology, are still being investigated (Dunk et al., 2019). These factors may also be exacerbated in highly religious or conservative areas of the United States (Hawley et al., 2011). Students may feel conflict between their religious beliefs and evolution curriculum, preventing them from engaging in this material (Kelley, 2000; Barnes & Brownell, 2017; Truong et al. 2018). This may be especially true in geoscience courses, where evolution instruction commonly moves beyond micro-evolutionary changes (natural selection) to macro-evolutionary processes across geologic time scales to speciation (Cuffey, 1999; Libarkin et al. 2005). This exploration of macro-evolutionary processes will provide much needed evidence about the process of evolution for some students, but may deter more fundamentalist Christian students from engaging in learning about evolution (Padian, 2010). Thus, it is important to assess the extent to which cultural factors like religiosity may be impacting student understanding of evolution in the classroom.

Undergraduate geology courses are critical sites of evolution instruction

In the U.S., students receive instruction about evolution in multiple contexts during their educational career. Evolution has been woven into the science curriculum learning objectives for biology and geosciences in the NGSS for elementary, middle, and high school (Next Generation Science Standards Lead States, 2013), and as such, students should encounter evolutionary principles multiple times in their education. However, because the NGSS standards have been implemented relatively recently, current undergraduate students have likely not had the same depth of exposure to evolution. Importantly, nearly all high school students in the U.S. (96%) complete a biology course as part of their curriculum (U.S. Department of Education, National Center for Education Statistics, 2016). Although curriculum standards vary by state, these biology courses generally focus on microevolution and natural selection (Catley, 2006; Hermann, 2013; Novick et al., 2014). Evolution is also taught in earth science courses during high school, where the focus is the co-evolution of Earth's surfaces and life on Earth (Next Generation Science Standards Lead States, 2013). However, only 23% of high school students complete an earth science course (Lewis & Baker, 2010). In general, high school students learn primarily about microevolution and natural selection, with somewhat limited exposure to other evolutionary ideas.

General education requirements of most colleges and universities in the U.S. require students to complete several science courses, including life and physical science (Miller, 2004). In these courses, students encounter evolution curricula of varying length, depth, and quality. These courses do not have a universal required curriculum, but four reform documents created over the last two decades inform 21st century geoscience education: Benchmarks for science literacy (AAAS, 1993), National Science Education Standards (National Research Council, 1996), Earth Science Literacy Initiative (2009), and the Next Generation Science Standards (NGSS, 2013). A recent review of these reform documents revealed 11 overarching concepts that should be taught in geoscience courses, two of which relate to evolution, "Earth's rocks allow us to reconstruct Earth's history, giving both relative and absolute dates" and "Fossils provide evidence about the types of organisms that lived long ago and the nature of the environments at the time" (Guffey and Slater, 2020). The exact topics covered in majors and non-majors courses may vary, but there is current agreement among geoscience educators that evolution is an appropriate and necessary topic for non-majors geoscience courses (King, 2008; Bulinski, 2012; Kelley, 2012). Thus, as a result of both high school and undergraduate experiences, U.S. students gain some exposure to evolution, with a focus on evolution by natural selection in biology courses and large-scale changes across geologic time in earth science courses. However, since the vast majority of college graduates in the U.S. do not pursue a degree in biology or geology (American Geological Institute (AGI), 2011; U.S. Census Bureau, 2012), courses that serve non-science majors need to offer a robust evolution curriculum. These courses could feasibly be the last formal opportunity for the majority of students to learn about evolution by natural selection.

In the present study, we sought to assess the evolution by natural selection understanding students acquire as a result of taking a non-majors geology course (Investigations in Environmental Geology, Geology 140) at a university in the southeastern United States. We collected data on students' understanding before and after instruction about natural selection in this course. We evaluated students' written responses for the presence and correctness of key principles of natural selection. We also surveyed students about their religiosity to consider the extent to which religiosity might act as a cultural barrier to learning natural selection for these students. Specifically, we asked the following research questions:

1a. How many key principles of evolution by natural selection do undergraduates enrolled in the non-majors geology course include in their written responses, both before and after instruction?
1b. Of those key principles included, how often are they used correctly?
2a. Which key principles of evolution by natural selection were students likely to include before and after instruction in the non-majors geology course?
2b. Which key principles of evolution by natural selection were students likely to correctly use before and after instruction in the non-majors geology course?
3. Does a student's reported religiosity predict the number of key principles of evolution by natural selection included before or after instruction?

Methods

Course context

Data for this research were collected from an undergraduate institution classified as a "Master's Colleges & Universities: Larger Programs" institution in a rural region of the southeastern United States (Indiana University Center for Postsecondary Research). Students were enrolled in one of four sections of Geology 140: Investigations in Environmental Geology. GEO 140 was taught by two separate instructors, who collaborated on instruction. Eighty-four students completed both a pre- and post-assessment, and 61 also completed a demographics questionnaire. Students (n=61) were 18-22 years old, 58% female, and had likely completed a high school biology course (NCES, 2016; Table 1). The classes included primarily freshman (60%) and sophomores (31%), with some juniors (6%) and seniors (3%).

Table 1.1. Demographics.

Variable		
Major	Health Sciences	5
	STEM field	8
	Business	10
	Elementary education	7
	Social sciences	18
	Other	13
Class	Freshman	35
	Sophomore	20
	Junior	4
	Senior	2
Ethnicity	White	52
	Black	5
	Asian/Pacific Islander	1
	Hispanic	2
	Native American	1
Sex	Female	37
	Male	24
Age	18-19	43
	20-21	17
	22+	1
Religiosity	Average score ± St.dev	4.49±2.09

Students completed a demographic questionnaire at the end of the survey

Both instructors used active-learning pedagogies and agreed to teach the same unit on evolution by natural selection. Evolution by natural selection was a one-week unit in the middle of the semester that included lecture, discussion, and a single group worksheet activity. The lecture specifically covered the definition of small-scale evolutionary changes generated through microevolution and large-scale evolutionary changes and speciation caused by macroevolution. The mechanisms of evolution and common misconceptions related to specific mechanisms were discussed, e.g. random genetic mutations occur in individual organisms, these mutations are not always bad for the organism. After students received instruction from the lecture, they completed an online group activity, “The Arthropod Story”, from the University of California Museum of Paleontology Understanding Evolution website (“The Arthropod Story”, 2020). The students worked in groups to complete the online tutorial and an accompanying worksheet designed by the course instructors. While the unit was designed to ensure that students were taught about both micro- and macro-evolutionary mechanisms and coincide with the rubric used for the open-response instrument used in the study, this course was a typical non-majors survey course, so the entire unit was limited to one week of class time. Other course topics included plate tectonics, rocks and minerals, paleontology, and climate change.

Assessment of student understanding of natural selection

Administration of open-response instrument

Knowledge of the principles of evolution by natural selection can be measured in multiple ways, including interviews, multiple-choice instruments, and open-response assessment items. Each approach has benefits and limitations (Nehm & Schonfeld, 2008; Kuechler & Simkin, 2010; Stanger-Hall, 2012). Interview studies are necessarily restricted to a small number of participants, and the most commonly used multiple-choice instrument, the Concept Inventory of Natural Selection (CINS), has not been validated with a non-majors population outside of biology (Anderson et al., 2002). For this study, we opted to use open-response assessment items because they allowed us to characterize the reasoning of a large number of students enrolled in a non-majors geology course at the undergraduate level.

Our instrument consisted of two open-response items assessing student understanding of natural selection, taken from the Bishop and Anderson diagnostic instrument (1990). The original instrument featured two constructed-response items (included in our survey), one assessing trait gain in cheetahs and the other assessing trait loss in cave salamanders. Some research indicates the trait loss question may be more conceptually difficult and result in students including fewer correct conceptions and more misconceptions in their responses (Anderson et al., 2002; Nehm & Schonfeld, 2008; Ha & Nehm, 2016; Smith, 2017). However, it is important to assess student understanding of evolution by natural selection in multiple contexts (Nehm et al., 2012), so we included both prompts in our instrument and analysis.

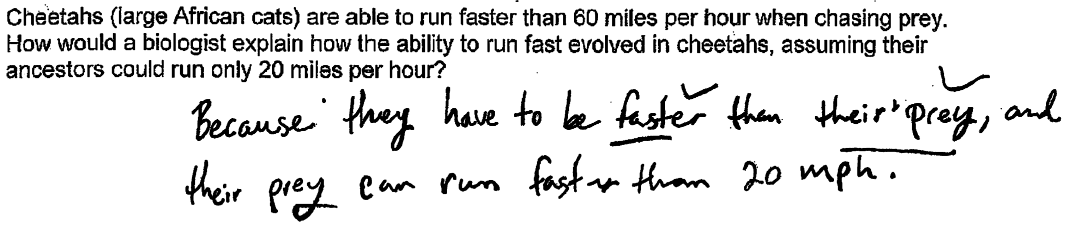
The study population voluntarily completed the instrument during class in a pre/post-instructional format, where the pre-assessment occurred just before relevant instruction and the post-assessment occurred immediately after relevant instruction and prior to the relevant exam.

Survey Questions

1. Cheetahs (large African cats) are able to run faster than 60 miles per hour when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could run only 20 miles per hour?
2. Cave salamanders (amphibian animals) are blind (they have eyes that are not functional). How would a biologist explain how blind cave salamanders evolved from ancestors that could see?

Coding of Student Responses

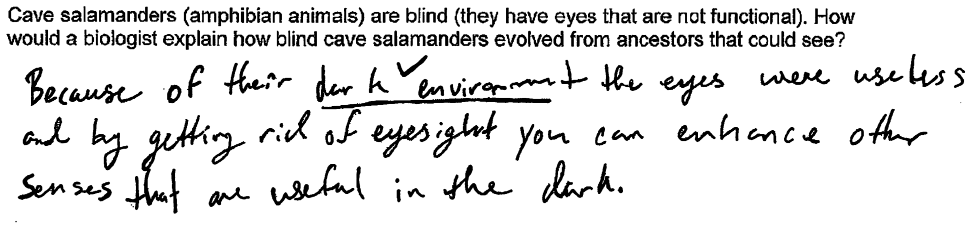
Bray Speth et al. (2009) modified the Bishop and Anderson (1990) rubric, and it is this modified rubric that we used to code our student responses (Table 2). Two independent raters (R.L.S. and M.P.) coded each student response for the presence and correctness of five key principles of natural selection: variation in a population, origin of variation, inheritance, fitness, and change in a population over time. Specifically, each key principle was coded as absent (key principle not present in the response), present (key principle present but incorrect), or correct (key principle present and correctly described in the context of the prompt). (See Fig. 1 and Fig. 2 for example student responses.) To establish coding reliability, two researchers independently coded 20% of student responses with greater than 90% agreement. Code disagreements were discussed between the two coders until consensus was reached. One researcher (R.L.S.) then coded the remaining student responses. The instructors of the course did not review or code the open-response instruments.



Cheetahs (large African cats) are able to run faster than 60 miles per hour when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could run only 20 miles per hour?

Because they have to be faster than their prey, and their prey can run faster than 20 mph.

Figure 1.1. Student response to cheetah prompt. Example student response to the cheetah trait-gain question from the Bishop and Anderson diagnostic instrument (1990).



Cave salamanders (amphibian animals) are blind (they have eyes that are not functional). How would a biologist explain how blind cave salamanders evolved from ancestors that could see?

Because of their dark ✓environment the eyes were useless and by getting rid of eyesight you can enhance other senses that are useful in the dark.

Figure 1.2. Student response to salamander prompt. Example student response to the salamander trait-loss question from the Bishop and Anderson diagnostic instrument (1990).

Table 1.2. Coding rubric for the open-response assessment items.

	Category		
Principle	0 – Absent	1 – Incorrect	2 – Correct
Variation within a population [V]	No mention	Only one of the variations is mentioned, or only one of the organisms is mentioned (e.g., some cheetahs are faster, fastest, etc **OR** some prey is faster, fastest etc)	There is a clear reference to the different phenotypes existing, for example: fast and slow, faster (comparison) at the same time, within the cheetah population and other organisms
Origin of variation [O]	No mention	Phenotypic differences are the result of "**mutations"**	Variation within populations has genetic origin (is caused by **random genetic mutation,** resulting in different alleles)
Inheritance [I]	No mention	**Traits** are inherited by offspring	The **genes** responsible for phenotypic traits are inherited by offspring. Also – propagated or perpetuated in the gene pool
Fitness [F]	No mention	Individuals whose characteristics are favored by the environment are more likely to **survive** OR Individuals whose characteristics are not favored by the environment are more likely to **die**	Individuals whose characteristics are favored by the environment are likely to **reproduce** more and produce more viable offspring
Change in populations [P]	No mention	Populations change over time, and shift from a variety of phenotypes to selected **phenotypes** becoming predominant Change "over time" and *implies* that the population is changing	**Allele frequencies** change in populations over time. OR Population is changing over time

Religiosity

Because social and cultural factors can be related to evolution acceptance and understanding (Hawley et al., 2011; Dunk et al., 2019), we investigated whether our non-majors geology students' religiosity was related to their understanding of evolution. While we recognize the diversity of religious beliefs and experiences that students bring to geology classrooms, research on evolution has focused on the specific construct of religiosity, which is defined as the degree to which a person's religious beliefs impact their daily life, habits, and decisions (Hawley et al., 2011).

We administered the religiosity subscale of the Evolution Attitudes and Literacy Survey (EALS; Hawley et al., 2011) as part of a larger demographic questionnaire on the pre-assessment. Students rated their religiosity based on their agreement with six statements on a 7-pt Likert scale, with 1 = not at all and 7 = very. Ratings of agreement to the six indicator statements were then averaged for each of the 61 students who completed the demographic questionnaire to create a mean religiosity score (Table 1). This mean was used to predict student inclusion of key principles on the pre- and post-assessments, as described below.

Statistical analyses

We coded student responses for the presence and correctness of five key principles of natural selection (Table 2), both before and after instruction. Code frequencies were computed for all codes. For some analyses, we summed the total number of key principles included to calculate a total score for each prompt. Since students did not necessarily correctly use all of the key principles they included, we separately calculated the total number of key principles correctly used based on our coding rubric. Changes in the total number of key principles included or correct from pre- to post-test were assessed using paired sample t-tests. To analyze changes in the use of specific key principles, we performed an exact version of the McNemar test, which is more accurate for smaller sample sizes (Fagerland et al., 2013). Patterns of student responses were also qualitatively analyzed by inspection of transition matrices (contingency tables showing joint frequencies of the number of key principles included or correct on the pre-test vs. post-test) (Collins and Lanza, 2009). Because these analyses of change in student responses from pre- to post-test require matched data, we excluded students who did not complete both the pre- and post-test, resulting in 84 matched sets of responses. To determine whether a student's religiosity predicted their performance on the assessment, we performed a series of ordinary least-squares (OLS) regression analyses. We modeled students' pre-test scores (the total number of key principles included) and post-test scores for both the cheetah trait-gain prompt and the salamander trait-loss prompt as a function of their religiosity, measured by the average response to six statements on a 7-pt Likert scale. We then computed estimated marginal means from each model to predict the average number of key principles students at each point of the religiosity scale would include. Because these regression analyses require data about student religiosity and assessment responses, we excluded 23 students from the religiosity analyses who were missing religiosity data due to not completing the demographic questionnaire (n = 61). All statistical analyses were conducted using Stata version 15.1 (StataCorp, 2017).

Results

In order to assess students' understanding of natural selection before instruction about evolution in their non-majors geology course, we coded student responses to two open-response items about natural selection. On the cheetah trait-gain prompt, the majority of undergraduates (71%) included zero or one key principle of natural selection in their pre-instruction responses (Fig. 3A). Similarly, on the salamander trait loss prompt, 87% of students included zero or one key principle (Fig. 3B). Moreover, many students (45%) did not use any of the key principles correctly on either prompt (Fig. 3A, 3B). Of responses reporting just one key principle, 93% (cheetah) and 95% (salamander) wrote about variation in populations (Fig. 4A, 4B). The second most commonly attempted key principle was fitness, with 23% (cheetah) and 6% (salamander) of students including it. However, of these, just 32% (6 students; cheetah) and 0% (salamander) of students were able to correctly describe fitness in the context of the problem scenario. In spite of being taught about evolution in high school biology, the overwhelming majority of non-majors geology students were unable to explain how natural selection occurs prior to instruction.

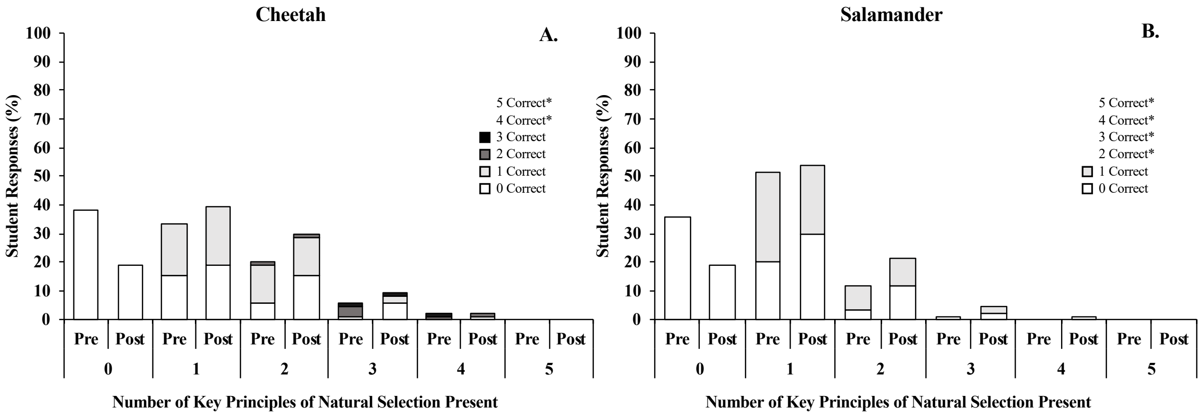


Figure 1.3. Distributions of student scores on the pre- and post-tests. **A**: cheetah trait-gain prompt; **B**: salamander trait-loss prompt. The total height of each bar represents the percent of student responses (y-axis, n = 84) including from zero to all five key principles of evolution by natural selection (x-axis). For each total number of key principles included, percentages for the pre-test and the post-test are shown side-by-side to assess change in responses after instruction. Students including key principles of natural selection in their responses did not necessarily do so correctly (see Table 2 for coding scheme used). The number of key principles students used correctly is indicated by shading within the bar. For example, of the students who included two key principles on the pretest, the proportion of students using both key principles incorrectly is shown in white; the proportion using one incorrectly and one correctly is shown in light gray; and the proportion of students using both key principles correctly is shown in dark gray. No student correctly described four or all five key principles correctly, so the color is scaled from zero to three key principles correct. Possible codings that were not observed in this dataset are marked with an asterisk.

Following instruction, the total number of key principles students included in their post-test responses increased significantly, although these increases were small (cheetah: 1.37 post vs. 1.01 pre, paired sample t-test, *t*(83) = 2.58, *p* = 0.0115; salamander: 1.15 post vs. 0.79 pre, paired sample t-test, *t*(83) = 3.50, *p* = 0.0008). There was, however, no significant increase in the overall number of key principles that undergraduates used correctly from the pre-assessment to the post-assessment (cheetah: 0.44 post vs. 0.50 pre, paired sample t-test, *t*(83) = –0.87, *p* = 0.3873; salamander: 0.36 post vs. 0.39 pre, paired sample t-test, *t*(83) = –0.52, *p* = 0.6045; Fig. 3A, 3B). Fully 48% of non-majors geology students failed to correctly include any key principles of natural selection on either prompt after direct instruction. The majority of students (cheetah: 71%; salamander: 61%) included the same number (either zero or one) of key principles correctly on the pre-test and the post-test. Of the remaining students, roughly equal numbers of students increased and decreased in the total number of key principles correctly included (cheetah: 11 inc. vs. 13 dec.; salamander: 15 inc. vs. 18 dec.). However, increases tended to reflect movement from including zero to just one key principle correctly, but students who originally included more key principles correctly tended to decrease in the number of key principles they included in their response. Of the seven students who correctly included at least two of the five key principles of natural selection pre-instruction on the cheetah prompt, six included fewer key principles correctly post-instruction, with two including zero key principles correctly. Although no students included more than one key principle correctly on the salamander prompt either pre- or post-instruction, more than half of those that had correctly included one key principle pre-instruction did not include any key principles correctly post-instruction.

Looking at the inclusion of specific key principles, the number of responses that included change in a population over time did increase significantly (cheetah: 8% pre vs. 19% post, McNemar exact test, $\chi^2(1) = 5.40$, $p = 0.0352$; salamander: 6% pre vs. 17% post, McNemar exact test, $\chi^2(1) = 5.40$, $p = 0.0352$; Fig. 4A, 4B), although no student in either prompt described change in a population over time correctly. There were no other significant changes among the remaining key principles (variation, mutation, inheritance, and fitness) in terms of presence. Thus, in spite of being taught about evolution in their non-majors geology course, the majority of students were unable to explain how natural selection occurs even after direct instruction.

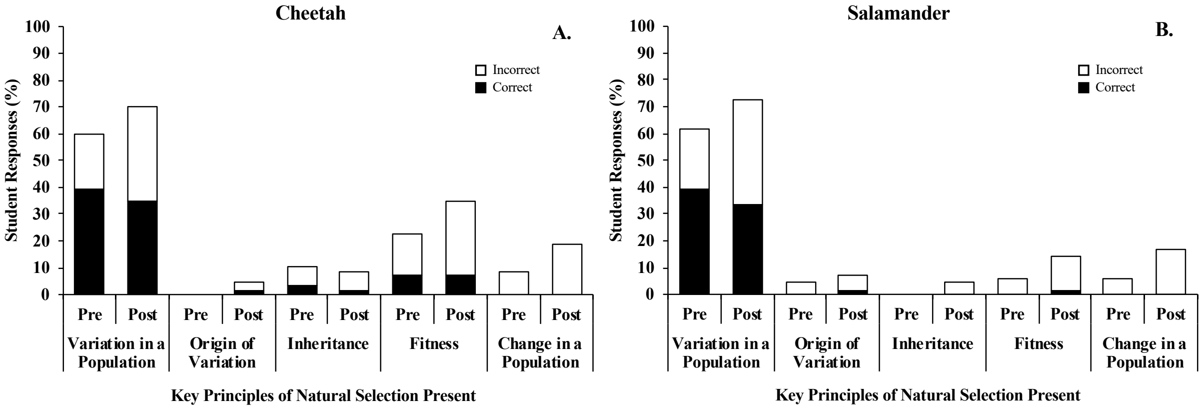


Figure 1.4. Frequencies of inclusion of each of the five key principles of natural selection before and after instruction. **A**: cheetah trait-gain prompt; **B**: salamander trait-loss prompt. The total height of the bar represents the percent of student responses including that key principle. Students including the key principle of natural selection did not necessarily do so correctly (see Table 2 for coding scheme used). The proportion of students using the principle correctly is indicated by shading within the bar, with black representing a correct response and white used to indicate incorrect or incomplete usage of the key principle. Frequencies of codings for the pre- and post-tests are shown side-by-side to facilitate comparison.

To assess the degree of a student's self-reported religiosity, we administered the religiosity subscale of the EALS (Hawley, 2011). The average religiosity score for this sample of college students in the rural southeastern U.S. was 4.49 (SD: 2.09), which represents a neutral value between "not at all" and "very", although students occupied the entire range of the scale (from 1 to 7, Table 1). Patterns in student responses to the six items were similar, with the exception of students' responses to the statement about their belief in god(s), to which greater than fifty percent of students reported a 7.

We investigated whether the degree of a student's religiosity predicted their understanding of evolution before or after instruction. To do this, we analyzed three ordinary least-squares (OLS) regression models for each prompt. First, we tested whether a student's average religiosity score (measured on a 7-pt Likert scale) predicted the total number of key principles included on their pre-test. Next, we modeled their post-test scores, first as a function of religiosity alone, followed by testing the effect of religiosity while controlling for pre-test score. The first two models, using religiosity as the only predictor of student performance, describe the statistical relationship between a student's religiosity and the number of key principles they included. The third model describes the remaining variance in student scores on the post-test that can be explained by a student's religiosity after partialling out variance that is explained by their score on the pre-test. Since we would expect that students who do well on the pre-test would also do well on the post-test, the third model tests whether test scores of students who are more religious increase as much as their less religious peers after taking their pre-test scores into account.

We observed a significant effect of religiosity on student performance pre-instruction on the cheetah prompt ($\beta = -0.177$, $p = 0.002$; Table 3). Religiosity explained 15% of variance in the total number of key principles included on the pre-test for the cheetah question ($R^2 = 0.15$, $F(1,59) = 10.42$, $p < 0.01$; Table 3). The model estimates that a student who reported that they were "not at all" religious for all six statements would include, on average, 1.59 key principles of natural selection in their response; a student with a more neutral reported religiosity, marking a "4" for all six statements, would include 1.05 key principles; and a student that expressed a high sense of agreement with the religiosity statements, marking that they are "very" religious on all six would on average include 0.52 key principles (Fig. 5A). However, the statistical relationship between religiosity and the total number of key principles included disappeared after instruction ($\beta = -0.057$, $p = 0.359$; Table 4), with students at all levels of religiosity including on average 1.38 key principles (Fig. 5A). Contrary to what might be expected, students' scores on the pre-test did not significantly predict the number of key principles they included on the post-test (β = 0.091, *p* = 0.536; Table 5) when pre-test score and religiosity were both included in the model. Religiosity continued to show no significant relationship with post-test score when controlling for pre-test score on the cheetah prompt (β = –0.041, *p* = 0.547; Table 5).

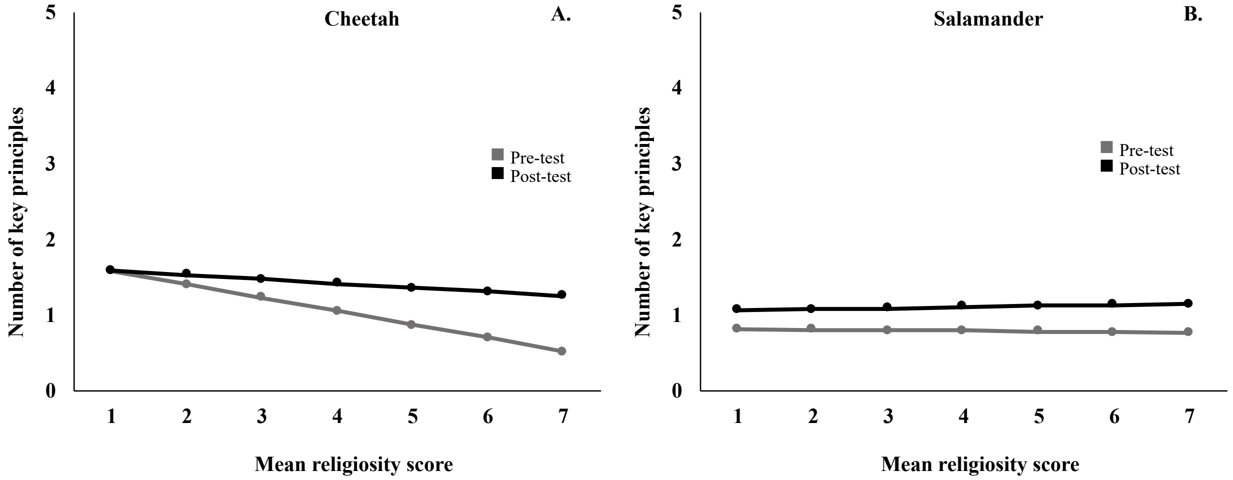


Figure 1.5. Estimated marginal mean number of key principles included (y-axis) on the pre- vs. post-test by students with varying levels of religiosity (x-axis). **A**: cheetah trait-gain prompt; **B**: salamander trait-loss prompt. Ratings across the six statements were averaged to generate a student's mean religiosity score, which was used for regression analysis. The mean number of key principles included by (hypothetical) students rating at each point along the religiosity scale is estimated using the OLS regression models reported in Tables 3–8.

Students' religiosity was not statistically related to the number of key principles they included on the salamander prompt at either time point (Tables 6–7), nor after controlling for pre-test score (Table 8). Like the cheetah prompt, the number of key principles students included on the pre-test for the salamander prompt was not a significant predictor of their post-test score (β = 0.220, *p* = 0.156; Table 8). None of the three models for the salamander prompt explained more than 0.2% of the variance in how students responded (Tables 6–8). Students at all levels of religiosity included on average 0.77 key principles on the pre-test and 1.13 key principles on the post-test for the salamander prompt (Fig. 5B).

Table 1.3. Model 1[a,b] (n=61) Cheetah pre-test.

# KP[c] present	*β*	std. err.	*t*[d]	*p*[d]	95% Confidence Interval
religiosity	−0.177	0.055	−3.230	0.002	(−0.286, −0.067)
intercept	1.758	0.270	6.520	0.000	(1.218, 2.300)

[a] # KP present on the Cheetah pre-test question = mean religiosity score + intercept + ε

[b] $R^2 = 0.15$, general linear F-test: $F(1, 59) = 10.42$, $p < 0.01$

[c] KP: key principles, see Table 1

[d] For Tables 3-8 one-sample t-tests, H_0: $\beta = 0$

Table 1.4. Model 2[a,b] (n=61) Cheetah post-test.

# KP present	*β*	std. err.	*t*	*p*	95% Confidence Interval
religiosity	−0.057	0.061	−0.920	0.359	(−0.180, 0.066)
intercept	1.647	0.303	5.440	0.000	(1.042, 2.253)

[a] # KP present on the Cheetah post-test question = mean religiosity score + intercept + ε

[b] $R^2 = 0.014$, general linear F-test: $F(1, 59) = 0.85$, $p > 0.05$

Table 1.5. Model 3[a,b] (n=61) Cheetah post-test.

# KP present	*β*	std. err.	*t*	*p*	95% Confidence Interval
religiosity	−0.041	0.067	−0.610	0.547	(−0.175, 0.093)
#KP pre-test	0.091	0.147	0.620	0.536	(−0.203, 0.385)
intercept	1.487	0.399	3.730	0.000	(0.688, 2.285)

[a] # KP present on the Cheetah post-test question = mean religiosity score + #KP present on pre-test + intercept + ε

[b] $R^2 = -0.021$, general linear F-test: $F(2, 58) = 0.62$, $p > 0.05$

Table 1.6. Model 4[a,b] (n=61) Salamander pre-test.

# KP present	*β*	std. err.	*t*	*p*	95% Confidence Interval
religiosity	−0.008	0.047	−0.170	0.865	(−0.103, 0.087)
intercept	0.823	0.233	3.530	0.001	(0.357, 1.289)

[a] # KP present on the Salamander pre-test question = mean religiosity score + intercept + ε

[b] $R^2 = 0.001$, general linear F-test: $F(1, 59) = 0.03$, $p > 0.05$

Table 1.7. Model 5[a,b] (n=61) Salamander post-test.

# KP present	*β*	std. err.	*t*	*p*	95% Confidence Interval
religiosity	0.014	0.056	0.260	0.798	(−0.098, 0.127)
intercept	1.050	0.276	3.800	0.000	(0.497, 1.603)

[a] # KP present on the Salamander post-test question = mean religiosity score + intercept + ε

[b] $R^2 = 0.0011$, general linear F-test: $F(1, 59) = 0.07$, $p > 0.05$

Table 1.8. Model 5[a,b] (n=61) Salamander post-test.

# KP present	β	std. err.	t	p	95% Confidence Interval
religiosity	0.016	0.056	0.29	0.771	(−0.095, 0.128)
#KP pre-test	0.220	0.153	1.44	0.156	(−0.087, 0.526)
intercept	0.869	0.301	2.88	0.006	(0.266, 1.473)

[a] # KP present on the Salamander post-test question = mean religiosity score + #KP pre-test + intercept + ε

[b] $R^2 = 0.0022$, general linear F-test: $F(2, 58) = 1.07$, $p > 0.05$

Discussion

In this study, we examined student understanding of evolution by natural selection and religiosity as a potential predictor of that understanding in a population of undergraduates enrolled in a geology course for non-science majors. Students struggled to reason about evolution by natural selection, as evidenced by the limited number of key principles included correctly in their responses. This pattern persisted even after explicit instruction on natural selection with 71% (cheetah) and 61% (salamander) of students correctly including zero to one key principle on both the pre- and post-test. Based on these data, it appears that instruction did not prepare students to reason about natural selection, as students exhibited limited to no improvement from the pre- to the post-assessment (Fig. 3A, 3B).

Prompt language

In most cases where students discussed one of the key principles of natural selection, that key principle was that variation exists in populations. In interpreting this result, we are forced to consider that, in contrast with the other key principles of natural selection, the assessment items themselves describe traits and phenotypic variation in those traits (i.e., speed of a cheetah as fast or slow, Box 1). Thus, students may not spontaneously identify “variation in a population” as a key principle of natural selection. Rather, the inclusion of this principle so frequently may reflect students cueing on and using aspects of the prompt. Future research should consider using other methods to more robustly assess student ideas about the roles of biological variation in evolution.

Course context

The only key principle that showed increased usage after instruction in this non-majors geology course was that natural selection drives changes in populations over time. This observation might reflect the conceptual emphasis on geologic time and the history of the Earth throughout the course. However, the majority of students did not reference change over time in describing the evolution of either the cheetah or the salamander, and no student in any of the four sections studied discussed change over time correctly. Student responses that were coded as including “change in a population over time” typically used the phrase “over time” in their response and did not indicate how the specific phenotypes or allele frequencies in the population were changing (Table 2). The key principles used by the fewest number of students were that mutation is the origin of variation in populations and that mutations (and consequent variation) are heritable. The lack of discussion of the physical basis for inheritance is perhaps unsurprising considering the topics and emphases of the course. Together, these findings suggest that, despite receiving instruction that explicitly included all five key principles of evolution by natural selection, the broader, geologic context of the course may have guided students to focus on different key principles than would be expected in a biology class. Biology courses include content on genetics and tend to focus on microevolutionary processes, whereas geology courses do not discuss genetics but consistently focus on large time scales and macroevolution. This difference in course context may unintentionally support development of fragmented and incomplete understandings of evolution, which could promote misconceptions (Veal & Kubasko, 2003). Integrating understandings of micro- and macro-evolutionary mechanisms is critical for understanding the history of life on Earth and is a needed outcome of geology and biology education (Fichter et al., 2010; St. John, 2018). Developing curricula that can help broad segments of the college-student population achieve these understandings will likely require cross-departmental collaboration between geology and biology instructors. Further research on the intersection of course context with student reasoning about evolution by natural selection is needed to support such efforts (Fichter et al., 2010).

Religiosity

Broad research has shown a relationship between religiosity and evolution acceptance (Hawley et al., 2011; Heddy and Sinatra, 2013; Dunk et al., 2017; Dunk et al., 2019) and evolution understanding (Rutledge and Warden, 2000; Nadelson and Sinatra, 2009; Nehm et al., 2009; Shtulman and Calabi, 2012) in the United States. In our sample of non-science majors from the American southeast, we found that religiosity was predictive of students’ pre-instruction scores on the cheetah trait-gain question but not on the salamander trait-loss question. After instruction, religiosity was not significantly related to scores on either the cheetah or the salamander prompt. It is important to consider, in the context of these data, that student performance on both prompts at both time points was quite low. This is especially true of the salamander prompt, for which no student at either time point used more than one key principle correctly. Trait loss and trait gain prompts are commonly used to assess student understanding of natural selection (Nehm et al., 2012), but the biological causes behind the common trait loss prompts (e.g., blindness in cave salamanders or cavefish) are still unknown, and therefore more difficult for students to explain (Smith, 2017). The use of other trait loss contexts in future work may provide better insight into student understanding of how natural selection can lead to trait loss in organisms. It is possible that our data exhibit a floor effect, in which true variation in students' knowledge of evolution is masked by the restricted range of responses to the measurement tool used (Everitt & Skrondal, 2010). If this is the case, the true relationship between students' religiosity and their knowledge of evolution might be obscured. What is clear from our analyses of these students' descriptions of evolution by natural selection, however, is that most students, at all levels of religiosity, struggled to correctly describe how evolution by natural selection occurs.

Limitations

This study, which uses a sample of four sections of a non-majors geology course at a university in the southeastern United States, is not meant to be a diagnostic survey of the level of understanding non-majors geology students achieve using a nationally-representative sample. Such a survey would be valuable to the geoscience education community for its ability to generalize (or refute) the findings of our report on a broad scale. Our case study approach can speak only to the materials, students, and instructors involved in the course studied. In many ways, we believe the classes we studied to be typical cases (Flyvbjerg, 2006) of geology instruction about evolution for non-majors: Geology 140 was a survey course that covered a broad range of topics relating to the evolving physical nature of earth systems, of which natural selection was a small part. Course instructors were aware of our research interests; given this, we might even expect that the instructors involved would have been especially conscientious about their natural selection instruction. We encourage other instructors and researchers to add to the data we report here with studies of evolution understanding in their own classrooms, particularly non-majors courses.

Another important limitation of our study is that we focused exclusively on students' understanding of evolution in terms of five key principles of natural selection, conceptually grounded in Darwin's postulates and validated for research use with undergraduate biology students (Bray Speth et al., 2009). Because of our interest in students' use of the key principles of natural selection, we did not code student responses for specific misconceptions about natural selection (e.g., Nehm & Reilly, 2007). Evolution, a cross-cutting theoretical perspective as much as a topic in its own right, has many facets that are used to explain diverse natural phenomena. Although natural selection is a core concept of biological evolution, evolutionary ideas relating to geologic time, the history of life on Earth, and biogeography are also important learning outcomes for geoscience education (Next Generation Science Standards Lead States, 2013; St. John, 2018). The non-majors geology students in our study are not unique in their difficulties in describing evolution by natural selection—a large body of literature over the last two decades of research has documented persistent misunderstandings of evolution in high school and undergraduate biology classrooms, in which evolution by natural selection is a focus (Bishop and Anderson, 1990; Anderson et al., 2002; Nehm and Reilly, 2007). Undergraduate geology classrooms represent an important site for developing evolutionary ideas that (taking a historical perspective) sparked the imaginations of the early theorists of biological evolution in the nineteenth century. We encourage instructors and education researchers in the biological and geosciences to further investigate how geological and microevolutionary perspectives can work together to promote an integrated understanding of earth systems.

Implications for instructional reform

Students' limited understanding of evolution by natural selection after explicit instruction in a geology course for non-science majors is discouraging, but reinforces the need for instructional improvements across the evolution education landscape. Students enrolled in this course likely have different motivations and background knowledge than biology and geology majors (Glynn et al., 2007); however, recent research on student understanding of evolution has centered on undergraduate biology courses for science majors (e.g., Nehm & Schonfeld, 2008; Kalinowski et al., 2016). There is limited research on student understanding of evolution from non-major science courses outside of biology (e.g., Jensen & Finley, 1996; Passmore & Stewart, 2001). The present manuscript represents one of the only studies to explore student understanding of evolution in courses outside of biology for majors and non-majors. Further, there is a distinct dearth of research exploring how geoscience instruction impacts students' understanding of evolution in these important non-majors courses.

Evolution is a core concept of biological and geological literacy (American Association for the Advancement of Science, 2011; Wysession, 2012; Next Generation Science Standards Lead States, 2013; St. John, 2018) and it underpins many of the challenges facing the world today, from antibiotic to pesticide resistance. As a result, all citizens, not just biologists and geologists, need a basic understanding of evolution. Thus, we argue that research on student understanding of evolution must expand beyond undergraduate courses for science majors. In addition, research on effective instructional approaches is essential to ensure that the limited time non-science majors spend in science courses is effective and efficient in promoting a robust understanding of evolution. We urge the community to better define learning expectations for developing evolutionary literacy and develop curricula to best support those learning expectations for our students. In doing so, we will promote the generation of a more scientifically literate citizenry.

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CHAPTER 2. A PATH ANALYSIS OF ACCEPTANCE OF EVOLUTION

Introduction

Background

Evolution is a divisive topic in American classrooms. Even with an overwhelming majority of scientists and biology education researchers in agreement about the importance of evolution education, evolution acceptance is still shockingly low among American adults, with only 22% believing the humans have evolved over time without God's intervention (Gallup, 2019). Acceptance among undergraduates varies by location and type of acceptance assessment used but has been shown to be generally low (Barnes and Brownell, 2018). Following the trends of the general public, Brem et al. (2003) found that many undergraduates believe that evolution was guided by an intelligent designer. Several studies of undergraduate biology majors found that 40-50% of students did not accept evolution (Verhey, 2005; Moore and Cotner, 2009). Rice et al. (2011) found theistic views did not change before and after evolution instruction, while acceptance of evolution did increase slightly from freshman to senior students.

Evolution acceptance is a multi-faceted issue, often impacted by sociocultural factors, in particular religiosity (Hawley et al., 2011; Barnes et al., 2017) and cognitive factors such as an understanding of the process of science (Lombrozo, 2008; Dunk et al., 2017), and knowledge of evolution (Weisberg et al., 2018). Over the last several decades, biology education researchers have tried to determine which variables lead to an increase in acceptance of evolution with mixed results. These studies typically evaluate the relationship of a single variable to evolution acceptance. In contrast to evaluating variables in isolation, we adopted a systems approach that enabled us to explore a complex network of interactions between variables and the subsequent relationship to evolution acceptance. Specifically, we investigated a sociocultural predictor (religiosity) and four cognitive predictors commonly found in evolution education literature (knowledge of evolution, knowledge of the nature of science, number of science courses, openness to experience).

Religiosity

A common area of study when determining evolution acceptance is the relationship between a student's religious beliefs and their acceptance of evolution. There is agreement that Christian denominations have more disbelief about the topic of evolution, especially macroevolutionary patterns and human evolution (Gallup, 2019). Many studies show a negative correlation between religious beliefs and levels of acceptance of evolution (e.g., Nehm and Schonfeld, 2007; Barone et al. 2014; Carter and Wiles 2014; Glaze et al. 2015; Dunk et al., 2017). However, religious beliefs or denomination may not be the largest indicator of acceptance; instead, a student's religiosity (i.e., how important religion is in their everyday life) may better predict their acceptance of evolution. In a study of undergraduates enrolled in a non-major's geology course, we found that students with a higher level of reported religiosity scored lower on a natural selection pre-test (Harding et al., 2020). Dunk et al. (2017) found that among a group of factors, religiosity had a significant negative impact on evolution acceptance. While religiosity has a large impact on acceptance, cognitive factors also play a significant role in predicting evolution acceptance.

Knowledge of evolution

Knowledge of evolution is one of the most well-studied predictors of evolution acceptance. In their seminal work, Bishop and Anderson (1990) found no relationship between knowledge and acceptance, where student performance on a pre-test and post-test had no relationship to their reported belief in evolution. Notably, this study included new curriculum that *did* moderately impact student understanding, but this did not lead to any increase in evolution acceptance (Bishop and Anderson, 1990). In the 30 years since this research was published, many other studies have reported that a higher level of knowledge of evolution is related to increased acceptance. Weisberg and colleagues (2018) found that a higher level of knowledge of evolution was related to a greater level of acceptance, even when accounting for religiosity and political views, within a sample of the general public. This relationship also surfaced among secondary science instructors and preservice teachers (Rutledge and Warden, 2000; Rutledge and Mitchell, 2002; Deniz et al., 2008; Glaze et al., 2015). When evaluating undergraduate students, Talbot et al. (2020) found that biology majors' acceptance increased as they moved through their undergraduate coursework and learned more about the evidence for evolution. Carter and Wiles (2014) also found that student acceptance of evolution was positively influenced by their understanding of evolution. Increased knowledge does correlate with increased acceptance in many populations, but the strength of this relationship varies by study.

Knowledge of the nature of science

Along with specific knowledge of evolution, an understanding of the process of science is another important cognitive factor that impacts evolution acceptance (Dunk et al., 2017; Nelson et al., 2019). The nature of science (NOS) includes a person's knowledge of scientific facts and how science works (Weisberg et al., 2021). In a large study of the general public, Weisberg et al. (2021) found that an increase in a person's understanding of the nature of science led to an increase in acceptance of evolution along with two other commonly controversial topics, climate change and the safety of vaccines, regardless of political identity and religiosity. Carter and Wiles (2014) found that undergraduates enrolled in an introductory biology course had increased levels of understanding of the nature of science on pre/post-assessments and this was positively correlated with an increase in their level of acceptance of evolution. Akyol et al. (2012) found that in a group of pre-service teachers, a more sophisticated understanding of the nature of science and knowledge of evolution accounted for 17% of the variance in a model acceptance of evolution. Together, these studies and others demonstrate that as a person's understanding of the process of science increases, so will their acceptance of evolution.

Openness to experience

The five-factor model of personality is commonly used by psychologists to describe five dimensions of personality (neuroticism, agreeableness, conscientiousness, extroversion, and openness to experience; McCrae and John, 1992). Openness to experience relates to a person's willingness to learn about new material and general intellectual curiosity (McCrae and John, 1992; Hawley et al., 2011). Sinatra et al. (2003) found that undergraduates enrolled in a non-majors' biology course with a more open-minded disposition were more likely to accept human evolution. Hawley et al. (2011) investigated the relationship between openness to experience and several factors related to acceptance of evolution, including political activity, knowledge, exposure to evolution, and creationist reasoning in a large group of undergraduate students. In this study, openness to experience was negatively correlated with creationist reasoning and political conservatism, factors that were associated with a lower level of acceptance of evolution. Dunk et al. (2017) found similar results in a group of undergraduates, where openness to experience was a significant predictor of acceptance and explained almost twice as much of the variation in their model than knowledge of evolution.

Number of science classes

Along with religiosity and the other cognitive factors related to acceptance of evolution, exposure to evolutionary content may also influence a student's acceptance of evolution (Hawley et al., 2011). Hawley et al. (2011) found that exposure to evolution, both through self-exposure (e.g. documentaries, museums) and youth exposure (e.g. classroom experiences), was positively correlated to knowledge of evolution and negatively correlated to creationist reasoning. Dunk et al. (2017) found that the number of college biology courses that a student had completed was positively correlated with acceptance of evolution. Siciliano-Martina and Martina (2020) found that an online evolution course for non-majors did not impact reported religiosity, but did increase acceptance of evolution, demonstrating that exposure to evolutionary content may be enough to increase acceptance while other barriers remain unchanged.

Path analysis

The five predictors described above were shown to all impact evolution acceptance in various ways depending on the population and combination of variables included in the particular study. Typically, these studies used regression analyses to evaluate the relationship between one or more predictor variables and their impact on evolution acceptance. These analyses provide information about the direct relationship between one or more predictors and an outcome variable along with the possible correlations between the predictor variables. We propose there is a system of relationships to explore. In order to do this, we used path analysis to examine the direct and indirect relationships of the five predictor variables. Path analysis has several important benefits, first it allows the researcher to create a visual representation of the relationships in a system, second it allows us to estimate as many multiple regression analyses as needed to represent all the proposed relationships, and third it allows researchers to determine the causal and non-causal relationships within a model (Lleras, 2005).

Path analysis requires the creation of a theoretical model based on either previous research or theory (Lleras, 2005; Garson, 2008). To generate our theoretical model (Fig. 1), we reviewed evolution acceptance literature and determined five common variables that impact evolution acceptance as described above: religiosity, knowledge of the nature of science, knowledge of evolution, openness to experience, and number of science courses completed.

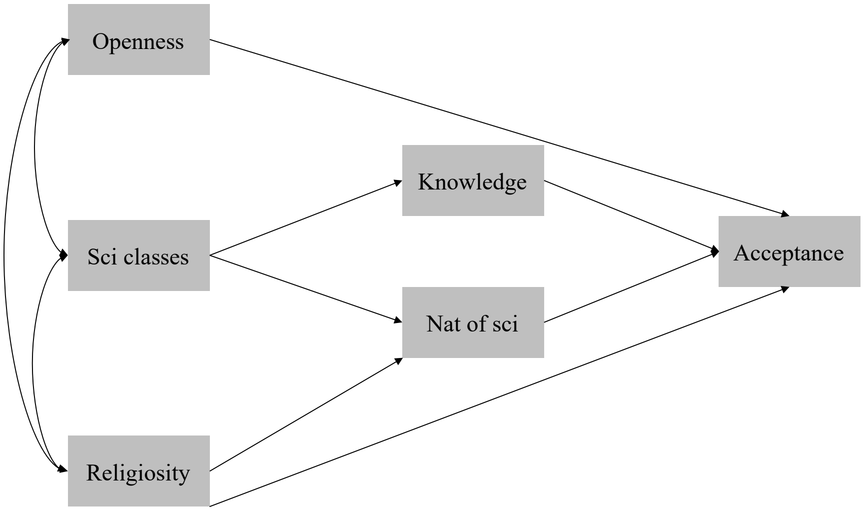

Figure 2.1. Theoretical path model for predictors of evolution acceptance. Curved arrows represent correlations, straight arrows represent direct and indirect causal relationships.

The reviewed literature also provided evidence for how these variables should be connected to one another and our endogenous variable of interest, evolution acceptance. In our model, we have three exogenous variables: religiosity, number of science classes, and openness to experience. These variables were not directly predicted by any other variables in our model but were allowed to correlate with one another. Our other predictor variables were knowledge of the nature of science and knowledge of evolution. All five of these variables had direct and/or indirect relationships with acceptance of evolution.

We used our theoretical model to test the following research questions:

1. Which of the chosen predictor variables have a significant causal relationship with acceptance of evolution?
2. Are these relationships consistent across different populations?

Methods

To test our hypothesized theoretical model of the direct and indirect relationships between five predictor variables (religiosity, number of science classes, openness to experience, knowledge of the nature of science, and knowledge of evolution) and a student's evolution acceptance, we followed methodology consistent with Dunk et al. (2017), except where noted. This previously published survey consists of the most commonly studied predictors of evolution acceptance and provided an opportunity for direct comparison between our student population and another large sample of undergraduate students from a different geographic region and institution type.

Study population and course context

We administered our survey (Modified Survey of Evolutionary Knowledge and Attitudes, Appendix 1) to 599 students enrolled in Human Anatomy and Physiology I at North Dakota State University in Fall 2017 (N = 335) and Fall 2018 (N = 264). This course primarily serves allied health major students and biology majors. The students were primarily female (72%), white (91%), health majors (78%), including nursing, pharmacy/pre-pharmacy, radiological sciences, and other health majors (Table 1). A large majority of students reported being Christian (79%), with a mixture of other religious identities including no religious affiliation (17%) (Table 1). We chose to sample from this course because it was similar to the course used in the Dunk et al. (2017) study, and it provided an opportunity to collect data from a different population than a typical introductory biology course for science majors.

Table 2.1. Demographics.

Variable			**NDSU**	**Dunk et al. 2017***
Major	Nursing/Pre-nursing		30%	28%
	Non-nursing health majors		48%	53%
		Pharmacy/Pre-pharmacy	15%	
		Exercise science	14%	
		Radiological sciences	9%	
		Other health majors	10%	
	Biology		13%	7%
	Other		10%	12%
	Total		591	224
Religious affiliation	Protestant (Lutheran, Baptist, Pentecostal)		36%	15%
	Catholic		30%	26%
	None (Atheist, Agnostic, None)		17%	37%
	Non-denominational Christian		13%	14%
	Other (e.g., Jewish, Muslim, Buddhist)		5%	8%
	Total		591	273
Importance of Church	1 (low)		22%	33%
	2		11%	26%
	3		19%	13%
	4		15%	7%
	5 (high)		33%	20%
	Total		581	276
Ethnicity	White		91%	67%
	Black		3%	7%
	Asian/Pacific Islander		2%	12%
	Hispanic		1%	7%
	Other		2%	7%
	Total		579	269

Table 1. Demographics (continued).

Variable		**NDSU**	**Dunk et al. 2017***
Sex	Female	72%	70%
	Male	28%	30%
	Total	598	284

Students completed a demographic questionnaire at the end of the Modified Survey of Evolutionary Knowledge and Attitudes. Percentages may sum to over or under 100 due to rounding, *Dunk et al., 2017 from University of Wisconsin-Milwaukee

Procedure

In order to reach a large sample of students, we administered the survey during two separate semesters of the Human Anatomy and Physiology I Lab course. In Fall 2017, students were allotted 40 minutes to complete a paper version of the survey during class time. In Fall 2018, class time was limited, and the instructor asked us to distribute the survey outside of class, so students completed a digital version of the survey using the survey platform Qualtrics (265 students completed the survey out of 350 enrolled in the course, 76% response rate). In the online survey, students were not given a time limit, but 79% of the students completed the survey in 40 minutes or less. During both semesters, students received a 5-point bonus in class for completing the consent form page of the survey and were then able to choose whether or not they wanted to complete the entire survey.

The paper survey responses were entered into a secure online database file by two of the researchers (RLSH and undergraduate researcher MR). After entering the responses, one researcher (RLSH) completed random checks to ensure that student responses were entered correctly. Before merging the paper and online survey responses, we evaluated a multi-group model of the two versions of the survey. When we constrained the parameters to be equal between the paper and online administrations, the model fit did not significantly worsen (Satorra-Bentler chi-squared difference test: $\chi^2(8) = 19.23773$, $p = 0.0570$). This indicated that we could combine the survey responses into one data set. All other analyses in this paper were completed using a pooled data set of both the paper and online administrations of the survey.

Measures

Our instrument consisted of six previously published surveys and a demographic questionnaire (Table 2). The order of the six surveys was purposeful to reduce survey order effects including priming (McFarland, 1981; Strack, 1992) and followed Dunk et al. (2017) with the addition of the Conceptual Inventory of Natural Selection (CINS, Anderson et al., 2002) to our survey.

Knowledge of evolution (Knowledge)

To assess knowledge of evolution (Knowledge), we included two measures: a terms index (Barone et al., 2014) and the Conceptual Inventory of Natural Selection (CINS, Anderson et al., 2002). The terms index consists of a 28-word checklist that was developed to study evolution acceptance among visitors to the Milwaukee Public Museum (Barone et al., 2014; Dunk et al., 2017). The checklist contained a range of terms from common (fossil, evolution) to more scientific terms (Scopes trial, Cenozoic Era). Students were asked to mark words they were familiar with and then the number of words selected were added together to create an overall score. We modified the Dunk et al., (2017) survey by using an additional survey of student knowledge of evolution, the Conceptual Inventory of Natural Selection (CINS, Anderson et al., 2002). The CINS is a concept inventory developed for use with non-major undergraduate students to assess understanding of natural selection (Anderson et al., 2002). It consists of 20 multiple choice questions covering 10 key concepts with 2 questions for each topic (e.g. origin of variation, variation inheritable, differential survival). A score was calculated based on the number of correct answers a student provided from 0-20 correct. To determine if the terms index and CINS performed similarly in our theoretical model, we compared the standardized path coefficients in a model with the terms and in a model with the CINS. All the path coefficients were within 0.01 decimal places, most with differences smaller than the thousandths place. We therefore used only the terms index in all additional analyses. This allowed us to compare our results from NDSU to data collected from the University of Wisconsin-Milwaukee (Dunk et al., 2017).

Acceptance of evolution (Acceptance)

To measure student acceptance of evolution (acceptance), we used the Measure of the Acceptance of the Theory of Evolution (MATE, Rutledge and Warden 1999, 2000). The MATE is one of the most commonly used instruments to measure acceptance of evolution and has been used with a range of populations from high school teachers to undergraduate students (Rutledge and Sadler, 2007; Barone et al., 2014; Carter and Wiles, 2014; Dunk et al., 2017). The MATE has 20 5-point Likert items (1-disagree strongly, 3-neither agree or disagree, 5-agree strongly) and includes topics on evidence for evolution, scientific consensus on evolution, and understanding of the age of the earth. A score is calculated by summing student responses from each question with a possible range of 20-100.

Religiosity

We measured religiosity by using the Evolutionary Attitudes and Literacy Survey - Short Form (EALS-SF; Short and Hawley, 2012). The survey was developed for use with undergraduate students from diverse majors. We administered the full instrument; however, Dunk et al., (2017) used three questions from the "Religious Activity" subscale to measure religiosity: 1) My religion impacts my daily life, 2) My religion influences my decisions, and 3) I am a religious person. We added the additional missing item in our analysis to have a complete version of the original subscale, 4) Religion is especially important to me because it answers many of my questions about the meaning of life. The questions were 5-point Likert items (1-disagree strongly, 3-neither agree or disagree, 5-agree strongly), and a score was calculated by summing student responses for a possible range of 4-20.

Openness to experience (Openness)

We administered the Big Five Inventory (BFI, John et al., 2008) to measure a student's openness to experience (openness). The instrument measured five aspects of personality (openness to experience, conscientiousness, extraversion, agreeableness, and neuroticism) and consists of 44 general statements about personality that begin with "I see myself as someone who…" followed by various statements (e.g., is curious about many different things, is easily distracted). Students used a 5-point Likert scale to respond to each statement (1-disagree strongly, 3-neither agree or disagree, 5-agree strongly). Again, we gave the full instrument following the Dunk et al. (2017) methodology. The analysis only included the openness to experience scale which consists of 10 questions with a score ranging from 10-50.

Knowledge of the nature of science (Nature of science)

To measure student knowledge of the nature of science (nature of science) we used the Understanding of Science instrument designed by Johnson and Peeples (1987). This particular instrument has been used to compare student knowledge of the nature of science in conjunction with evolution acceptance in both college students (Johnson and Peeples, 1987; Dunk et al., 2017) and more recently with high school teachers (Rutledge and Warden, 2000; Trani, 2004; Glaze et al., 2015). The instrument consists of 20 5-point Likert questions (1-disagree strongly, 3-neither agree or disagree, 5-agree strongly) with topics including hypothesis testing, direct observations, and how science and religion interact. A score was calculated by summing student responses with a range from 20-100.

Number of science classes (Science classes)

In addition to knowledge, we also included the Number of science classes (science classes) that a student had completed (Dunk et al., 2017). This number serves as a proxy for exposure to scientific content that may or may not have included specific evolution instruction. This number was collected as a free-response question in the demographic questionnaire portion of our instrument. If a student reported a range of completed courses, the lower number was used in our analysis.

Table 2.2. Variables measured and sources.

Variable measured	Name of survey instrument	Source	Portion used
Knowledge of evolution (Knowledge)	Familiarity with Evolutionary Terms	Barone et al., 2014	Full*
Acceptance of evolution (Acceptance)	Measure of the Acceptance of the Theory of Evolution (MATE)	Rutledge and Warden, 1999	Full
Religiosity	Evolutionary Attitudes and Literacy Survey – Short Form (EALS-SF)	Short and Hawley, 2012	Religious activity subscale
Openness to experience (Openness)	Big five inventory	John et al., 2008	Openness to experience subscale
Knowledge of the nature of science (Nature of science)	Understanding of science	Johnson and Peeples, 1987	Full
Number of science classes (Science classes)	--	Dunk et al., 2017	Reported science classes

*One word missing from online distribution, 27 out of 28 words used in analysis

University of Wisconsin-Milwaukee data

We used data from two samples of students in the current study, one from NDSU and one from previously collected data from the University of Wisconsin-Milwaukee (UWM) (doi:10.6084/m9.figshare.5072137; Dunk et al., 2017). Dunk et al. (2017) surveyed students enrolled in an introductory anatomy and physiology course (n=284) with an identical instrument as used in our analyses. We used a multi-group model approach to compare the direct and indirect relationships between the five variables and student acceptance of evolution in both populations.

Statistical analysis

We conducted a path analysis using Mplus version 8.4 (Muthén & Muthén, 1988–2017) to test a theoretical model of the direct and indirect relationships between five predictor variables of evolution acceptance (religiosity, science classes, openness, nature of science, and knowledge) and a student's reported evolution acceptance. One of our predictor variables was skewed (number of science classes), so we used maximum likelihood (MLR) for parameter estimation. We examined model global fit statistics for statistical significance and adequate fit of the final model (Kline, 2011; χ^2 $p \geq 0.05$, RMSEA ≤ 0.06, CFI ≥ 0.95, TLI ≥ 0.95, SRMR ≤ .08 for good fit; Marsh, Hau, & Wen, 2004).

Results

Summary statistics

The average score on the MATE was 78.3 (SD = 10.63, Rutledge and Sadler, 2007; Table X. Number of respondents in each category of evolution acceptance). Scores on the MATE ranged from 40 to 98, with the majority of students falling between the moderate and high levels of evolution acceptance (Table 3).

Table 2.3. Number of respondents in each category of evolution acceptance.

Acceptance Level	Score	Number of respondents
Very low	20-52	12
Low	53-64	42
Moderate	65-76	169
High	77-88	258
Very high	89-100	98

Acceptance level and corresponding score as defined in Rutledge and Sadler, 2007; number of respondents from NDSU-pooled data

Student scores on the Familiarity of Evolutionary Terms checklist ranged from 3 to 27 words (Table 4). Scores on the knowledge of the nature of science were moderate with scores ranging from 52 to 91, but a larger portion of students in the moderate level (Table 4). The mean religiosity score was 13.41 and there was a range of responses from 4 to 20. Students scored moderately on openness to experience, with scores ranging from moderate to high. Students reported a large range of science classes taken (1-40; mean = 7).

Table 2.4. Summary statistics for theoretical model variables.

Variable	Mean	St. dev	Minimum (min. possible)	Maximum (max. possible)
Acceptance	78.3	10.63	40 (20)	98 (100)
Knowledge	14.96	4.35	3 (0)	27 (27)
Religiosity	13.41	4.78	4 (4)	20 (20)
Openness	35.35	4.83	23 (10)	49 (50)
Nature of science	66.38	6.36	52 (20)	91 (100)
Science classes	7.06	5.08	1	40

Mean and st. dev for each variable from NDSU-pooled data; Minimum and maximum score for each variable from NDSU-pooled data, along with the minimum and maximum number based on the type of measure or question

Overall, students had a moderate to high level of evolution acceptance, moderate level of evolution content knowledge and knowledge of the nature of science, were typically Christian with a high religiosity score, a moderate level of openness to experience, and had taken several college science courses.

Correlation matrices

All correlations among variables were tested and shown in the three tables below, NDSU pooled data (Table 5), UWM data (Table 6), and UWM and NDSU multi-group model data (Table 7). In all three sets, religiosity had the largest correlation with acceptance, followed by nature of science and knowledge. In the NDSU pooled data, religiosity had a negative correlation with all variables (Table 5). In the UWM data, religiosity had a negative correlation with all variables except openness to experience (Table 6). In the UWM and NDSU multi-group model, religiosity had a negative correlation with acceptance, knowledge of evolution, and knowledge of the nature of science (Table 7). All other relationships were positively correlated.

Table 2.5. NDSU pooled data correlation matrix.

NDSU, pooled	Acceptance (10.497)	Knowledge (4.291)	Religiosity (4.778)	Openness (4.865)	Nature of science (6.194)	Science classes (4.815)
Acceptance	1.000	0.273	-0.456	0.154	0.366	0.216
Knowledge		1.000	-0.064	0.275	0.255	0.282
Religiosity			1.000	-0.063	-0.140	-0.084
Openness				1.000	0.034	0.183
Nature of science					1.000	0.214
Science classes						1.000

Table 2.6. UWM data correlation matrix.

UWM	Acceptance (12.617)	Knowledge (4.083)	Religiosity (5.013)	Openness (5.600)	Nature of science (6.863)	Science classes (4.043)
Acceptance	1.000	0.336	-0.524	0.230	0.532	0.251
Knowledge		1.000	-0.115	0.230	0.342	0.260
Religiosity			1.000	0.072	-0.252	-0.029
Openness				1.000	0.267	0.177
Nature of science					1.000	0.340
Science classes						1.000

Table 2.7. UWM and NDSU multi-group model correlation matrix.

UWM+NDSU	Acceptance (11.253)	Knowledge (4.233)	Religiosity (5.016)	Openness (5.135)	Nature of science (6.483)	Science classes (4.754)
Acceptance	1.000	0.299	-0.462	0.182	0.431	0.225
Knowledge		1.000	-0.089	0.253	0.288	0.260
Religiosity			1.000	0.007	-0.211	0.011
Openness				1.000	0.108	0.183
Nature of science					1.000	0.209
Science classes						1.000

Model fit

Theoretical model

Our theoretical model can be found in Figure 1. To test our theoretical model we used the NDSU-pooled data set. We found that our initial theoretical model provided a poor fit to the data ($\chi 2(5)=63.401$, *p*<0.0001 Scaling factor=1.0771, RMSEA = 0.140, CFI = 0.835, TLI = 0.604, SRMR = 0.064, Table 8).

Table 2.8. Model fit statistics + modifications.

Global fit statistic	Good	Theoretical Model	+ path O → K	+ cov N ↔ K
χ2	Small, NS	χ2(5)=63.401, p<0.0001 Scaling factor=1.0771	χ2(4)=33.222, p<0.0001 Scaling factor=1.0922	χ2(3)=4.158, p=0.2449 Scaling factor=1.1051
RMSEA	≤.06	0.140	0.110	0.025
CFI	≥.95	0.835	0.917	0.997
TLI	≥.95	0.604	0.752	0.987
SRMR	≤.08	0.064	0.046	0.014

Acceptable global fit statistics shown under the “Good” fit, Theoretical model and two model adjustments shown

To improve the poor model fit, we reviewed the modification indices that were above 10 (Table 9) and the normalized residuals for covariances that were above 2 (Table 10). The largest MIs and the largest normalized residual covariance indicated that the correlation between knowledge and openness was stronger than was accounted for by the initial model. Because a direct effect of openness on knowledge is plausible (DeYoung et al., 2005; Silvia and Sanders, 2010), the model was modified by adding a path from openness to knowledge.

Table 2.9. Theoretical model modification indices greater than 10.

Parameter	MI	EPC
Knowledge ON Openness	28.584	0.200
Openness WITH Knowledge	28.472	4.519
Knowledge ON Nature of science	25.932	0.149
Nature of science WITH Knowledge	25.856	5.540
Nature of science ON Knowledge	25.854	0.319
Science classes WITH Knowledge	20.971	-19.712

All modification indices above 10 shown

Table 2.10. Theoretical model normalized residual for covariances.

	Knowledge	Acceptance	Nature of science	Religiosity	Openness	Science classes
Knowledge	–0.001					
Acceptance	1.733	0.386				
Nature of science	**4.632**	0.670	–0.070			
Religiosity	–0.382	–0.067	0.099	0.002		
Openness	**5.248**	0.716	–0.255	–0.026	0.009	
Science classes	–0.139	1.267	–0.233	0.006	–0.164	–0.038

NCRs > 2 in bold, NCRs above 2 indicates a correlation that is higher than what is explained by the current model

Revised theoretical model

Adding a direct path from openness to knowledge improved model fit ($\chi2(4)=33.222$, $p<0.0001$ Scaling factor=1.0922, RMSEA = 0.110, CFI = 0.917, TLI = 0.752, SRMR = 0.046; Table 8) and the direct effect from openness to knowledge significantly improved the model fit over the initial model (Satorra-Bentler scaled chi-squared difference test: $\chi^2(1)=31.47846$, $p=2.016652E–08$). However, the revised model was still not a good fit to the data. We again reviewed the modification indices that were above 10 (Table 11) and the normalized residuals for covariances that were above 2 (Table 12).

Table 2.11. Revised theoretical model modification indices.

Parameter	MI	EPC
Nature of science WITH Knowledge	27.731	5.625 (STDYX=0.228)
Knowledge ON Nature of science	27.543	0.150 (STDYX=0.220)
Nature of science ON Knowledge	25.650	0.320 (STDYX=0.218)

MIs above 10 shown

Table 2.12. Revised theoretical model normalized residual for covariances.

	Knowledge	Acceptance	Nature of science	Religiosity	Openness	Science classes
Knowledge	0.000					
Acceptance	1.416	0.316				
Nature of science	**4.634**	0.668	–0.070			
Religiosity	–0.239	–0.046	0.099	0.001		
Openness	0.008	–0.066	–0.233	0.003	0.002	
Science classes	–0.092	1.282	–0.211	0.017	–0.065	–0.027

NCRs > 2 in bold, NCRs above 2 indicates a correlation that is higher than what is explained by the current model

Based on the MIs above 10 and the normalized residual covariance > 2, the relationship between knowledge of evolution and understanding the nature of science was stronger than what was accounted for by the revised model. Since we are not hypothesizing a direct effect between them, we modified the revised model to include a residual correlation between knowledge and nature of science.

The final model had excellent fit with the NDSU-pooled data ($\chi 2(3) = 4.158$, $p = 0.2449$ Scaling factor = 1.1051, RMSEA = 0.025, CFI = 0.997, TLI = 0.987, SRMR = 0.014; Table 8). Adding the residual covariance between knowledge and nature of science significantly improved the model fit compared to the model with the O->K path (Satorra-Bentler scaled chi-squared difference test: $\chi^2(1) = 30.08074$, $p =$ 4.144262E–08). For the final model, there were no modification indices above 10 and no normalized residuals for covariances greater than 2.

Multiple-group model

To ensure that our final revised model was robust and could expand beyond our own student population, we created a final multiple-group model using publicly available data from the University of Wisconsin-Milwaukee (UWM, Dunk et al., 2017; doi:10.6084/m9.figshare.5072137). Initially, the multiple-group model had poor model fit (χ2(6) = 28.485, *p* < 0.0001 Scaling factor = 1.0506, RMSEA = 0.092, CFI = 0.962, TLI = 0.848, SRMR = 0.039; Table 13). We followed the same procedure as above to modify our model, evaluating the modification indices and normalized residual covariances for both of the groups (NDSU and UWM).

Table 2.13. Multiple-group model fit statistics + modifications.

Global fit statistic	Good	Initial multiple-group model	+ path O → N for UWM
χ2	Small, NS	χ2(6) = 28.485, *p* < 0.0001 Scaling factor = 1.0506	χ2(5) = 11.535, p = .0417 Scaling factor = 1.0719
RMSEA	≤.06	0.092	0.054
CFI	≥.95	0.962	0.989
TLI	≥.95	0.848	0.947
SRMR	≤.08	0.039	0.024

Global fit statistic comparisons to unconstrained initial multiple-group model and final model with additional UWM path

The MIs and NRCs were all below the threshold for the NDSU group, which would be expected because this data set was used to fit our final revised model. There were several MIs greater than 10 for the UWM group. They all related to nature of science, but were all equivalent, so this was not enough information to decide on an appropriate change to the model (Table 14). There was one NRC above 2, between nature of science and openness (Table 15). This indicated that the correlation between nature of science and openness was stronger than what was explained by the initial multiple-group model. As with the relationship between openness and knowledge, a relationship between openness and nature of science is supported by the literature, so we chose to add a direct path from openness to the nature of science (DeYoung et al., 2005; Silvia and Sanders, 2010).

Table 2.14. Initial multiple-group model modification indices for UWM.

Parameter	MI	EPC
Openness WITH Nature of science	16.099	8.442 (STDYX=)
Science classes WITH Nature of science	16.098	–34.025 (STDYX=)
Nature of science ON Openness	16.090	0.283 (STDYX=)
Religiosity WITH nature of science	16.089	–102.160 (STDYX=)
Nature of science ON knowledge	15.969	2.993 (STDYX=)

All MIs above 10 for UWM

Table 2.15. Initial multiple-group model normalized residual for covariances for UWM.

	Knowledge	Acceptance	Nature of science	Religiosity	Openness	Science classes
Knowledge	0.155					
Acceptance	1.417	0.518				
Nature of science	0.952	0.752	0.106			
Religiosity	–1.980	–0.379	–0.405	0.000		
Openness	0.934	1.321	**4.084**	–0.057	0.002	
Science classes	0.000	0.879	–0.004	–0.001	0.011	0.000

NCRs above 2 bolded, NCRs above 2 indicates a correlation that is higher than what is explained by the current model

The final multiple-group model had good fit with the NDSU and UWM data (χ2(5) = 11.535, *p* = 0.0417 Scaling factor = 1.0719, RMSEA = 0.054, CFI = 0.989, TLI = 0.947, SRMR = 0.024; Table 13). There were no additional MIs above 10 for either group and there were no NCRs greater than 2 in the NDSU group. The UWM group did have one additional NCR above 2, religiosity and knowledge was –2.040 for the UWM model, however we did not make any additional changes to the model.

Final multiple-group model results for NDSU and UWM

All of the predictors used in the final multiple-group model had a significant causal effect on evolution acceptance in both groups (Fig. 2). Religiosity had an inverse relationship with acceptance and had the largest total effect on acceptance in both groups (β = –0.442, –0.533; Table 16; Fig. 2). Nature of science (β = 0.279**,** 0.337) was the second largest predictor of evolution acceptance in both groups. In the

NDSU group, knowledge (β = 0.168) was the third largest predictor and was not significantly different from nature of science (Wald test, χ2(1) = 3.330, *p* = 0.0680). In the UWM group, the third largest predictor was openness (β = 0.245), followed by knowledge (β = 0.131) and science classes (β = 0.129). In the NDSU group, the final two predictors were science classes (β = 0.108) and openness (β = 0.092). These final two predictors were also not significantly different from one another in the NDSU group (Fig. 3; Wald test, χ2(1) = 0.126, *p* = 0.7223).

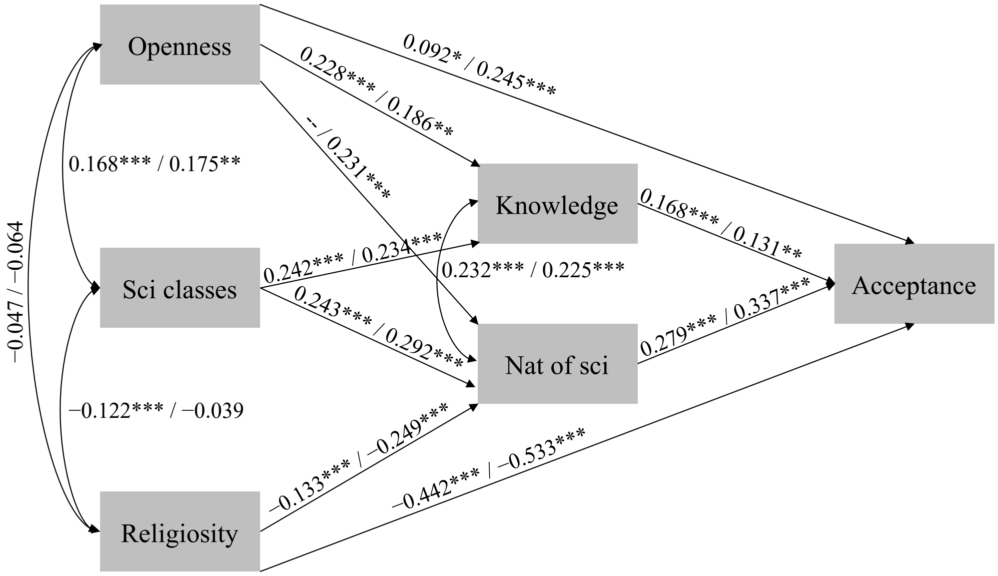

Figure 2.2. The full empirical path model for predictors of evolution acceptance. Total and indirect effects (β) shown on arrows, **p* ≤ 0.05, ***p* ≤ 0.01, ****p* ≤ 0.001.

Table 2.16. Total effects for final multiple-group model with NDSU and Dunk et al., 2017.

	NDSU				**Dunk et al., 2017**			
	β	Std error	95%CI	*p*	β	Std error	95% CI	*p*
Knowledge	**0.168**	0.039	0.092 0.244	0.000	**0.131**	0.043	0.047 0.215	0.002
Religiosity	**–0.442**	0.032	–0.505 –0.379	0.000	**–0.533**	0.043	–0.617 –0.449	0.000
Openness	**0.092**	0.040	0.014 0.170	0.021	**0.245**	0.047	0.153 0.337	0.000
Nature of science	**0.279**	0.037	0.206 0.352	0.000	**0.337**	0.062	0.215 0.459	0.000
Science classes	**0.108**	0.021	0.067 0.149	0.000	**0.129**	0.033	0.064 0.194	0.000

95% CI computed from β±1.96*SE

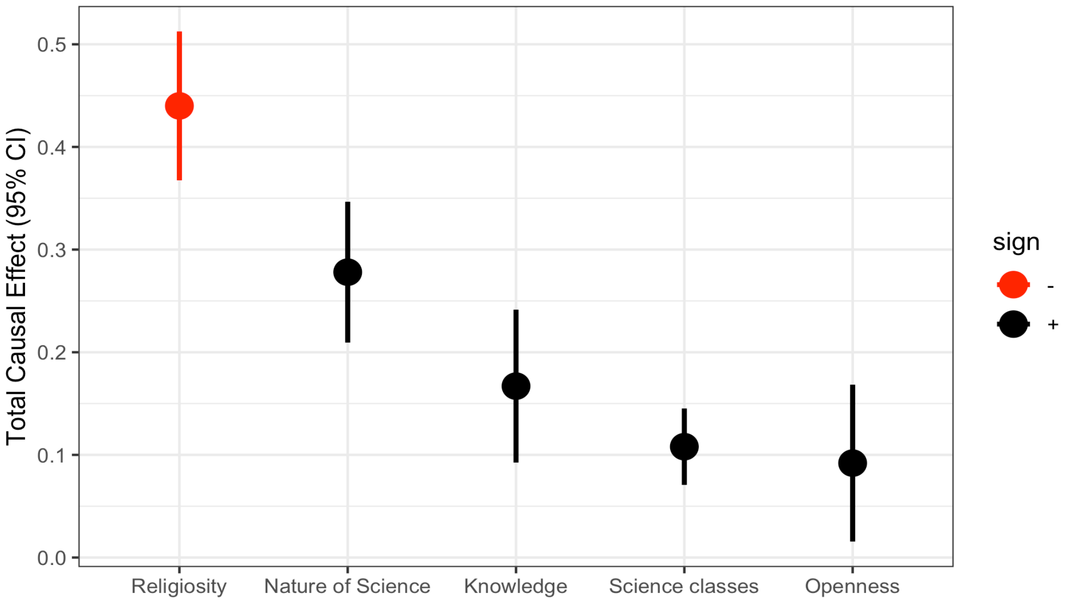

Figure 2.3. NDSU final model total causal effect comparison. 95% confidence intervals were constructed by taking the estimated total causal effect ± 1.96*standard error.

Discussion

Over the last several decades numerous studies have evaluated the relationship between sociocultural and cognitive predictors that impact a person's level of evolution acceptance (e.g. Bishop and Anderson, 1990; Glaze and Goldston, 2015; Dunk et al., 2017). We used path analysis to take a systems view of this question and test our theoretical model of five predictors of evolution acceptance (religiosity, knowledge of evolution, nature of science, openness, and number of science classes). First, we found that our student acceptance of evolution fell within the lower range of a high level of acceptance (Rutledge and Sadler, 2007; Table 3). This differs from the typical reportedly low level of acceptance found in the general public (Gallup, 2019) where survey questions are limited to human evolution but is similar to other studies of undergraduates (Dunk et al., 2017) and research of the general public where the survey questions were updated from the traditional Gallup Poll options (Weisberg et al. 2018).

Our theoretical model had a poor fit with the NDSU population. We reviewed the modification indices and normalized covariance residuals and added an additional path from openness to experience to knowledge of evolution (DeYoung et al., 2005; Silvia and Sanders, 2010) and a correlation between knowledge of the nature of science and knowledge of evolution. Additionally, in our multiple-group model, the UWM group required an additional path from openness to experience to knowledge of the nature of science (DeYoung et al., 2005; Silvia and Sanders, 2010). The revised models both had excellent fit with the data. In our final multiple-group model, four of our chosen predictors (knowledge, religiosity, openness, and nature of science) had a direct significant causal effect on evolution acceptance. Our fifth predictor, number of self-reported science classes that a student completed, had multiple significant indirect effects on evolution acceptance.

Religiosity had a large, negative impact on acceptance

Religiosity had the largest total causal effect on evolution acceptance and was an inverse relationship: the higher a person's reported religiosity, the lower their acceptance of evolution. Notably, this was the largest predictor in both populations in our multiple-group model, whereas in the original Dunk et al. (2017) study, nature of science was the largest predictor. In the Dunk et al. (2017) study, the final ANCOVA reported the relationship between evolution acceptance and one of the four religiosity questions in the Hawley et al. (2011) scale: "My religion influences my decisions". In our model, we used all four questions from the religiosity scale, which provides a more holistic view of the student's religious activities and may be the reason we captured a larger impact of religiosity on student acceptance of evolution. Religiosity also had an indirect significant negative path to evolution acceptance through knowledge of the nature of science in both populations. Finally, religiosity had a significant negative correlation with number of science classes for the NDSU population.

Understanding the nature of science and evolution content knowledge increase acceptance

Our second largest predictor in both populations was knowledge of the nature of science. Knowledge of the nature of science relates to a student's ability to understand the process of science and interpret the evidence for scientific findings such as evolution (Lombrozo et al., 2008). Our results further validate the importance of focusing on improving student understanding of the nature of science, similar to other recent evolution education literature (Dunk et al., 2019; Weisberg et al., 2021). In our model, knowledge of the nature of science was negatively predicted by religiosity and positively impacted by the number of science courses that a student had completed. It was also positively correlated with knowledge of evolution. Together these relationships imply that as a student moves through their academic career, they are gaining skills in understanding the process of science, leading to a higher level of acceptance of evolution. This reinforces findings from Akyol et al. (2012) where nature of science positively predicted acceptance of evolution, but the model did not include any predictors of nature of science. Our research helps clarify the relationship between academic career and religiosity with the knowledge of the nature of science, but more work needs to be done to determine what factors may predict both knowledge of the nature of science and knowledge of evolution outside of number of science courses and religiosity.

Knowledge of evolution and the number of science classes completed both had significant positive impacts on acceptance of evolution. The number of science classes had two indirect paths through knowledge and nature of science to student acceptance of evolution. Our theoretical model did not include a direct path from the number of science courses completed and acceptance because we hypothesized that simply being in a science class would not directly impact acceptance; instead, the improvement in understanding the nature of science and course curriculum that included evolution would work together to improve a student's acceptance of evolution. Knowledge of evolution did have a direct path to acceptance of evolution, and this was significant in both populations in our final multiple group model. Although it was the third and fourth largest predictor respectively in the NDSU and UWM populations, it is still an important predictor in explaining a student's evolution acceptance. Following work from Ziadie and Andrews (2018), curriculum that moves beyond natural selection and includes more evolutionary concepts (e.g. genetic drift, gene flow, sexual selection) is key to continuing to improve student understanding of evolution which will positively impact their acceptance of evolution.

Geographic location may impact acceptance

Only one of our predictors differed in our multiple-group model, openness to experience. In both groups, our original direct path from openness to experience and acceptance of evolution and the indirect path from openness to knowledge of evolution had significant positive causal effects. However, in the UWM population, we also had to add an additional path from openness to knowledge of the nature of science. Openness had the lowest total causal effect for the NDSU population but was the third largest in the UWM population. We believe one explanation for these differences relate to the geographic region of our populations, urban versus rural. The NDSU population comprises students from primarily rural areas of North Dakota and Minnesota with a total population of 124,662 in Fargo, whereas the UWM population has a larger student body from a larger area with a total population of 590,157 in Milwaukee (QuickFacts, 2019). Students at UWM have more access to scientific community programs (i.e. science museums and exhibits), whereas students at NDSU have limited to no access to these types of programs unless they travel to larger areas. Our model provides evidence that students with more access to extracurricular and outreach science opportunities may have an increase in their acceptance of evolution, which supports current efforts in Fargo to create a science museum and expand programs at the university that benefit the local community population. This finding also emphasizes the importance of testing our model with more diverse populations. Even though our two populations do differ in population size, they are still both midwestern moderately sized institutions and we do not know if these patterns will be the same in much larger or much smaller universities.

Conclusion

While religiosity had the largest causal effect in our final multiple-group model, knowledge of evolution and understanding of the nature of science had the second largest effect and were not statistically significantly different from one another. This indicates that classroom instruction about evolution content knowledge and the process of science are essential components of increasing acceptance of evolution in university students. Currently, there are resources for educators that focus on religious cultural competency in the classroom (e.g. Barnes and Brownell, 2017; Barnes et al., 2020), which can provide a bridge of trust between religious students and instructors when learning new scientific content. Instructors who utilize this strategy will still require improved curriculum, specifically curriculum focused on a systems view of evolution. We are encouraged by our findings that as students take more science courses and improve their understanding of the nature of science, they have an increased acceptance of evolution. We also believe more research to understand the opportunity to leverage student’s openness to experience to improve acceptance of evolution will be important, along with an expansion of data collected from rural and urban colleges to determine if these relationships are present in varied populations.

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CHAPTER 3. DEVELOPMENT AND IMPLEMENTATION OF A RAPID RESPONSE RUBRIC: 3R EVOLUTION

Introduction

Background

Natural selection is an essential, but commonly misunderstood, topic in introductory biology (Bishop and Anderson, 1990; Anderson et al., 2002; Nehm and Schonfeld, 2008; Novick et al., 2014). Research on student difficulties with natural selection has proliferated over the last four decades (Glaze, 2015; Ziadie and Andrews, 2018) and validated curricular tools that effectively address these issues are more readily available for undergraduate instructors than ever before (e.g. CourseSource.org, NABT's American Biology Teacher journal). A literature review of topics investigated by evolution education researchers revealed that natural selection is often the subject of interest (Ziadie & Andrews, 2018). Despite copious research and implementation ideas, students still leave our classrooms with limited or fragmented understanding of natural selection (Bray Speth et al., 2009; Barnes et al., 2017; Harding et al., 2020).

Natural selection is an emergent process where processes at the cellular level create organisms that interact at the population level and are influenced by a particular ecosystem, all without any central controlling agent at work (Mitchell, 2009; Cooper, 2017). A classic example of an emergent process can be found in Boag and Grant (1981) and Grant and Grant's (2003) seminal work where they describe the shift in Darwin's finches beak size from 9.44mm to 9.96mm in response to seeds available during a drought. The 6% change in beak size was not due to any particular centralized force, but rather an emergent process: the interactions between the individual birds, their reproductive success and survival, and their current environment (Boag and Grant, 1981; Grant and Grant, 2003; Cooper, 2017). This process has no endpoint or in this case, a perfect beak size, as evidenced by an El Niño event 6 years later that lead to smaller beaks being favorable (Grant and Grant, 2003). Chi (2005) proposed that these emergent processes, like natural selection, are particularly difficult for students to understand because students tend to miscategorize them as having an external directing force. This mindset leads to common misconceptions about natural selection, including the idea that a perfect "end-goal" for particular organisms exists and that natural selection is goal-driven to help species survive in various conditions (Al-Shawaf et al., 2018).

Natural selection is also challenging to students because it requires them to incorporate key principles across multiple biological levels (Catley et al., 2005; Catley & Novick, 2009). These levels range from the microscopic (genetic, cellular, protein) to macroscopic (organism, population, species; Tsui and Treagust, 2013; Göransson et al., 2020). In addition, these key principles are not equally understood by students. For example, students tend to include the key principle of inheritance less often than variation in written responses about natural selection, demonstrating a lack of understanding of the underlying genetic components that are involved (Göransson et al., 2020). Students must also contend with the various context effects of natural selection prompts (Nehm and Ha, 2011; Nehm et al., 2012; Federer et al., 2015; Heredia et al., 2016). For example, in a large study of undergraduates, Federer et al. (2015) found that students included more scientifically normative elements in their responses when the item described a familiar animal than when items contained unfamiliar animals or plants. These documented student difficulties with natural selection have led to a large body of research and evidence-based pedagogy. While there is an abundance of pre-made curriculum for natural selection available to instructors, there is still a disconnect between the curriculum instructors use and what students know about natural selection.

Feedback

Many of these ready-made curriculum pieces may be missing a critical element, iterative feedback to the student during the learning process. Feedback is essential for improving student understanding of evolution because it can directly combat the persistent misconceptions students have while learning about evolution (Bishop and Anderson, 1990; Chi et al., 2012). Historically, feedback has been transmissionist: the instructor simply tells the learner what they need to know (Nicol and Macfarlane-Dick, 2004). However, learning theories posit that students learn when they construct their own knowledge; thus, constructivist assessment and feedback should lead to increased understanding of content knowledge (Yorke, 2003; Irons, 2007; Gedye, 2010). Formative assessments are one way to generate feedback for students during the learning process. These activities produce feedback for the student that can improve performance and speed the learning process (Sadler, 1998). High quality feedback requires: 1) the instructor to provide the ideal solution to the student, 2) the instructor to tell the student what they did wrong or what is missing from their work, and 3) the instructor to guide the student with written or verbal communication about how to fix their answer and get it closer to the ideal answer (Nicol and Macfarlane-Dick, 2006; Hattie and Timperley, 2007). There has been an increase in the use of formative assessments and active learning over the course of the last decade, with benefits for all students enrolled in STEM courses (Freeman et al., 2014) and especially for under-represented minorities (Theobald et al., 2020). However, the number of courses individual instructors are responsible for and the number of students enrolled in those courses continue to rise (Pardo et al., 2019), bringing with it a question as the whether or not open-response formative assessments and individualized feedback are sustainable processes in large-enrollment courses.

Rubrics

One tool that can help instructors provide high quality feedback to a large number of students is rubrics. Rubrics became popular in the 1980s when standards-reform efforts began in order to help students move away from the simple memorization of facts to critical thinking (Brookhart, 2013) and are now commonplace in all levels of K-16 education (Brookhart and Chen, 2015). Rubrics provide a framework for students to judge their own work or the work of others in a peer-evaluation or group work scenario (Tai et al., 2018; Panadero et al., 2019). Rubrics can also help novice instructors feel more comfortable in the classroom. Timmerman et al. (2011) found that a universal rubric for scientific writing eased the grading for graduate student teaching assistants and provided a learning tool for both the TAs and the students. One criticism of rubrics is the potential to train students to match a particular set of standards without providing the background knowledge or ability for them to reason through the material on their own (Torrance, 2007; Gyamfi et al., 2021). Andrade and Du (2005) found that undergraduates reported using rubrics as a guide for certain instructors “demands”, but that many students also reported using them to guide or reflect on the general standards of the subject material. Another common criticism is the direct tie between a rubric and the points that a student can earn on a particular assignment, but the focus of a constructivist rubric should be on the development of knowledge (Popham, 1997; Andrade and Du, 2005). By altering the focus from the number of points available to the use of concepts and skills, rubrics become a teaching tool rather than a grading scheme for students (Knowledge, 2020). The ability to use rubrics for assessment purposes and to promote learning by making the objectives transparent for the students continue to make them an excellent tool in higher education classrooms (Jönsson and Panadero, 2017).

An important function of rubrics in a large-enrollment classroom is the ability to provide individualized feedback on open-response items to students in a short amount of time. An instructor can use the sections of a rubric to leave short text or symbols without having to write additional, often time-consuming, comments on student documents (Nordrum et al., 2013). Rubrics can also be paired with machine-learning, eliminating the need for an instructor to read through each student response individually (Ha et al., 2011; Nehm et al., 2012). In the current study, the instructor used the rubric to provide written feedback to the students without the use of machine-learning, but a similar rubric has shown promise with that technique.

To mitigate student misconceptions and incorrect ideas about natural selection we used feedback as our framework for Study 1 to develop a rapid response rubric that focuses on evolution by natural selection (3R: Evolution) for our undergraduate biology classrooms. Along with creating a curriculum that focused on high quality feedback, we also wanted to meet the challenge of the ever-increasing number of students enrolled in a typical undergraduate biology course. Therefore, the focus of Study 2 is to determine how our rubric can provide direct and actionable feedback to help students modify their understanding of evolution in large-enrollment courses.

Specifically, we address the following research goals and questions:

1. Develop and evaluate the use of a rubric to promote student learning of natural selection that can be used across prompt styles (essay, model) and contexts (3R: Evolution).
2. When using the 3R: Evolution, how many key principles of natural selection do undergraduates enrolled in Introductory Biology II (Biol 151) include in their responses, both before and after instruction?
3. Which key principles do students include in their responses?
4. How do student groups vary in their scores on the pre- to post-assessment, and the evolution unit exam and final exam?

Study 1

Methods

Initial rubric development

We chose to focus on the creation of a rubric because they are familiar to both students and instructors. They provide multiple opportunities for students to have their work evaluated quickly and evaluate the work of their peers. Rubrics reduce the amount of time instructors need to process student responses and can be used across core concepts. They also clarify instructor expectations, going beyond right or wrong, telling the student *how* they can build a conceptual knowledge and competencies (Sadler, 1989). This allows instructors to use constructed response items, while lessening the amount of time the instructor requires for grading. Our rubric is conceptually grounded in Darwin's postulates and research on student difficulties with natural selection and models expert thinking using language accessible to novice learners.

To create the 3R: Evolution (3R) rubric, we began with an existing coding rubric used by Bray Speth et al. (2009) to evaluate an open-response prompt. Their research team created this rubric through an iterative process. First, they began by focusing on five key principles of natural selection as outlined by Anderson et al. (2002) in the Conceptual Inventory of Natural Selection (CINS) and Nehm and Schonfeld (2008), who evaluated the CINS, an open-response instrument, and an interview to ensure that students used those same five key principles in their responses. The five key principles included variation within a population (V), origin of variation (O), inheritance (I), fitness (F), and change in populations (P; Bray Speth et al., 2009). Second, they read through post-instruction student responses and evaluated whether or not the responses included the five key principles (Bray Speth et al., 2009). After this process, they developed a coding rubric (Table 1) to score their student responses.

To create Version 1 of our rubric (Table 2), we added two additional sections to the Bray Speth (2009) coding rubric. A code for "natural selection" (NS), to represent no mention of natural selection processes and a code for the "central dogma" (CD) that asked students to evaluate the inclusion of the central dogma in their responses (Table 2).

Table 3.1. Bray Speth et al. 2009 – Original coding rubric.

	Score*		
Principle	0	1-novice	2-expert
Variation within a population [V]	No mention or misconception	Variation between individuals is only described in one of the populations—trees or animals	There is a clear reference to the different phenotypes existing, at the same time, within the animal and the tree populations
Origin of variation [O]	No mention or misconception	Phenotypic differences are the result of “mutations”	Variation within populations has genetic origin (is caused by random genetic mutation, resulting in different alleles)
Inheritance [I]	No mention or misconception	Traits are inherited by offspring	The genes responsible for phenotypic traits are inherited by offspring
Fitness [F]	No mention or misconception	Individuals whose characteristics are favored by the environment are more likely to survive	Individuals whose characteristics are favored by the environment are likely to reproduce more and produce more viable offspring
Change in populations [P]	No mention or misconception	Populations change over time, and shift from a variety of phenotypes to selected phenotypes becoming predominant	Allele frequencies change in populations over time

*Student responses were coded with a binary coding scheme, student received either zero or one for each cell of the frame for a maximum of ten possible points

Table 3.2. 3R – Version 1.

Code	Function problem[1]	Suggestion
V	Variation in traits is not represented or is only partially represented. Example: representing only one phenotype or variation in just one organism.	In any population, there is variation in traits/ phenotypes, which is the result of genotypic differences. Variation in phenotypes/traits is essential to natural selection.
O	The ultimate origin of phenotypic variation is not described or is incorrect. For example: Terminology is not biological Mutation is used incorrectly (e.g., mutated trait)	Variation within a population has an ultimate genetic origin of mutation.
I	Inheritance is missing	Natural selection can only act on traits that are heritable.
F	Fitness is missing or focuses on survival only	Individuals whose characteristics are favored by the environment are likely to reproduce more and produce more viable offspring.
P	A change in populations over time is either missing or focuses only on phenotypes.	Ultimately, natural selection results in a change in allele frequencies in a population over time.
NS	Selection is missing, incomplete, or vague	Some aspect of an organism's environment must actively select one phenotype over another. The selective agent results in increased reproduction and/or survival of one phenotype.
CD	Flow of genetic information represented is inconsistent with the central dogma	The Central Dogma of biology explains how genetic information flows in a biological system. Specifically, it states that DNA codes for RNA which codes for proteins.

[1] For each function, identify whether the function is present (e.g., V), incorrect (V^-), or absent (V^0) Code when present, Code- when incorrect, and Code^0 when absent

Results

We piloted our modified rubric in one section of Introductory Biology II in Spring 2016. During the evolution unit, students worked in groups to answer an open-response ACORNS-style prompt to describe the process of natural selection. After students had completed the prompt, we instructed students to review their work and peer review another group's work using the provided 3R: Evolution rubric. The course instructor then coded the student work using the 3R and returned the worksheet to the students in the next class period. We then asked the students to fill out a short survey to provide us with feedback about the usefulness of the rubric.

Students reported that Version 1 (Table 2) was too long, and they had difficulty using the abbreviations that we asked them to use during the peer review process. For example, they would label a section of a response with the letter "F" for fitness but leave off the superscript to represent if it was present, incorrect, and/or absent. In addition to asking for student feedback, we also asked for feedback on the rubric from an additional instructor of Introductory Biology and received similar advice. The instructor encouraged us to simplify the rubric to make it more accessible for students to quickly review their own work and peer review others, and to make the coding scheme clearer by labeling each section of the rubric with its own code.

In our second version of the rubric (Table 3), we made several modifications. First, we went back to the original formatting of the Bray Speth (2009) coding rubric, with the key principle and code clearly labeled; along with short, clear phrases to describe each key principle. We then replaced the codes of novice and expert with phenotypic and genotypic reasoning.

Table 3.3. 3R – Version 2, coding rubric.

	Phenotypic Reasoning (1)	**Genotypic Reasoning (2)**
Variation [V]	Phenotypic variation exists in a population at the same time. (1) <V_2> causes some individuals to be faster	Variation in a population has genetic origins.
Inheritance [I]	Phenotypes are inherited by offspring. (1) 'Fastest' passed on most genes (2) Passing genes to make an overall faster population (3) Pass on trait	Inheritance of phenotypes is due to genetics. (1) Pass on its genes (even if not directly linked to trait/allele of interest) (2) Creating more mutated individuals (3) [trait] allele is inherited (e.g., 60 mph allele is passed on…)
Fitness [F]	Differential reproduction or fitness based on phenotypes. (1) Can say 'fitness' (2) Can say more fit (fitter) phenotype	(3) Look for implied reproduction, e.g., 'passed on…'
Evolution [E]	Phenotypes of a population change over time. (1) 'Next generation' is not sufficient (2) Phenotype changed over time – clear or implied that one phenotype increases while another decreases (versus speed gradually increasing over time)	Genetics of a population change over time. (1) Genotype changed over time (2) Allele increased/spread in the population (3) [trait] allele increases in frequency (e.g., 60 mph allele increases in frequency…)

Notes: If student discusses gene flow or genetic drift, don't try and code for natural selection. However, if they simply say the term but then describe natural selection, try to code.

After reviewing our student responses from Spring 2016 and Spring 2017, we found that novice descriptions tended to include only phenotypic differences, e.g. cheetahs are able to run fast and slow, but did not mention the underlying genetic mutations that would lead to those differences. We believed the label of phenotype and genotype would be more informative to students, rather than trying to determine if something was novice versus expert. Then, we condensed the key principles from five to four by combining the “Origin of Variation” key principle to the genotypic reasoning component of the “Variation” key principle.

We also changed the name of the “Change in Populations” to “Evolution”. This change allowed us to make a direct connection between the components of natural selection and the outcome of this process, evolution. These changes left us with four key principles and less overall text for students and instructors to review. The required code acronyms for students and instructors still had two components, the key principle and a number to indicate if it was the phenotypic or genotypic component. There were now eight possible codes that a student: V1, V2, I1, I2, F1, F2, E1, and E2. We piloted this modified rubric (Fig 1) in Spring 2017 in two sections of Introductory Biology II.

Key Principle	**Code Descriptions**	
Variation **[V]**	**V_0** No mention	**V_1** Phenotypic variation exists in a population at the same time.
		V_2 Variation in a population has genetic origins.
Inheritance **[I]**	**I_0** No mention	**I_1** Phenotypes are inherited by offspring.
		I_2 Inheritance of phenotypes is due to genetics.
Fitness **[F]**	**F_0** No mention	**F_1** Some phenotypes have greater survival
		F_2 Some phenotypes reproduce more
Evolution **[E]**	**E_0** No mention	**E_1** Phenotypes of a population change over time.
		E_2 Genetics of a population change over time.

Figure 3.1. 3R – Version 2, student view. Students were shown this simplified rubric during the Evolution lecture in class and received a copy on their worksheets.

Again, we asked students to review their own work, peer review other group’s work, and provide us feedback on the usefulness of the rubric. Students reported that the rubric was easy to use and that they could interpret the codes from the instructor and provide peer feedback. A remaining criticism was that the numerical superscripts were difficult to remember. Students had difficulty remembering that a “1” indicated phenotypic reasoning versus a “2” for genotypic reasoning and would commonly interchange these numbers. In our final iteration of the rubric, we replaced the “1” and “2” with a “P” for phenotype and a “G” for genotype. We also combined “Fitness” into one key principle because the separation between survival and reproduction could not be easily split into a phenotypic and genotypic component (Table 4). In the final rubric, students could receive seven possible codes: VP, VG, IP, IG, F, EP, and EG.

Table 3.4. 3R: Evolution.

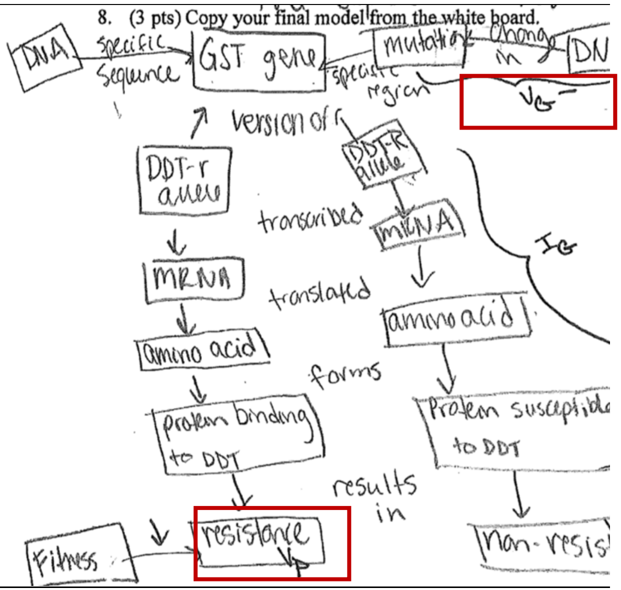
Key principle	Code descriptions		
Variation [V]	**V_0** No mention	**V_P**	Phenotypic variation exists in a population at the same time
		V_G	Variation in a population has genetic origins
Inheritance [I]	**I_0** No mention	**I_P**	Phenotypes are inherited by offspring
		I_G	Inheritance of phenotypes is due to genetics
Fitness [F]	**F_0** No mention	**F**	Some phenotypes have greater survival and reproduce more
Evolution [E]	**E_0** No mention	**E_P**	Phenotypes of a population change over time
		E_G	Genetics of a population change over time

A minus symbol (-) may be added to any code to indicate that the key principle is present, but still needs improvement.

Discussion

With our finalized rubric (Table 4), students were able to use the 3R: Evolution to decode feedback and translate that feedback into action. We were still able to provide a continuum of information, including the use of a “-” symbol added to the code to indicate that the phenotypic or genotypic key principle was present, but could still use improvement (Table 5). The students were able to decide what steps were necessary to improve their answer to the prompt, thereby improving understanding of that concept. The 3R also informed the instructor of each student’s learning progress and cued students to instructor expectations, allowing students to process their own understanding.

Table 3.5. Excerpt from 3R: Evolution rubric with sample student response.

Key principle	Code descriptions			Sample response with codes
Variation [V]	V_0 No mention	**V_P**	Phenotypic variation exists in a population at the same time	
		V_G	Variation in a population has genetic origins	

Note: Student response received a code for VP and a VG-, telling them their answer includes VP, but VG could be improved, 3R and instructor feedback in class provides ways to improve their answer

Study 2

Methods

Course context and implementation

We implemented our finalized rubric in Introductory Biology II at North Dakota State University (NDSU) in Spring 2018. Students (N = 107) were primarily white (85%), females (67%), with a mean GPA of 3.4 (SD = 0.56). The course is intended for science majors and purposefully designed to implement the AAAS *Vision and Change* (AAAS, 2011) core concepts and competencies, with a focus on information storage and flow and model-based pedagogy. Specific course topics included the central dogma (transcription and translation), cell cycle, evolution, and ecology. Students in the course were placed in permanent groups of 2-3 at the beginning of the semester to support collaborative learning and all assessments include open-response items with little to no multiple-choice questions outside of clicker-style prompts. Students were taught to create box-and-arrow style structure-behavior-function (SBF) models at the start of the semester (Goel et al., 1996; Dauer et al., 2013; Bray Speth et al., 2014) and provided with feedback on the construction and content of these models. For the evolution curriculum, students were taught how to create box-and-arrow models with one case study and then write open-response essays for the next case study. The natural selection and associated 3R: Evolution curriculum spanned one and half weeks of instruction, including a pre- and post-assessment day (Fig. 2).

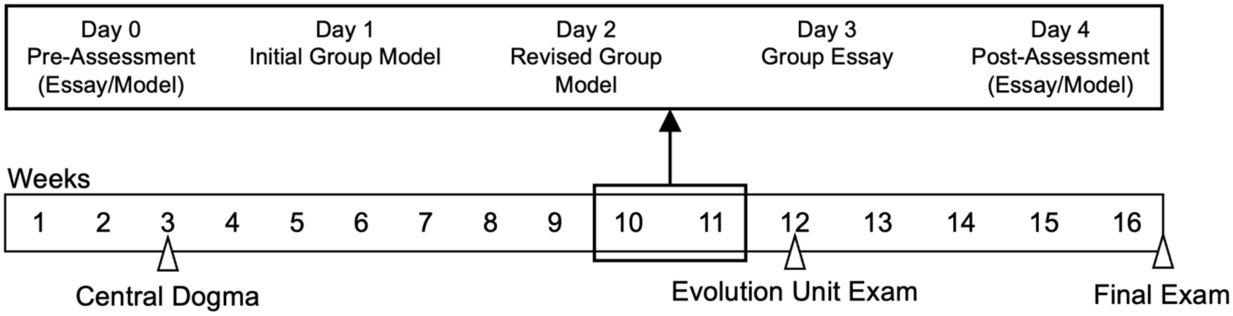


Figure 3.2. Timeline of instruction. Students worked in groups of 2 or 3 students and had previously learned how to make box-and-arrow structure-behavior-function models on earlier course material. *On the evolution unit exam and final exam, students could choose to construct a model or write an essay.

On Day 0 and Day 4, students completed an open-response pre-assessment and post-assessment modeled after the Nehm et al. (2012) ACORNS instrument (Fig. 3). Students were randomly asked to create a model or essay on their pre-assessment and then completed the same style prompt for their post-assessment.

The instructor of the course coded the student-generated models and essays to provide individualized feedback to students on group assignments in class between the pre-assessment and the post-assessment using the 3R. Students also received feedback on their evolution unit exam. For data analysis, three researchers (RLSH, JLM, and an undergraduate researcher, RG) re-coded 20% of the data to establish an IRR of at least 90% and then one researcher (RLSH) coded the remaining 80% of the data. We also collected course artifacts from each group through the end of the semester including the evolution unit exam and final exam. These were also re-coded for inclusion in our analyses.

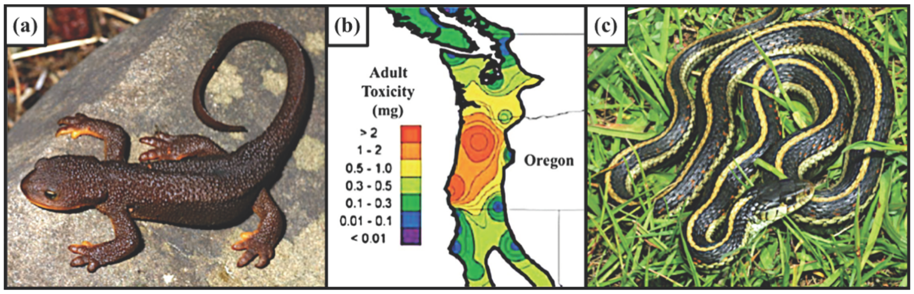


Figure 1. a) rough-skinned newt, b) toxicity of rough-skinned newts, c) common garter snake

Rough-skinned newts (*Taricha granulosa*; Figure 1a) are native to the west coast of Canada and the United States, from Alaska to California. Some of these newts, especially populations living in Oregon, accumulate a lethal neurotoxin in their skin for defense against predators (Figure 1b).

Common garter snakes (*Thamnophis sirtalis*; Figure 1c) are native to most of North America and feed on earthworms, small fish, and amphibians such as newts. Researchers have discovered that some of these snakes are able to resist the lethal neurotoxin and consume rough-skinned newts.

Construct a box-and-arrow model that explains how the ability to resist the neurotoxin of rough-skinned newts evolved in a population of common garter snakes that lacked this adaptation.

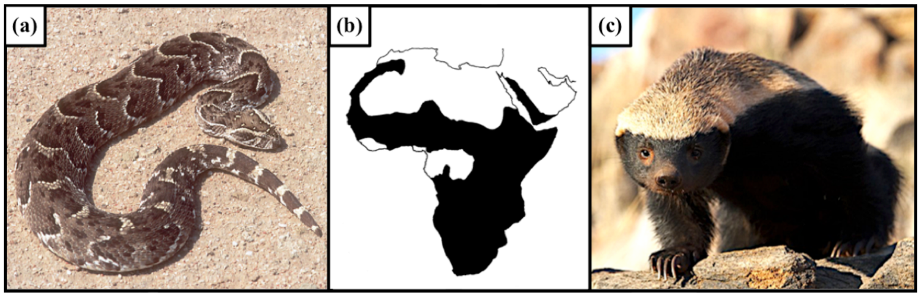


Figure 1. a) puff adder, b) geographic distribution of puff adders, c) honey badger

Puff adders (*Bitis arietans*; Figure 1a) are native to the savannas and rocky grasslands of Africa and southwestern Asia, from Saudi Arabia to South Africa (Figure 1b). These snakes use deadly venom to immobilize prey, and as a last resort, to defend against predators.

Honey badgers (*Mellivora capensis*; Figure 1c) are native to Africa and Asia, and feed on small mammals, snakes, lizards, and bee larvae. Researchers have discovered that some honey badgers are able to resist the deadly venom when bitten and routinely consume puff adders.

Construct a box-and-arrow model that explains how the ability to resist the venom of puff adders evolved in a population of honey badgers that lacked this adaptation.

Figure 3.3. Pre and post-assessment prompts.

Statistical analyses

Student responses were coded for the presence of four key principles of natural selection (Table 4), both before and after instruction, for a total of seven possible codes per prompt. Code frequencies were computed for all codes. For some analyses, we summed the total number of key principles included to calculate a total score for each prompt. Since students did not necessarily include the phenotypic and genotypic portion of all of the key principles they included, we separately calculated the total number of key principles used based on our coding rubric. Because these analyses of change in student responses from pre- to post-test require matched data, we excluded students who did not complete both the pre- and post-test, resulting in 107 matched sets of responses for the pre- and post-assessment. To evaluate whether or not the style of the pre-assessment and post-assessment prompt impacted student score, we used non-paired t-tests. Changes in the total number of key principles within each group from pre- to post-assessment were measured using paired sample t-tests. To analyze changes in the use of specific key principles, we calculated an exact version of the McNemar test, which is more accurate for smaller sample sizes (Fagerland et al., 2013; Harding et al., 2020). Patterns of student responses within groups were also qualitatively analyzed by inspection of student artifacts across the 4 days of instruction, the evolution unit exam, and the final exam.

Results

Responses on essay and model prompts varied on pre-assessment

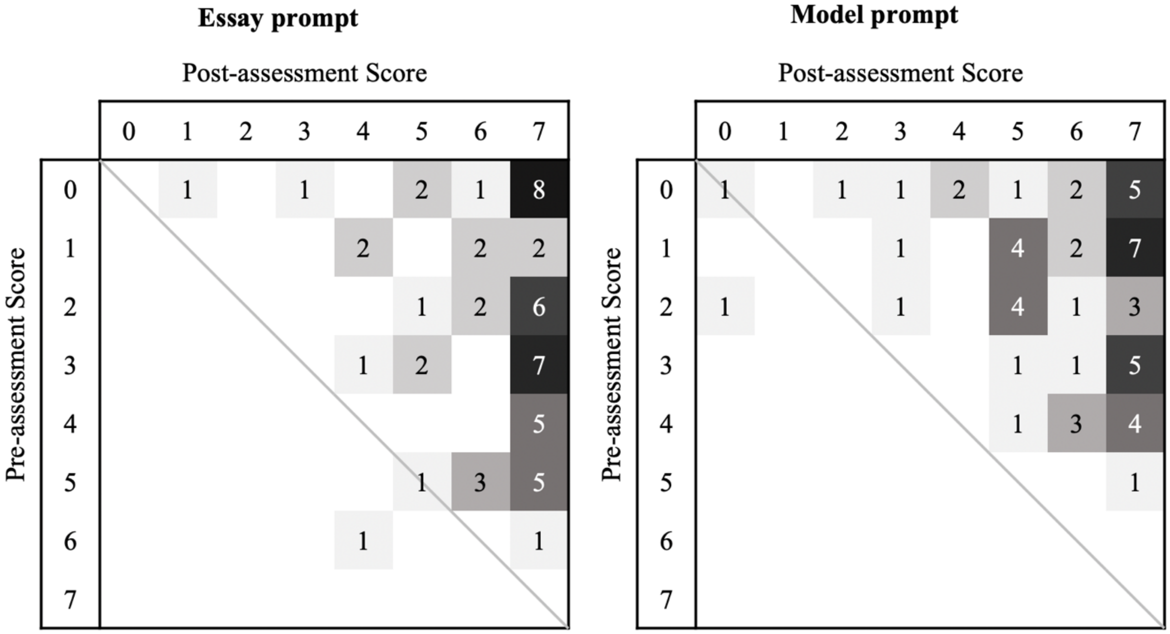
Before instruction, students were randomly assigned to complete the essay or model version of our pre-assessment. The 54 students who completed the essay prompt pre-assessment (M = 2.43, SD = 1.90) performed significantly better than the 53 students who completed the model pre-assessment (M = 1.74, SD = 1.46; t(105) = 2.1, *p* = .038). However, on the post-assessment this difference was no longer present (essay: M = 6.22, SD = 1.28, model: M = 5.72, SD = 1.73; t(105) = 1.70, *p* = .092). For our additional analyses, we split the students into two groups (essay and model).

Student knowledge of evolution

To assess students' understanding of natural selection before instruction and after the 3R: Evolution curriculum, we coded student responses for four key principles of natural selection on a set of isomorphic ACORNS-style prompts using the 3R: Evolution rubric (Nehm et al., 2012; Table 4). The maximum total score on each prompt was seven points. On the pre-assessment, a majority of students included 0 to 2 key principles in their responses on the essay (52%), whereas the majority of students included 0 or 1 key principles on the model (51%) prompt (Fig. X-B). The most commonly included key principle on the pre-assessment was variation, 59% (essay) and 49% (model) of students included phenotypic variation and 43% (essay) and 45% (model) included genotypic variation (Fig. X Key principles). Notably, a large portion of students included genotypic variation on the pre-assessment, while other studies using similar coding rubrics found little to no inclusion of this key principle (Bray Speth et al., 2009; Harding et al., 2020). This is most likely due to the prior curriculum on transcription and translation, so students were primed to discuss DNA and mutations.

On the post assessment, the majority of students included 6 or 7 key principles on both the essay and model prompts (essay: 78%, model: 64%; Fig. 4-B). On the essay prompt, the inclusion of key principles ranged from 83% (EG) to 96% (VP), demonstrating a high level of understanding of natural selection across all key principles. Similar to the pre-assessment essay, the most commonly included key principle on the post-assessment was variation, 96% of students included phenotypic variation and 93% included genotypic variation. On the model prompt, inclusion of the key principles was still high, but slightly below the essay prompt, ranging from 74% (IP) to 92% (F). The most common key principle on the post-assessment model was fitness (92%), followed by phenotypic variation (91%) and genotypic variation (87%). Overall, students performed significantly better on the post-assessment than the pre-assessment for both the essay and the model prompts (essay-pre: M = 2.43, SD = 1.9, essay-post: M = 6.22, SD = 1.28; paired sample t-test, $t(53) = 13.25$, $p < .0001$; model-pre: M = 1.74, SD = 1.46, model-post: M = 5.72, SD = 1.73; paired sample t-test, $t(52) = 14.97$, $p < .0001$; Fig. 4 A. Pre- and Post-assessment scores). The most drastic improvement occurred in within the evolution key principle, with the inclusion of genotypic evolution on the essay increasing from 7% to 83% and on the model from 4% to 77%. All pre- and post-assessment comparisons across key principles were significant (McNemar tests, $p < 0.0001$; Fig. 5 Key Principles)

	Essay		Model	
	Pre	Post	Pre	Post
Mean score	2.43	6.22	1.74	5.72
SD	1.9	1.28	1.46	1.73
p	<0.0001		<0.0001	



Essay prompt	0	1	2	3	4	5	6	7
0		1		1		2	1	8
1					2		2	2
2						1	2	6
3					1	2		7
4								5
5						1	3	5
6					1			1
7								

Model prompt	0	1	2	3	4	5	6	7
0	1		1	1	2	1	2	5
1				1		4	2	7
2	1			1		4	1	3
3						1	1	5
4						1	3	4
5								1
6								
7								

Figure 3.4. Pre- and post-assessment scores. A (top), B (bottom). Students' knowledge about four key principles of evolution by natural selection was measured with the ACORNS prompt before and after instruction using the 3R (essay: N = 54; model: N = 53). The maximum possible score on each instrument was seven points. A. The mean score improved on the post-assessment for both essay and model, paired samples t-test were statistically significant B. Following Bray Speth et al. (2009), we show a visual representation of the data, indicating the pre- and post-assessment score distribution among individual students. The number of students is shaded in grayscale to represent the number of students that received each combination of scores. Students that fall on the diagonal line had no change between the pre- and post-assessment; individuals above the diagonal line performed better on the post-assessment. The majority of students in both the essay and model prompt groups improved their scores, represented above the diagonal line.

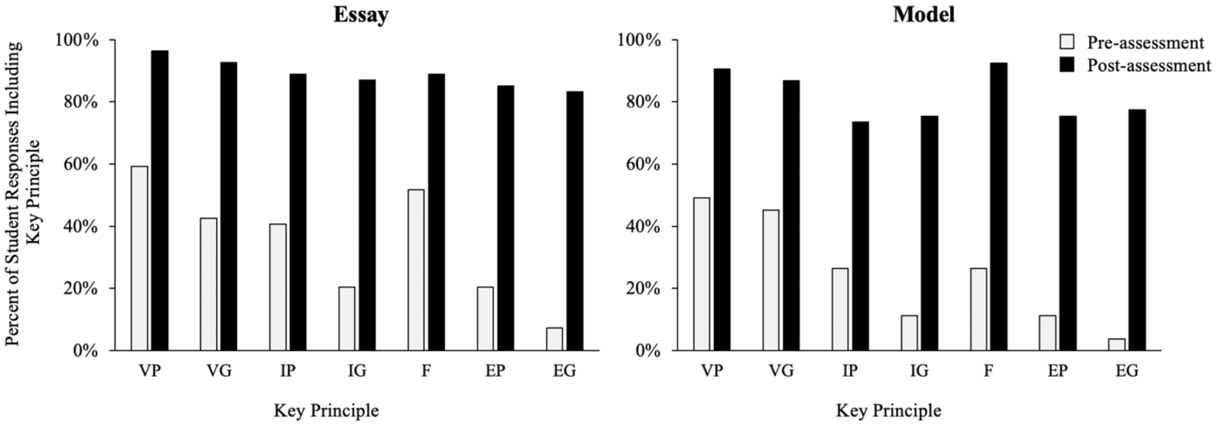
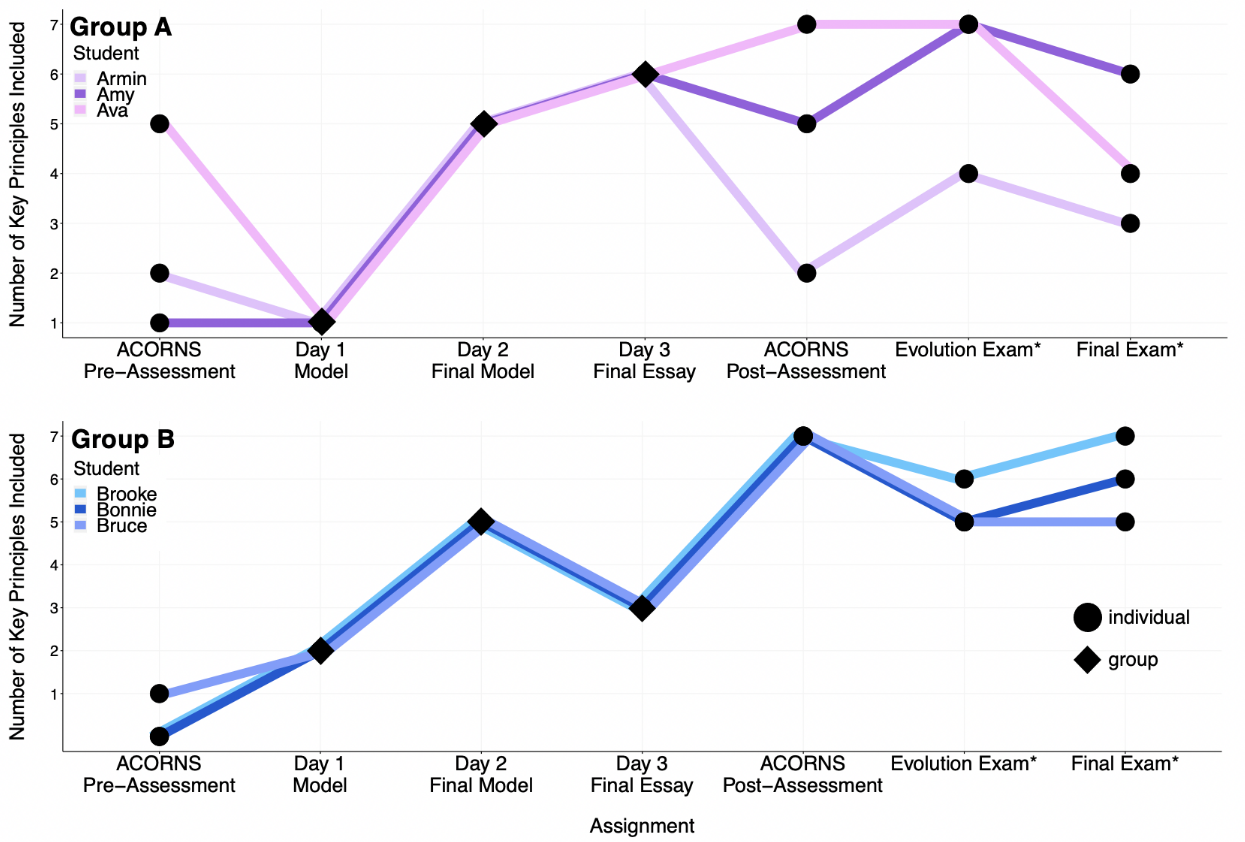


Figure 3.5. Key principles included on essay and model pre- and post-assessment. Students' knowledge about four key principles of evolution by natural selection was measured with the ACORNS prompt before and after instruction using the 3R (essay: N = 54; model: N = 53). The maximum possible score on each instrument was seven points. McNemar tests for all comparisons $p<0.01$.

After evaluating the pre- and post-assessment data, we examined individual and group course artifacts from the 3R: Evolution curriculum to evaluate how student understanding of natural selection progressed throughout the unit. To gain more insight into how the 3R works, we chose contrasting cases from student groups where the 3R had limited impact versus cases where students showed the greatest learning (Flyvbjerg, 2006). Our first case, Group A (Fig. 6 Group A), demonstrated an understanding of some concepts of natural selection, but struggled to communicate a complete and coherent mechanistic explanation of evolution by natural selection through their essays and models. Analysis of their interactions with the 3R indicated that Group A consistently struggled to accurately decode the information from the 3R and apply it appropriately to their work. They would code their own work using the wrong code at times, showing that they did not understand what each letter code was referring to in the rubric. Group A showed “mixed” performance, with one student scoring much worse than their peers, a pattern observed in several cases where the rubric had limited impact.

Our second case, Group B (Fig. 6 Group B), scored low on the pre-assessment, but was able to achieve high scores on the post-assessment across all individual group members. Idiosyncrasies in their individual essays and models demonstrated that their responses were not simply memorized group products but represented a level of understanding they personally attained during the curriculum, which (unlike Group A) they retained through the end of the course. However, even though they were successful, Group B still struggled to differentiate between codes and apply them to their work. Similarly, to Group A, the students would miscode their own work or their peers but did show great improvements on their individual and group assignments.



Individual and group course artifacts were scored with the 3R to track their inclusion of the key principles of natural selection across the semester. Spacing represents the order of assignments, not time between them. *Students could choose to draw a model or write an essay.

Figure 3.6. Contrasting cases course artifacts.

Discussion

In our study, we evaluated student understanding of natural selection before and after instruction using the 3R: Evolution in a population of undergraduates enrolled in Introductory Biology II. Students showed significant improvement from their pre- to post-assessment on all key principles and codes (Fig. 5, McNemar tests $p < 0.01$ for all comparisons). The majority of students included 6 to 7 of the 7 possible codes from the four key principles on the post-assessment on both the essay (78%) and model (64%) prompts. Student performance on the open-response ACORNS-style prompts before and after evolution instruction with the 3R: Evolution rubric demonstrate that our curriculum improved student understanding of natural selection.

The 3R: Evolution rubric was usable across prompt formats

In response to the call for improved undergraduate biology curriculum, the National Science Foundation (NSF) and the American Association for the Advancement of Science (AAAS) published *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, 2011). This report includes a list of five core concepts (evolution; structure and function; information flow, exchange, and storage; pathways and transformations of energy and matter; systems) and six core competencies (apply the process of science; use quantitative reasoning; use modeling and simulation; tap into the interdisciplinary nature of science; communicate and collaborate with other disciplines; understand the relationship between science and society) that all biology undergraduate curriculum should incorporate (AAAS, 2011). Over the last several years, the faculty and instructors in the biological sciences department at NDSU have worked together to incorporate the core concepts and competencies into their classrooms, including a focus on model-based pedagogy. Students in our course were taught to create conceptual models to convey conceptual understanding (Bray Speth et al., 2014; Long et al., 2014; Wilson et al., 2020) beginning at the start of the semester and had experience creating them to depict the central dogma (transcription and translation). We expected that students would perform similarly on the pre-assessment, regardless of the prompt style that they were assigned to but found that students included significantly fewer key principles on the model prompt (Fig. 5). However, we found that on the post-assessment this difference was no longer present, and students were including a similar number of key principles on both prompt styles. This may indicate that students needed additional practice with the creation of SBF models, especially when asked to explain novel material, but that they were able to improve their ability to construct models over the evolution curriculum. On the post-assessment, students included 6 to 7 of the possible 7 codes, regardless of prompt style (Fig. 5). On the evolution unit exam, students were asked to choose whether to write an essay or draw a model to describe the process of natural selection. We found that 41% of students chose to write an essay and 59% of students drew a model. On the final exam students were again given a choice between prompt style. For this exam, each of the styles was chosen by an equal number of students. We were encouraged that students chose to draw models, even when given the choice to write a more traditional essay response. This suggests that students do not have a bias against drawing models, and that they are able to use them across various topics and improve their model construction over the length of the semester.

Students included phenotypic and genotypic components in their responses

Previous research assessing student understanding of natural selection using open-response instruments has found that genotypic concepts are more difficult for students to accurately describe (Nehm and Schonfeld, 2008; Bray Speth et al., 2009; Nieswandt and Bellomo, 2009; Bray Speth et al., 2014; Harding et al., 2020). To mitigate this, we created the 3R: Evolution rubric to explicitly tell students that a phenotypic and genotypic component is necessary for three of the four key principles included in their explanations of natural selection (variation, inheritance, and evolution; Table 4). Bray Speth et al. (2014) found that even after explicit instruction about the importance of mutation and genetic variation in their models, only 39% of students included this key principle in a midterm exam and 65% on a final exam. Similarly, in a previous study with undergraduate non-majors, we found that origin of variation was included by the lowest number of students, both before and after instruction (Harding et al., 2020). In the current study, 43% of students included genotypic variation in their essays and 45% of students included this key principle in their models prior to evolution instruction. This high level of inclusion in the pre-assessment is most likely due to the model-based pedagogy that was used to teach students the central dogma, which occurred before instruction on evolution. During this curriculum, students were shown how to construct box-and-arrow conceptual models and received feedback on model construction and content related to transcription and translation. We also had significant increases in the use of this key principle on the post-assessment, with 93% of essays and 87% of models including genotypic variation. We believe the use of the 3R during instruction and as a tool for feedback from their peers and instructor helped students increase their understanding of how to incorporate genotypic variation (mutation) into their responses.

Students vary in their success with the 3R across the semester

To explore the usefulness of the 3R: Evolution rubric more closely, we chose two contrasting cases (Flyvbjerg, 2006). All the members of both groups were present for all instructional days and completed all the associated 3R assignments. The 3R had an overall positive impact on student learning for both groups, but they exhibited different learning patterns across the semester. This variability of student performance captured by the 3R may help instructors identify at risk students early in the unit and provide a tool for them to give timely individualized feedback to those students. Specifically, in Group A, we found that one student performed worse than their group members on the post-assessment, evolution exam, and final exam. Even though their performance was not as high as their group members, they still had a net increase of key principles in their response over the course of the semester. In our typical case, Group B, we saw a low number of key principles included on the pre-assessment followed by improvement throughout the semester, through the final exam. The entire group included all key principles on their post-assessment and continued to include most of the key principles on the evolution unit exam and final exam. Two of the three group members improved from the evolution unit exam to the final exam, indicating that they used the feedback provided on the unit exam to improve their responses on the final exam. Because their responses changed over time, we believe this provides evidence that students are not simply regurgitating a memorized model or essay. This is important because we do not want students to focus on creating identical models and essays, but rather focusing on the inclusion of the key principles in their responses. This again moves the focus away from points or grades, to the formation of concepts and skills. The ability to easily track a group over time through the use of the 3R coding scheme provided feedback about student learning to the student's themselves and the instructor, creating multiple opportunities to support student learning.

Feedback promotes learning of difficult concepts

Large-enrollment classrooms are not simply lecture halls anymore. There has been a surge in the use of active learning techniques in the undergraduate classroom (Freeman et al., 2014) and as pedagogy changes, so must curriculum and assessment practices. In the current study, we used a rubric in conjunction with constructivist teaching techniques (model-based pedagogy, formative assessment, feedback) and found significant improvement in student learning of natural selection over the course of the semester. Many instructors have experienced a lack of improvement in student understanding of natural selection and evolution in their courses and this study attempts to provide one tool to address this issue. The rubric can be used as a stand-alone activity or, as we did, become part of a larger curriculum strategy. The rubric itself is not directly tied to a particular case study or content, making it transferable to various prompts. This is important because prior research has found that student responses to natural selection prompts is impacted by the context of the prompt (i.e. animal vs plant, trait gain vs loss; Nehm and Ha, 2011; Nehm et al., 2012). In our curriculum, we only used animal-based trait gain case studies but did vary the species. As a next step in testing our curriculum, we would like to develop isomorphic trait loss prompts and apply it to existing train gain plant-based prompts. Trait loss prompts are typically more challenging for students (Bray Speth et al., 2014; Harding et al., 2020), so the 3R: Evolution rubric may provide even more benefits for students. The use of the 3R would allow instructors to provide individualized feedback in a timely manner, which will help to directly support student learning of this difficult concept.

Conclusion

The 3R: Evolution curriculum shows great promise in introductory biology. Gains from the pre- to the post-assessment indicate that our students learned a great deal about evolution by natural selection during our course. However, closer inspection of course artifacts suggests that even the most successful groups need more practice and guidance decoding and applying the 3R. Continued refinement of the curriculum and testing of various prompts context is necessary. We hope that instructors will use the 3R: Evolution in their own classrooms and use it as inspiration to develop rubrics for other topics in their course that have proven challenging for students in the past.

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CONCLUSION

The goal of this dissertation research was to characterize student understanding and acceptance of evolution and to create a curriculum unit focused on evolution by natural selection to meet the needs of both instructors and students in large-enrollment courses. Evolution is a topic that can be divisive for some learners, requiring me to both evaluate student knowledge and their respective beliefs about evolution (Dunk et al., 2019). This allowed me to create curriculum to meet student learning needs while being mindful of what impacts student acceptance of evolution.

Commonly, research about student understanding of evolution focuses on majors or non-majors biology courses (Glaze and Goldston, 2015; Ziadie and Andrews, 2018). I wanted to expand this research beyond the biology classroom into a non-majors geology course, a typical course that students would enroll in to meet their science requirement. This provides valuable information about the current understanding of evolution by natural selection that students attain during their college science curriculum. I surveyed students before and after instruction using open-response items from the Bishop and Anderson Diagnostic Instrument (Bishop and Anderson, 1990) and a religiosity scale (Hawley et al., 2011). Specifically, I coded for five key principles of natural selection: variation in a population, origin of variation, inheritance, fitness, and change in a population over time. I found that students included very few of the five key principles of natural selection in their responses. The most commonly included key principle was variation in a population, but I believe that students were primed by the prompt text to include this particular key principle in their response.

Our results mirrored student performance in a similar study where students used an online educational software to learn about natural selection (Bray Speth et al., 2009). This indicates that student populations struggle with describing the process of natural selection and require improved curriculum to meet their learning needs. I also investigated the relationship between knowledge of natural selection and a student’s religiosity. In this population, students’ self-reported religiosity was only related to knowledge on the trait gain cheetah prompt. All other prompts showed no relationship to religiosity. I believe this relationship could not be properly measured because of the floor effect of our sample. Students simply performed so poorly on the prompts that I could not detect a significant difference. The results from this study demonstrate that, even with direct instruction, non-majors geology students cannot describe the process of natural selection using the selected key principles. To meet the needs of undergraduate students, I encourage the development of cross-disciplinary evolution curriculum.

I used our findings from study one, along with previous research, to create a rapid response rubric (3R) focused on evolution by natural selection. This rubric can be used as a tool to provide feedback to the instructor about student understanding early in the learning process and serve as a model for students to follow when describing the process of natural selection. The curriculum follows best practices of formative assessment and feedback (Sadler, 1998). I began rubric development by using coding rubrics from prior research that were developed based on Darwin's postulates (Bray Speth et al., 2009; Nehm and Reilly, 2007). I refined the rubric through an iterative process of testing the rubric with undergraduate students enrolled in introductory biology courses and requesting feedback from instructors of those courses. The final rapid response rubric, 3R: Evolution, features four key principles of natural selection: variation, inheritance, fitness, and evolution. These four key principles are split into 7 distinct codes that instructors use to provide feedback to students and students use to evaluate their own responses to an open-response prompt.

Similarly to study one, I used a pre/post-assessment format to evaluate the usefulness of the rubric. In addition, I collected student artifacts from their in-class activities and course exams. On the pre/post-assessment, students performed significantly better across all key principles on post-assessments. The difference was especially promising on the genotypic variation code. Previous studies have shown very little improvement in student understanding of the origin of variation (genetic mutation), but in our population I saw 93% (essay) and 87% (model) of students including this key principle in their responses. I chose two student groups that represented contrasting cases to examine how the students used the rubrics over the course of the unit (Flyvbjerg, 2006). In one group, all students improved from pre- to post-assessment and continued to maintain their scores across the semester. Whereas the other group had one group member who continued to struggle on individual assignments, although they did show improvement from the pre-assessment to the final exam. This case illustrated the importance of individual formative assessments during the curriculum. The rubric would enable instructors to provide this valuable feedback with a quick turnaround time, which is necessary in a large-enrollment course. I believe the 3R: Evolution rubric is an excellent tool for instructors to use in their evolution unit, regardless of prompt context. Further, this style of tool, rapid response rubrics, could be created and used for numerous topics that students struggle with in introductory biology such as protein synthesis and climate change.

Study one and study two focused on student *knowledge* of evolution by natural selection. But prior research shows that knowledge of evolution and *acceptance* of evolution are intertwined (Nadelson and Southerland, 2010; Dunk et al., 2019). Previous studies exploring students' acceptance of evolution used methodologies that examined the impact of one variable at a time and its role in acceptance (Dunk et al., 2017; Weisberg et al., 2018). I chose to use a systems approach to study this topic. I used a path analysis to more wholistically describe what impacts student acceptance of evolution. I chose five commonly studied variables to include in the theoretical model: openness to experience, number of science courses completed, religiosity, knowledge of evolution, and understanding of the nature of science. These variables were also used in a study conducted at the University of Wisconsin: Milwaukee (Dunk et al., 2017). This allowed me to create a multiple-group model to directly compare our own results with those of a student population from another institution in a different geographic area.

I made several modifications to our theoretical model based on the modification indices and normalized covariance residuals. After these modifications, the final multiple-group model had excellent fit with the data. Religiosity had the largest causal effect in our model and had an inverse relationship with all other variables. However, knowledge of evolution and knowledge of the nature of science both had large positive effects on acceptance. Educators may lessen the negative impact of religiosity on acceptance by using culturally competent instructional strategies (Barnes and Brownell, 2017; Barnes et al., 2017), which would then strengthen the relationship of knowledge and nature of science on acceptance. The model pathways also show that exposure to evolution content positively impacts acceptance of evolution. This reinforces the results from study one, more evolution curriculum should be included in non-major's science courses, leading to an increase in the number of students that receive exposure to evolution instruction in college. A students' reported level of openness to experience also impacted their acceptance of evolution more than I expected, especially in the UWM-Milwaukee group. This may again relate to exposure, where the more opportunities that students must engage with science outside of the typical biology classroom the better. Even with these positive trends in acceptance, the model only accounted for 35% (NDSU) and 48% (UWM) of the total variation in evolution acceptance by using these five common predictors. This means there are other predictors impacting evolution acceptance that are not commonly measured by education researchers. One of these may be a student's perceived conflict with evolution from their family and community (Sbeglia and Nehm, 2020). This newly designed instrument, the Scales of Evolutionary Conflict Measure (SECM), could be used in tandem with our proposed model and may explain more of the variation in student acceptance of evolution (Sbeglia and Nehm, 2020). However, it is difficult to measure multiple factors at one time, as students may experience survey fatigue. Path analysis and structural equation modeling frameworks are an important methodological advance in the area of student acceptance of evolution, but improved survey design and increased sampling from various institutions and geographic areas are a vital next step in this research area.

Implications for research

The results from the three research chapters presented in this dissertation provide further evidence that evolution education and assessment is a multifaceted issue that requires continued work from researchers and instructors. Data on student understanding of evolution is typically collected from majors' and non-majors' biology courses at the undergraduate level (e.g., Bishop & Anderson, 1990; Anderson et al., 2002; Catley & Novick, 2009; Opfer et al., 2012; Kalinowski et al., 2016). I moved beyond that population and chose to collect data from a non-majors geology course and found that, even with direct instruction, students did not improve their knowledge of evolution by natural selection in this course (Chapter 1). I believe this is evidence that current levels of understanding of evolution may be even lower than traditionally accounted for and more data must be collected from non-biology science courses at the undergraduate level and from community colleges, an additional understudied population. This research would guide discipline-based education researchers and instructors as they create new educational materials that could be used in various courses and contexts. It would also be beneficial to work with current instructors from earth science, geology, physical science, and non-majors biology courses to determine what lesson plans and knowledge gaps they feel their students have and how they believe we can best address these gaps (Ziadie & Andrews, 2018).

The 3R: Evolution rubric was developed based on data gathered at two similar institutions, one "Master's Colleges & Universities: Larger Programs" in the southeast and one "Doctoral Universities: High Research Activity" in the Midwest as classified by the Carnegie Classification of Institutions of Higher Education (Indiana University Center for Postsecondary Research). I would like to expand its use to more populations, including higher enrollment courses at large universities and to community colleges, where students are typically in smaller classes, but have more varied educational backgrounds. This would provide valuable information about how the rubric can be adjusted for course size, students' background knowledge, and instructor time limitations. I would also like to use the 3R: Evolution in upper division courses, where students are more familiar with the basic concept of natural selection but may hold more deep-seated misconceptions about how evolution by natural selection occurs (Bray Speth et al., 2009; Kalinowski et al., 2016). By expanding the use of the 3R: Evolution rubric, we will be enhancing student understanding of natural selection, while encouraging instructors to provide meaningful feedback to their students.

Implications for instruction

This work described two barriers of evolution education, student *understanding* of evolution and student *acceptance* of evolution. We found that students enrolled in a science majors biology course were able to significantly improve their understanding of evolution by natural selection while using a new teaching tool, the 3R: Evolution (Chapter 3). This provides much needed evidence that curriculum that centers formative assessment and feedback provides students with the opportunity to improve their understanding of evolution and retain that knowledge throughout the course of the semester. The rapid response rubric is a framework instructors can use to create a structured format for giving descriptive feedback to students on their learning. It follows best practices of formative assessment and feedback by allowing instructors to give immediate, actionable, and meaningful feedback, all while not increasing the typical time it takes to grade assignments (Sadler, 1998). While this research specifically tested the 3R: Evolution rubric, rapid response rubrics could be used to teach other core concepts in biology and STEM courses. For example, another commonly taught controversial topic in biology and geology is climate change (Mosher et al., 2014; St. John, 2018). One way to introduce students to climate change is to discuss the process of the carbon cycle and explain how plant sequestration of carbon dioxide is a great tool in the fight against increasing global temperature. The carbon cycle could be broken down into the most important steps or key concepts and then the instructor could create a rapid response rubric that describes these key concepts, again allowing them to provide descriptive feedback to students about their understanding of this important topic. This is just one example, but instructors could use this framework to create numerous rubrics for important concepts in their courses.

In addition to the rapid response rubric serving as a tool for students to receive formative assessment and feedback, it could also be used in the new wave of mastery learning and ungrading (Wolf & Stevens, 2007; Ashby-King et al., 2021). Unlike commonly used analytical rubrics, the rapid response rubric is focused on student understanding of a particular set of concepts or goals that the instructor has decided are important for student success. These rubrics could be used as part of a set of standards needed to complete a course or as a tool to check for understanding at various course checkpoints. Regardless of how an instructor decides to add points or grades to the rubric, it will provide feedback to the student on their understanding of the material and go beyond a typical letter grade (Wolf & Stevens, 2007).

The 3R: Evolution is only one potential tool that instructors could use to improve their curriculum. I encourage instructors to use resources including CourseSource and HHMI BioInteractive to find curriculum that matches their learning goals (CourseSource, n.d.; HHMI BioInteractive, n.d.). CourseSource is an open-access journal that provides evidence-based and peer-reviewed lesson plans for undergraduate biology and physics courses (CourseSource, n.d.). These lessons can be a springboard for instructors to include more evolution content in their classroom. HHMI BioInteractive provides free lesson plans for undergraduate biology that each feature scientific data sources. Instructors can access large data sets or case studies to incorporate more evolution content into their courses and can use the attached peer-reviewed articles to dive deeper into a particular evolution topic (HHMI BioInteractive, n.d.). Whether instructors choose to implement the 3R: Evolution, other rapid response rubrics, or resources from freely available sources, they will all work towards the goal of improving student understanding of evolution.

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