Evolution: Education and Outreach

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Exploring patterns of evolution acceptance, evolution understanding, and religiosity among college biology students in the United States

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Abstract

Background Some of the most consistent factors associated with college students' evolution acceptance are how much they know about evolution (understanding), and the extent to which they identify as religious (religiosity). However, few studies explore how the relationship between understanding and acceptance can be impacted by student religiosity levels. Further, students show different levels of acceptance of evolution depending on the scale of evolution and context of evolution, but few studies explore how evolution understanding is related to acceptance at different scales and in different contexts. In this study, we analyzed survey responses from 11,409 college biology students sampled from across the United States. Using linear mixed models, we explored the relationship between students' understanding and acceptance of evolution and how their religiosity impacted that relationship. We also explored how these relationships changed based on scale and context of evolution.

Results We found evidence of six different scales or contexts of evolution ranging from acceptance of microevolution to accepting that all life on Earth shares a common ancestor. We found that students were most likely to accept microevolution while they were the least likely to accept the common ancestry of life. Interactions between student religiosity and understanding of evolution were significant predictors of their acceptance of macroevolution, human evolution within the species, human common ancestry with other apes, and the common ancestry of life. Notably, among highly religious students, how much they understood about evolution was not related to how much they accepted the common ancestry of life.

Conclusions This study provides evidence for six different scales or contexts of evolution for which college students have different levels of acceptance. Students accepted the common ancestry of life the least indicating that this might be important to expand upon in future research. Further, we provide evidence that the relationship between evolution acceptance and understanding depends on scale and context of evolution as well as student religiosity levels. These results indicate that acceptance of evolution among college students is more multifaceted than previously thought and that highly religious students may find it particularly difficult to translate their understanding of evolution to their acceptance.

Keywords Evolution, Creationism, Religion, Evolution understanding, Acceptance of evolution, College, Higher education, Science denial, Trust in science, Science rejection

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Introduction

In evolution education research, there is a consistent negative relationship between students' religiosity (the extent to which students identify as religious) and their acceptance of evolution (the extent to which they think evolution is scientifically valid) (Barnes et al. 2020a; Heddy and Nadelson 2013; Lombrozo et al. 2008; Mantelas and Mavrikaki 2020; Manwaring et al. 2015). Further, researchers have reported that understanding of evolution (how much students know about evolution) is often positively related to their acceptance of evolution (Nadelson and Southerland 2010; Salazar-Enriquez et al. 2023; Tavares and Bobrowski 2018; Sloane et al. 2023; Rice et al. 2015). However, there is a paucity of research on how religiosity may impact the relationship between understanding and accepting evolution. Past quantitative research has explored how religiosity moderates the relationship between evolution acceptance and understanding in German samples (Beniermann et al. 2023) as well as within the public in the United States (Weisberg et al. 2018). In the US, which is the context of the current study, researchers found that religiosity moderated the relationship between evolution acceptance and understanding; while all religiosity groups showed a positive relationship between acceptance and understanding, as participants' religiosity increased, the relationship between their evolution acceptance and understanding decreased (Weisberg et al. 2018). This implies that individuals that score high on religiosity are less likely to use their understanding of evolution to inform their acceptance. In this study, we aimed to explore this phenomenon among college biology students to see if their religiosity also plays a moderating variable in how their understanding of evolution impacts their acceptance.

Background

An enduring lack of acceptance of evolution has alarmed scientists and science educators for decades due to its position as a core concept in the science of biology with a large amount of evidence supporting evolutionary theory (American Association for the Advancement of Science 2011; Brownell et al. 2014). Despite its position as a core concept in biology, the number of people in the U.S. public who do not think evolution is scientifically valid remains high: in 2019, approximately 40% of Americans believe that humans were created in their present form (Brenan 2019). Evolution is even controversial for incoming undergraduate majors and non-majors biology students with up to 35% of introductory college biology students rejecting the common ancestry of life on Earth (Barnes et al. 2020b, 2021a). This indicates that at the beginning of their undergraduate education, many biology students do not accept most of the evolution that has occurred in Earth's history (Nadelson and Southerland 2012; Sbeglia and Nehm 2019). This rejection of a highly supported foundation of the entire discipline of biology presents a barrier to educators who are trying to support students' learning of core concepts in biology.

Evolution acceptance is a complex and multifaceted phenomenon that is associated with a variety of psychological factors. Here we define evolution acceptance as "agreement that evolution is valid and the best explanation from science for the unity and diversity of life on Earth, which includes speciation, the common ancestry of life and that humans evolved from non-human ancestors" (Barnes et al. 2024). A variety of cognitive variables (for example, understanding of evolution (Weisberg et al. 2018; Dunk et al. 2017; Barnes et al. 2019; Glaze et al. 2014), understanding of the nature of science (Lombrozo et al. 2008; Dunk et al. 2017; Barnes et al. 2019; Glaze et al. 2014), affective variables (for example, perceived conflict between religion and evolution (Barnes et al. 2021b), religiosity (Dunk et al. 2017; Glaze et al. 2014; Barnes et al. 2021b; Jensen et al. 2019), feeling of certainty (Ha et al. 2012), trust in science and scientists (Nadelson and Hardy 2015) and demographic variables (for example, race/ethnicity (Barnes et al. 2019; Sbeglia and Nehm 2018), gender (Sbeglia and Nehm 2018), education level (Heddy and Nadelson 2013), and religious affiliation (Barnes et al. 2019, 2021a; Jensen et al. 2019), have been related to evolution acceptance. In this study, we focus on two variables that are some of the most widely explored in relation to evolution acceptance: (1) students' understanding of evolution (Akyol et al. 2012; Smith and Siegel 2004), and (2) students' religiosity (Dunk et al. 2017; Jensen et al. 2019).

Evolution acceptance and evolution understanding

Research has shown that biology instructors can conflate student evolution understanding with student evolution acceptance, thinking that if a student does not accept evolution they just do not understand evolution (Barnes and Brownell 2016). However, understanding and acceptance are two distinct domains (Sinatra et al. 2003; Barnes and Brownell 2017; Smith 2010). Evolution understanding refers to the extent to which one has accurate knowledge of evolution and may be measured by the extent to which they can correctly answer questions testing their understanding of evolutionary theory (Weisberg et al. 2018; Barnes et al. 2021b; Nadelson and Southerland 2009). Evolution acceptance, however, is based on one's personal evaluation of evolutionary theory as scientifically valid (Barnes et al. 2024) and is often measured by the

extent of agreement with evolutionary claims (Nadelson and Southerland 2012; Barnes et al. 2022; Glaze et al. 2020; Rutledge and Warden 1999).

Most quantitative studies find correlations between acceptance and understanding of evolution (Dunk et al. 2017; Barnes et al. 2019; Glaze et al. 2014; Rutledge and Warden 1999; Trani 2004; Wingert et al. 2022; Carter and Wiles 2014), while a few studies have found little or no relationship between the two constructs (Sinatra et al. 2003; Bishop and Anderson 1990; Brem et al. 2003; Lawson 1983; Ingram and Nelson 2006). What can explain these differential results across studies? Differences in studies may be due to differences in measurement tools or differences in samples. For instance, different evolution acceptance instruments have been shown to lead to different results; when administering several evolution acceptance instruments to the same population of students Barnes et al. (2019) found that evolution understanding predicted evolution acceptance to a greater extent when using a measure of microevolution acceptance than when using a measure of macroevolution or human evolution acceptance (Barnes et al. 2019). Also, Bishop and Anderson (1990) found no relationship between evolution acceptance and understanding when using the Conceptual Inventory of Natural Selection (CINS) to measure evolution understanding but Nadelson and Southerland (2010) used the Measure of Understanding of Macroevolution (MUM) and found a moderate positive relationship between acceptance and understanding.

Differences across studies may also be due to sample differences. Qualitative research has illuminated ways in which religious students can understand evolution well and yet still reject it; Hermann (2012) interviewed high school students who had a high understanding of evolution but still "did not believe evolution" (Hermann 2012). Students at an evangelical Christian university expressed rejecting evolution despite having an understanding of it because they would rather be "a bad scientist than a bad Christian", indicating a differential epistemological value placed on religious ways of knowing compared to scientific ways of knowing (Barnes et al. 2020c). These students reported their lack of evolution acceptance was due to a perceived conflict with their religious beliefs, so it is possible that the extent to which understanding evolution is related to acceptance of evolution depends on students' religiosity. It could be that when there are weak relationships found between acceptance and understanding, this may be due to the high religiosity levels of the sample being studied.

Evolution acceptance and religion

Religious denomination, religious commitment (religiosity), and perceived conflict between religion and evolution have been documented as the strongest variables predicting evolution acceptance in quantitative studies. Students from Judeo-Christian affiliations who score high on religiosity and/or perceived conflict between religion and evolution tend to have the lowest evolution acceptance (Barnes et al. 2021b; Jensen et al. 2019). Students' perceived conflict between their religion and evolution can stem from a variety of factors. If students interpret creation narratives literally that describe a God/god(s) creating groups of organisms separately from one another (fish, birds, humans, etc.), then this is in direct conflict with the claim from evolutionary theory that all life shares common ancestry (Baker 2013) even though there are many non-literal interpretations of religious text that can coexist with evolution (Collins 2006; Miller 1999; Dajani 2012; Jalajel 2009). For instance, one may interpret a "day" in the book of Genesis in the Bible to mean millions of years rather than a literal day and they may interpret the creation story of Adam and Eve as symbolic rather than literal. Further, despite that there are a substantial proportion of religious individuals who do accept evolution (Jensen et al. 2019; Miller et al. 2006) both religious beliefs and evolution acceptance must be revealed to be apparent to others; since evolution and religion are perceived as competing for epistemic authority in society (O'Dell 2010) there may be a lack of apparent religious individuals who accept evolution within religious students' close friends and family groups (Hill 2014) making it seem implausible that religion and evolution could be compatible. Finally, church leaders, science instructors, and the media often present narratives that emphasize only conflict between religion and evolution without discussing areas of potential compatibility (Barnes et al. 2017; Jackson et al. 1995; Unsworth and Voas 2021).

While instructors could discuss the bounded and agnostic nature of science (Barnes et al. 2020b; Gould 1999; Huxley 1884; Barbour 1990) as well as present examples of religious biologists who accept, teach, and even study evolution (Collins 2006; Miller 1999; Dobzhansky 1973; Dajani 2015) to show ways that evolution and religion can coexist they often report not doing so (Barnes and Brownell 2016). All of these factors could lead religious students to perceive that their religious identity and evolution can only be in conflict. A student who perceives high conflict between their religion and evolution may learn about evolution but still chooses to reject it, potentially explaining weak relationships between evolution understanding and acceptance

in some studies/populations. However, the relationship between evolution acceptance and understanding may also change by scale and context of evolution acceptance.

The scale and context of evolution: microevolution acceptance, macroevolution acceptance, and human evolution acceptance

Despite the fact that many incoming college biology students reject the common ancestry of life, these students often still accept small genetic and trait changes in populations over a few generations (which is called "microevolution") indicating that different time scales and species contexts of evolution can impact how evolution is perceived (Beniermann et al. 2023; Nadelson and Southerland 2012; Sbeglia and Nehm 2019). For instance, when students are given the opportunity to identify their position on evolution, some will indicate they accept that modern reptiles, mammals, and birds evolved from previous animals of the same clade, but that these different clades were created separately from one another, indicating an acceptance of common ancestry at the level of a clade but not at the level of all of life on Earth (Yasri and Mancy 2016). In the same study (Yasri and Mancy 2016), other students indicated they believe that humans have remained relatively unchanged while other organisms have evolved over time, indicating an acceptance of evolution for species other than humans. Thus, evolution education researchers have differentiated between acceptance of microevolution (small changes within a species), acceptance of macroevolution (large evolutionary changes and between species) and acceptance of human evolution (evolution of the human species specifically) (Beniermann et al. 2023; Nadelson and Southerland 2012; Sbeglia and Nehm 2019; Barnes et al. 2024; Pobiner 2016).

The varied acceptance of evolution for different contexts (humans and nonhumans) and scales (microevolution and macroevolution) among students is *not* representative of expert thinking in biology. Within biology, the strength of evidence for evolution across scales and contexts is seen as equally strong and valid (Dietrich 2010). Despite the mismatch with expert thinking in biology, the differential acceptance of evolution based on time scale and species context has been a prominent pattern uncovered in evolution acceptance research. As such, survey measures for evolution acceptance have been developed to differentiate among students' acceptance levels of microevolution, macroevolution, and human evolution (Beniermann et al. 2023; Nadelson and Southerland 2012; Sbeglia and Nehm 2019; Barnes et al. 2022; Glaze et al. 2020).

Disconnects between student and expert thinking could be caused by cognitive constraints that makes it conceptually difficult for students to imagine large transformations of species (macroevolution) over periods much longer than the human life span that cannot be observed (Blancke and Smedt 2013). Microevolutionary changes can be documented in a matter of hours in a petri dish or years on an island, but macroevolutionary changes occur at timespans that often outlast a human lifetime. Alternatively, higher acceptance of microevolution compared to macroevolution and human evolution may also be caused by perceived conflicts with religion that are apparent with macroevolution and human evolution but not for microevolution. For instance, Judeo-Christian creation narratives are often seen as in direct conflict with claims that humans have evolved from prior species but small evolutionary changes, like antibiotic resistance in bacteria are readily accepted with no perceived conflict (Numbers 2006). So, while most students may not have trouble translating their understanding of evolution to their acceptance of microevolution, some students, particularly religious students, may have trouble translating their evolution understanding to acceptance of larger evolutionary changes. In this study, we examined how the religiosity levels of students may differentially impact the relationship between their evolution acceptance and understanding at different scales and contexts of evolution.

Current study

The data from this study is part of a larger survey-based study of American undergraduate biology classes. For this study, we analyzed the relationships between students' evolution understanding, their evolution acceptance, and their religiosity to determine to what extent students' religiosity impacted the relationship between their evolution understanding and evolution acceptance. We also looked at these relationships as they relate to different scales and contexts of evolution (microevolution acceptance, macroevolution acceptance, and human evolution acceptance). Considering that most evolution education studies are completed with samples of a few hundred students or fewer, this study, which reached over 11,000 undergraduate biology students across 14 states, serves to illustrate broad trends in these relationships.

Methods

Survey distribution

Researchers recruited biology instructors via an email sent out initially to the Society for Advancement of Biology Education Research (SABER) for which many members are college biology instructors. The email was purposely vague so that instructors would not know the purpose of the study; the email indicated that we were interested in surveying students in classes in which

evolution was taught to gather data on how to implement evidence-based evolution instruction. Instructors who were interested were then asked to send our recruitment email to other instructors. Finally, research assistants visited the websites of the biology departments with large enrollment introductory courses and sent individual emails to instructors of these courses. Instructors from 14 states within the United States (AL, AZ, CA, FL, HI, MI, MN, NC, NY, OK, SC, TX, UT, WI) agreed to send our survey to their students. Between Fall 2018 and Spring 2021, the surveys were administered across 15 institutions and 74 different biology courses throughout the United States. Before receiving evolution instruction, students completed the survey in exchange for a small amount of extra credit. In addition to a demographic questionnaire, previously published measures of religiosity (Cohen et al. 2008), acceptance of evolution (Nadelson and Southerland 2012), and evolution understanding (Hawley et al. 2011) that have previous validation evidence with college biology students were included in this study. All questions analyzed for this study can be found in Supplemental Material. The survey was approved through Arizona State University's institutional review board protocol #8191.

Participants

Surveys were made available to approximately 16,894 students and 11,995 responses were collected for a response rate of approximately 71%. After removing data from individuals who indicated that they did not provide honest and thoughtful responses, individuals who had missing data from necessary items, and individuals in courses with less than 20 survey responses to account for nesting (Simmons et al. 2011), the sample included 11,409 students. Most courses we collected data from were for science majors, but many non-majors students. For a detailed breakdown of the demographics of the sample, see Table 1.

Measures

Religiosity of students was measured using four statements from a previously published measure meant to capture the extent of students' religious tendencies (Cohen et al. 2008). Students disagree or agree with four statements on a 5-point Likert scale ($\alpha = 0.88$). Examples of items include "I believe in God." and "I attend religious services regularly". Likert scores of all four items were averaged to produce a composite religiosity score, with 1 being the least religious and 5 being the most religious.

Acceptance of evolution was gathered using 24 items from the Inventory of Student Evolution Acceptance (I-SEA) (Nadelson and Southerland 2012; Xia and Yang 2019; Savalei 2021). The original conception of the I-SEA includes three sub constructs of evolution acceptance: microevolution acceptance (i.e., "I think that species exist today in exactly the same shape and form in which they always have."), macroevolution acceptance (i.e., "I think the forms and diversity of organisms have changed dramatically over time.") and human evolution acceptance (i.e., "I think that humans and apes share an ancient ancestor."). Students disagree or agree with each statement on a 5-point Likert scale. However, past research has indicated that this three-factor structure of the I-SEA may not always be the most accurate. For instance, one study found that there may be evidence that the human evolution scale of the I-SEA may represent two dimensions including human microevolution and human macroevolution acceptance (Sbeglia and Nehm 2019).

Table 1 Demographics of students ($n = 11{,}409$)

Religion		**Race**	
Atheist/Agnostic	29.90%	Asian	17.30%
Buddhist	2.00%	Black/African American	6.50%
Christian	54.50%	Hispanic/Latin(x)	17.40%
Hindu	2.00%	Multiracial	9.40%
Jewish	1.70%	Native American	0.50%
Muslim	2.60%	Pacific Islander	0.30%
Other	4.70%	White	48.50%
Decline to state	2.60%		
Gender		**Major**	
Woman	68%	Biology	53%
Man	32%	Non-biology	47%
[a]Non-Binary	–		

[a] We had 44 non-binary students in our data set, but we did not include them in the analysis due to low sample size and the lack of prior data on how gender including non-binary students may affect evolution acceptance

Further, there has been limited research that has done exploratory work on the factor structure of the I-SEA since its original construction, with most subsequent studies only running confirmatory analyses (Beniermann et al. 2023; Nadelson and Southerland 2012; Sbeglia and Nehm 2019). Thus, we ran exploratory and confirmatory factor analyses to determine the structure of this measure for our sample.

To determine the number of dimensions within the I-SEA, we explored the number of factors by evaluating the scree plot using parallel analysis (Rstudio 2024) and using the *psych* package in RStudio. We then reviewed the results from the exploratory factor analyses (EFA) with maximum likelihood extraction and oblimin rotation using a five, six, or seven factor solution because it was most appropriate from the result of the parallel analysis (see Supplemental Material Figure 1 for scree plots). A six-factor solution was chosen for both statistical and theoretical reasons. The seven-factor solution was eliminated as a possibility because it produced a factor that only had one item without a strong factor loading (0.32). The five-factor solution was eliminated as a possibility because one factor included eight items that were a mixture of what was originally conceptualized in the I-SEA as microevolution, macroevolution, and human evolution items. We chose the six-factor solution because it retained most items on the I-SEA with factor loadings above 0.32 (Tabachnick and Fidell 2007) and it was most in line with the theoretical distinction between contexts and scales of evolution originally proposed in the I-SEA. Essentially, in the six factor model the original three subscales of the I-SEA were divided into two subscales each. Microevolution acceptance now was split into two subscales that represented negatively worded items and positively worded items; macroevolution acceptance was now split into two subscales representing macroevolutionary change (mostly based on recognition of evidence) and the common ancestry of all life on Earth; and human evolution acceptance was split into two subscales representing human evolutionary change within the species and human common ancestry with other apes. We have arranged these constructs from least to most evolutionary change in Table 2. One limitation of the common ancestry of life measure is that it only consists of two items, which may mean that this construct has underrepresentation of content (AERA et al. 2014). Future research should explore whether these two items adequately cover content areas related to the acceptance of common ancestry of life. Three items did not produce factor loadings of more than 0.32 and thus were eliminated from the measure ("I think physical variations in humans (i.e., eye color, skin color) were derived from the same processes that produce variation in other groups of organisms.", I think the forms and diversity of organisms have changed dramatically over time.", and "I think that new species evolve from a lot of small changes occurring over relatively long periods of time").

Confirmatory factor analyses (CFA) were run using *lavaan* package in Rstudio to test whether the *new* six factor or the *original* three factor structure conceptualized by the I-SEA was most supported by our data. We found that the six-factor model produced better fit statistics than the three-factor model (see Supplemental Material Table 1 comparing the CFI and RMSEA statistics for the three factor and six factor structure). Thus, based on the EFAs, theoretical considerations, and the CFAs, we decided to use the I-SEA as a six-dimensional measure. See Table 2 for the final factor structure used in our analyses that includes items that fall within each new subscale, the exploratory factor loadings of each item, and the reliability of each subscale as measured by Cronbach's alpha.

Evolution understanding was measured using 13 true or false items from two subscales of the Evolutionary Attitudes and Literacy instrument (EALS) (Hawley et al. 2011). Example items include "In most populations, more offspring are born than can survive" (Evolutionary Knowledge subscale) and "Evolution is a linear progression from primitive to advanced species" (Evolutionary Misconceptions subscale). We conceptualize that a students' level of understanding of evolution should account for both their knowledge of evolution as well as the misconceptions that persist despite that knowledge. Thus, we combined the two subscales to create a single measure of students' evolution understanding. In the original EALS instrument, students rate their level of agreement with each item on a 7-point agreement scale to assess their knowledge or misconception about evolution (Hawley et al. 2011; Short and Hawley 2012). However, given we also measure evolution acceptance within the same survey, asking students their agreement with items may present response process errors in which they answer based on their opinion rather than their understanding of evolutionary theory. Thus, in this survey, students were given the opportunity to choose whether each statement is "True" or "False", or to indicate that "I don't know enough to answer" based on their understanding of evolution. The "I don't know" option was included to decrease the chances the student would guess the correct answer. Selecting this option was treated as an incorrect response.

Students' understanding scores were calculated using the proportion of correct answers. For example, a score of 0.53 would indicate the student answered 7 out of 13 items correctly. A limitation of this measure is that it does not disaggregate student understanding

of evolution at different scales and in different contexts. Therefore, although this measure allows us to probe relationships between a general understanding of evolution and acceptance of the six different scales and contexts of evolution acceptance, we were not able to determine the relationships between understanding of specific scales or contexts and acceptance of those scales our contexts. For example, we could not determine the relationship between microevolution understanding and microevolution acceptance or macroevolution understanding and macroevolution acceptance, because this measure of understanding is

Table 2 Final six factors identified within the I-SEA instrument

Subscales	Item wording	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Microevolution (–) (α = 0.787)	I think that species were created to be perfectly suited to their environment, so they do not change[a]	0.70					
	I think that organisms, as they exist now, are perfectly adapted to their natural environments and so will not continue to change[a]	0.62					
	I don't accept the idea that a species of organism will evolve new traits over time[a]	0.58					
	I think that species exist today in exactly the same shape and form in which they always have[a]	0.54					
Microevolution (+) (α = 0.745)	I think there are a large number of examples of organisms that have undergone evolutionary changes within the species (i.e., antibiotic resistance in bacteria, production of new strains of the flu virus)		0.48				
	I think there is an abundance of observable evidence to support the theory describing how variations within a species can happen		0.43				
	I think all groups of organisms will continue to change		0.38				
	I think there is overwhelming evidence supporting the theory of evolution to explain how variations in a species develop over time		0.37				
Macroevolution (α = 0.792)	I think that the fossil evidence that scientists use to support evolutionary theory is weak and inconclusive			0.64			
	I think there are a large number of fossils found all around the world that support the ideas that organisms evolve into new species over time			0.62			
	I think there is little or no observable evidence to support the theory that describes how one species of organism evolves from a different ancestral form			0.44			
	I think that new species evolved from ancestral species			0.36			
Evolution within the human species (α = 0.892)	I think that humans do not evolve; they can only change their behavior[a]				0.87		
	I think that humans evolve				0.84		
	I think that humans adapt, but they have not/do not evolve[a]				0.75		
	I think that the physical structures of humans are too complex to have evolved[a]				0.5		

Table 2 (continued)

Subscales	Item wording	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Common ancestry of humans and non-human apes (α = 0.914)	I think the many characteristics that humans share with other primates (i.e., chimpanzees, gorillas) can be best explained by our sharing a common ancestor					0.92	
	I think that humans and apes share an ancient ancestor					0.92	
	I think there is reliable evidence to support the theory that describes how humans were derived from ancestral primates					0.61	
Common ancestry of life (α = 0.725)	I think all complex organisms evolved from single-celled organisms						0.8
	I think that all organisms come from a single common ancestor						0.69

For each factor, the reliability statistic is reported and the EFA factor loadings for each item are reported

Microevolution (−) refers to the measures with negatively worded items and microevolution (+) and indicates the measures with positively worded items

[a] Indicates reversed items

not disaggregated by these areas in the same manner as the acceptance measure.

Analyses

Construct validity evidence

We performed confirmatory factor analyses on all measurements to provide evidence of internal validity, using the *lavaan* package in RStudio. Because the data are Likert scales, we used the Diagonal Weighted Least Square estimator (Shi and Maydeu-Olivares 2020). Hu and Bentler (1999) suggested that RMSEA smaller than 0.06 and CFI larger than 0.95 indicate relatively good model—data fit for continuous data and all of our final measures produced RMSEA and CFI statistics within this acceptable range. The RMSEA and CFI statistics of all CFAs for all final measures can be found in Table 1 of the Supplementary Material.

Differences in acceptance of evolution at various scales and contexts

We used ANOVA to determine if there were any statistically significant differences between the averages of evolution acceptance variables. Then, a Tukey's HSD post hoc test was conducted for pairwise comparisons to identify which specific evolution acceptance averages differed from one another. Distribution of scores and averages between variables are illustrated in Fig. 1.

To determine whether the relationship between evolution acceptance and understanding changed based on student religiosity, we ran mixed-effects linear regression models using the *lme4* package in Rstudio (Bates et al. 2015). We ran a total of six linear mixed models with random intercepts, one for each of the six scales or contexts of evolution acceptance. Based on design effects (D_{eff}) using *Himsc* package in Rstudio, we nested the data by the shared institution and course of students. To determine which demographic variables and interaction effects to include in the models, we compared AIC values of models including different combinations of demographic variables and either including or not including interactions between religiosity and evolution understanding. A different combination of demographic variables resulted in the lowest AIC value for different scales and contexts of evolution acceptance, so we chose to include all demographic factors in all analyses predicting evolution acceptance (race/ethnicity, gender identity, major, and religious affiliation). AIC comparisons of all models tested can be found in Supplemental Material. The final models were:

1. Microevolution acceptance (−) ~ evolution understanding * religiosity + race + gender + religion + biomajor + (1|institution) + (1|course)
2. Microevolution acceptance (+) ~ evolution understanding * religiosity + race + gender + religion + biomajor + (1|institution) + (1|course)
3. Macroevolution acceptance ~ evolution understanding * religiosity + race + gender + religion + biomajor + (1|institution) + (1|course)
4. Within species human evolution acceptance ~ evolution understanding * religiosity + race + gender + religion + biomajor + (1|institution) + (1|course)

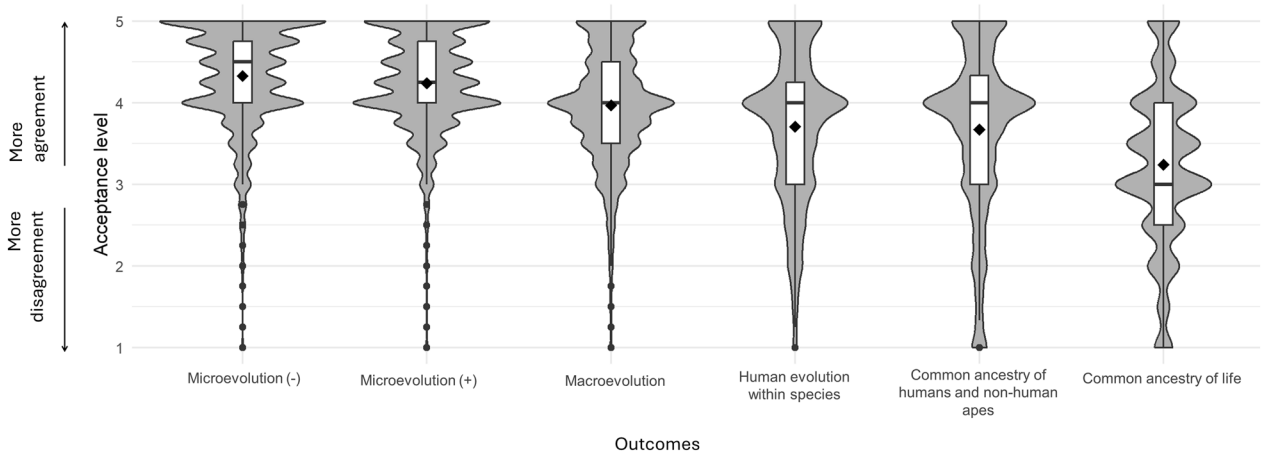

Fig. 1 Violin and box plots illustrating the acceptance of evolution broken down by six different scales and contexts of evolution. The shapes represent the distribution of student responses, dots indicate the means, and lines are the median. All means were significantly different from one another ($p < 0.01$) except for between within species human evolution acceptance and human common ancestry acceptance ($p > 0.01$). Exact p-values, and confidence intervals of pairwise comparison statistics are reported in Supplementary Material (Table 2)

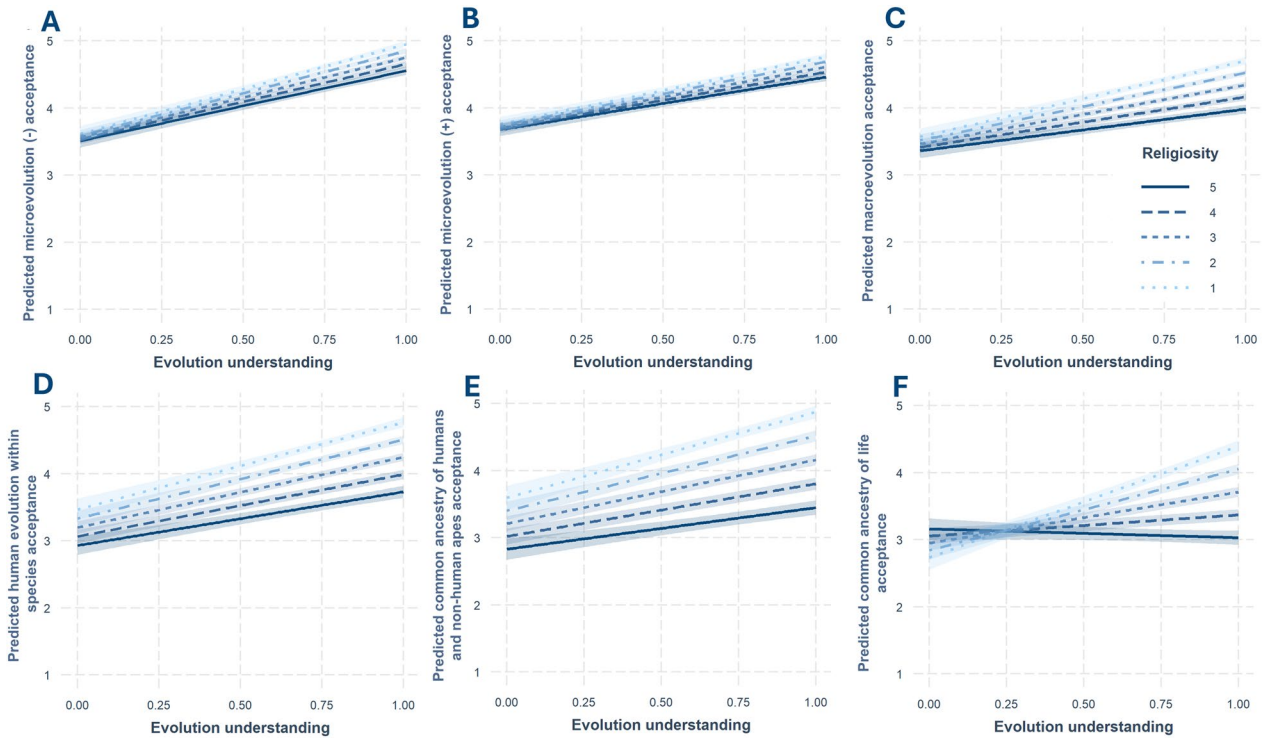

Fig. 2 Relationships between students' evolution understanding and acceptance of **A** microevolution (–), **B** microevolution (+), **C** macroevolution, **D** human evolution within species, **E** common ancestry of human and non-human apes, and **F** common ancestry of life disaggregated by religiosity level, 1 being the least religious and 5 being the most religious, determined by mixed effects regressions. The interaction between understanding and religiosity was statistically significant except for microevolution (–) and microevolution (+) outcomes ($p > 0.001$)

Table 3 Parameter estimates from linear mixed models for different context and scale of evolution acceptance

Outcome variables	Microevolution (−)	Microevolution (+)	Macroevolution	Evolution within the human species	Common ancestry of human and non-human apes	Common ancestry of life
(Intercept)	**3.64**	**3.78**	**3.62**	**3.6**	**3.78**	**2.63**
Evolution understanding	**1.41**	**1.06**	**1.27**	**1.42**	**1.44**	**2.11**
Religiosity	−0.03	−0.02	−0.05	**−0.13**	**−0.19**	**0.11**
Asian	**−0.12**	**−0.09**	**−0.08**	**−0.12**	−0.01	0.05
Black/African American	**−0.11**	**−0.1**	−0.04	**−0.11**	−0.08	0.05
Native American	−0.14	−0.01	−0.04	−0.04	0.18	0.19
Hispanic/Latinx	−0.04	−0.01	**0.08**	0.00	**0.11**	**0.13**
Multiracial	0.02	0.02	0.03	0.01	0.05	**0.08**
Native American	−0.15	−0.08	−0.15	−0.2	−0.22	0.00
Woman	**0.06**	0.01	−0.01	**−0.06**	−0.04	**−0.14**
Other religion	−0.04	−0.03	0.03	**0.07**	**0.13**	0.05
Christian	**−0.11**	**−0.11**	**−0.11**	**−0.17**	**−0.2**	**−0.21**
Muslim	**−0.15**	**−0.12**	**−0.14**	**−0.19**	**−0.34**	−0.13
Non-biology major	−0.03	**−0.04**	**−0.04**	**−0.04**	**−0.07**	**−0.08**
Evolution understanding * religiosity	−0.07	−0.06	**−0.13**	**−0.12**	**−0.16**	**−0.45**
Random effects						
R^2	0.17	0.12	0.15	0.19	0.25	0.16

Bolded numbers indicate $p < 0.01$

5. Human and non-human ape ancestry acceptance ~ evolution understanding * religiosity + race + gender + religion + biomajor + (1|institution) + (1|course)
6. Common ancestry of life acceptance ~ evolution understanding * religiosity + race + gender + religion + biomajor + (1|institution) + (1|course)

When interactions between acceptance and understanding were significant, we probed them by conducting a simple slopes analysis using the *interactions* package in Rstudio. These simple slopes analyses allowed us to estimate the relationship between acceptance and understanding for each level of student religiosity (Preacher et al. 2006). Since this dataset has large sample sizes, we consider a result statistically significant when $p < 0.01$ to avoid reporting statistically significant results that are practically insignificant.

Results

Finding 1: student acceptance of evolution varies by evolutionary scale and context, with students accepting the common ancestry of life the least

We compared student evolution acceptance scores and the analysis of variance (ANOVA) detected significant differences in acceptance scores between the six evolutionary scales and contexts, $F(5, 68{,}448) = 2776$, $p < 0.001$. Students were most accepting of microevolution (negatively worded items: $M = 4.33$, $SD = 0.633$; positively worded items: $M = 4.24$, $SD = 0.591$) and macroevolution ($M = 3.97$, $SD = 0.694$). Students were least accepting evolution within human species ($M = 3.71$, $SD = 0.893$), common ancestry of humans and non-human apes ($M = 3.67$, $SD = 1.01$), and the common ancestry of all of life ($M = 3.24$, $SD = 0.98$). The pairwise comparisons of these constructs indicated significant differences between all constructs ($p < 0.01$) except between acceptance of within species human evolution and common ancestry of humans ($p > 0.01$). See Fig. 1 for the distributions and central tendencies of students' evolution acceptance scores disaggregated by the different scales and contexts.

Finding 2: the relationship between students' understanding and acceptance of evolution depends on their religiosity and the context/scale of evolution

We examined how the relationship between acceptance and understanding changed based on student religiosity. Linear mixed-effects regressions (Table 3) showed that the interactions between evolution understanding and religiosity were statistically significant predictors of macroevolution acceptance ($\beta = -0.13$, $p < 0.001$), human evolution acceptance within species ($\beta = -0.12$, $p = 0.001$), acceptance of common ancestry of humans

Table 4 Results from the simple slope analyses testing to what extent evolution understanding predicts evolution acceptance for students of different religiosity levels (1 for the least religious and 5 being the most religious)

Outcome variable	Religiosity level	*β*	SE	*t*-statistic	*p*-value	CI
Macroevolution	1	1.22	0.09	14.4	0.00	1.06–1.39
	2	1.13	0.06	19.3	0.00	1.01–1.24
	3	1.03	0.04	24.9	0.00	0.95–1.11
	4	0.93	0.05	19.9	0.00	0.84–1.02
	5	0.83	0.07	11.9	0.00	0.70–0.97
Evolution within the human species	1	1.25	0.10	12.5	0.00	1.06–1.45
	2	1.16	0.07	17.1	0.00	1.03–1.30
	3	1.07	0.05	22.3	0.00	0.98–1.17
	4	0.99	0.05	18.0	0.00	0.88–1.09
	5	0.90	0.08	11.0	0.00	0.74–1.06
Common ancestry of human and non-human apes	1	1.20	0.11	11.2	0.00	0.99–1.42
	2	1.08	0.07	14.7	0.00	0.94–1.23
	3	0.96	0.05	18.4	0.00	0.86–1.06
	4	0.84	0.06	14.2	0.00	0.72–0.96
	5	0.72	0.09	8.2	0.00	0.55–0.89
Common ancestry of life	1	1.61	0.11	14.4	0.00	1.39–1.83
	2	1.19	0.08	15.6	0.00	1.04–1.34
	3	0.78	0.05	14.4	0.00	0.67–0.88
	4	0.36	0.06	5.9	0.00	0.24–0.48
	5	−0.06	0.09	−0.6	0.54	−0.23–0.12

and other apes ($\beta = -0.16$, $p < 0.001$), and acceptance of the common ancestry of all life on Earth ($\beta = -0.45$, $p < 0.001$) (see Fig. 2 for illustration of interactions). However, the interactions between evolution understanding and religiosity were not statistically significant as predictors for either microevolution acceptance scales (microevolution acceptance (−) ($\beta = -0.07$, $p = 0.011$); microevolution acceptance (+) ($\beta = -0.076$ $p = 0.042$). These results indicate that students' religiosity level only moderated the relationship between their understanding of evolution and evolution acceptance in specific evolutionary scales and contexts. To determine the relationship between acceptance and understanding for students of different religiosity levels at these four different scales and contexts of evolution for which we found statistically significant interactions, we examined the results of the simple slope analyses (Table 4).

Completed linear mixed model result can be found in Supplementary Material Table 5.

While the interaction effects showed the *presence* of a moderation effect, the simple slopes analyses more specifically reveal *how* the strength of relationships change depending on the moderating variable. From the outputs of the simple slopes analyses (Table 4), we examined the evolution understanding confidence intervals of students at the highest and lowest religiosity levels at the four contexts and scales of evolution for which there were statistically significant interactions detected. The relationship between acceptance and understanding was weaker for students at the highest levels of religiosity than for students at the lowest levels of religiosity for all four contexts and scales of evolution acceptance as indicated by non-overlapping confidence intervals. Of particular note, among students with a high religiosity level, there was no relationship between their understanding of evolution and their acceptance of the common ancestry of all of life ($\beta = -0.06$, $p = 0.54$).

Discussion

Among our sample of college biology students, we found that the I-SEA measured six distinct scales or contexts of evolution acceptance including: (1) microevolution acceptance with negatively worded items, (2) microevolution acceptance with positively worded items, (3) macroevolution acceptance, (4) within species human evolution acceptance, (5) acceptance of common ancestry between human and non-human apes, and (6) acceptance that all life shares a common ancestor. Further, we found that the relationship between understanding and acceptance of evolution depended on the religiosity of students for all contexts or scales of evolution except for microevolution. Below, we outline the six different scales or contexts of acceptance of evolution and discuss our results for each.

Two scales of microevolution acceptance

We found that I-SEA microevolution acceptance items fell onto two factors: (1) items that were negatively worded and indicated that species *do not* change and (2) items that were positively worded that indicated species *do* change (Table 4). This corroborates prior research showing items from measures of evolution acceptance fell onto two distinct factors that were primarily based on whether the items were positively or negatively worded (Romine et al. 2018). We also found that students were the most accepting of microevolution compared to the other four scales or contexts of evolution. In fact, there were very few students who scored low on either measure of microevolution acceptance. Box plots in Fig. 1 indicated that most students scored above a 4 out of 5 on both microevolution acceptance scales, indicating that they often "agreed" or "strongly agreed" with microevolution acceptance items. These results corroborate many prior studies that have found that few students report rejecting microevolution (Nadelson and Southerland 2012; Barnes et al. 2022; Pobiner 2016; Misheva et al. 2023). While research is showing that students struggle with *understanding* microevolutionary principles (Andrews et al. 2012; Beggrow and Nehm 2012; Champagne Queloz et al. 2017; Price et al. 2014; Sripathi and Hoskinson 2024) it appears they do not struggle with *accepting* microevolution. It is unsurprising then that we also found religiosity to have no impact on the relationship between understanding evolution and accepting microevolution. Students appear to translate their understanding to acceptance of microevolution regardless of their level of religiosity.

Macroevolution acceptance scale

Among our sample of students, macroevolution acceptance consisted of four items that mostly emphasized the evidence for speciation (Table 1). Using these four items, students were less accepting of macroevolution compared to microevolution. Box plots in Fig. 1 indicated that while many students scored above a 4 out of 5 on macroevolution acceptance, there were also many students who scored in the 3–4 range indicating they, on average, less than "agreed" with macroevolution acceptance items. Additionally, very few students scored less than a 3 on this scale, indicating that it is relatively rare for students to actively disagree with macroevolution. In contrast to microevolution acceptance results, we found that the relationship between understanding and macroevolution acceptance was moderated by students' religiosity. Students from higher religiosity groups showed a weaker relationship between their understanding and acceptance than lower religiosity students (Table 4). This indicates that among highly religious students, understanding of evolution may translate less to macroevolution acceptance compared to their non-religious peers.

Two scales of human evolution acceptance

We found that the I-SEA human evolution acceptance items fell onto two distinct factors: (1) evolution within the human species and (2) common ancestry of human and non-human apes. This corroborates prior research that indicated the I-SEA human items consisted of two factors that the researchers called human microevolution acceptance and human macroevolution acceptance (Sbeglia and Nehm 2019). We also found that students were less accepting of human evolution than microevolution and macroevolution. In contrast to microevolution and macroevolution acceptance, there were a substantial portion of students that disagreed with items on both human evolution acceptance measures (Fig. 2). So, while students were often more uncertain about macroevolution than microevolution, many students actively disagreed with human evolution. Further, like macroevolution acceptance, we found that the relationship between acceptance and understanding was moderated by religiosity for both measures of human evolution acceptance (Tables 3, 4). Highly religious students showed a weaker relationship between their understanding and acceptance of both human evolution scales compared to low religiosity students (Table 4).

Acceptance of the common ancestry of life

Our research discovered a new area of evolution acceptance that has received very little discussion to our knowledge in the evolution education literature. Two items originally from the macroevolution scale were found to fall on a distinct factor which we have called acceptance of the common ancestry of life. These items were distinct from the other items not only theoretically, but also in the EFA and CFA results. Further, these two items showed the most striking results. Students had the most difficulty agreeing with the common ancestry of life items compared to the other four contexts or scales of evolution acceptance. The distribution of student scores in Fig. 2 show that many students actively disagreed with these items compared to any other scale or context of evolution. These results corroborate research showing that students imagine acceptance of common ancestry at different taxonomic levels when answering questions on the I-SEA (Misheva et al. 2023). The low acceptance levels of common ancestry are also corroborated by previous research that showed approximately thirty percent of college biology students sampled nationwide did not accept that life shares a common ancestor (Barnes et al. 2020b). Further, the common ancestry measure was the only context of evolution for which highly religious

students' understanding of evolution was not at all related to their acceptance. This indicates that accepting the common ancestry of life will be the most difficult for students, and that highly religious students may have the most trouble translating their understanding of evolution to their acceptance of the common ancestry of life.

Despite these striking results coming from measuring acceptance of the common ancestry of life, there is much work to be done to fully understand students' conceptions of the common ancestry of life, their levels of acceptance, and the relationship between their understanding and acceptance of this relatively novel construct. Our current measure only consisted of two items (Table 2) and research into this construct has only been explored preliminarily in a handful of studies (Barnes et al. 2020b, 2021a, 2022; Misheva et al. 2023). Recently, 16 evolution education researchers from across disciplines, religious backgrounds, and religious expertise, came together to find common ground on definitions of evolution acceptance. The definition they all agreed upon was "agreeing that evolution is valid and the best explanation from science for the unity and diversity of life on Earth, which includes speciation, *the common ancestry of life*, and that humans evolved from non-human ancestors" (Barnes et al. 2024). Given that this relatively unexplored construct was highlighted as an important aspect of evolution acceptance by many experts in the field, this is likely an important area of research to build out. However, to build out a measure of acceptance of the common ancestry of life on Earth, we need much more qualitative work to explore students' conceptions further. Thus, we assert that this area is fruitful for future researchers to explore and may result in new insights into students' conceptualizations of their evolution acceptance, as well as how variables such as their understanding and religiosity may impact their acceptance.

Conclusion

This is the first quantitative study to our knowledge that has shown that for college biology students, the relationship between evolution understanding and acceptance for college biology students in the United States, is moderated by religiosity. Further, we provided evidence for six different scales and contexts for which students have different levels of evolution acceptance, including a relatively new construct not previously documented quantitatively: the common ancestry of life on Earth. These results suggest that evolution acceptance is more multifaceted than previously thought and that religiosity may impact students' translation of their understanding of evolution to their acceptance of evolution.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12052-024-00207-y.

Supplementary Material 1.

Acknowledgements
We would like to acknowledge the instructors of biology courses willing to implement our survey and the thousands of students who were willing to complete the survey.

Author contributions
Rahmi Aini analyzed the data, interpreted the results, reviewed and revised the manuscript draft; Madison Stewart analyzed the data, interpreted the results, and contributed to writing of the manuscript; Sara E. Brownell conceptualized the study, interpreted the results, and contributed to writing of the manuscript; M. Elizabeth Barnes conceptualized the study, collected and analyzed the data, interpreted the results, and contributed to writing of the manuscript.

Funding
This project was funded by NSF grant #1818659.

Availability of data and materials
The dataset supporting the conclusions of this article is available at GitHub https://github.com/BioedSPSlab/Evolution.Understanding.Acceptance.Religiosity.

Declarations

Ethics approval and consent to participate
The survey was approved through Arizona State University's institutional review board protocol #8191 and student participants consented to participate and have their data published.

Competing interests
The authors declare no competing interests.

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Received: 13 March 2024 Accepted: 23 July 2024
Published online: 19 August 2024

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