Analyzing Upper Level Undergraduate Knowledge of Evolutionary Processes: Can Class Discussions Help?

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For biologists, a proper understanding of evolutionary processes is fundamentally important. However, undergraduate biology students often struggle to understand evolutionary processes, replacing factual knowledge with misconceptions on the subject. Classroom discussions can be effective active learning tools used to address these misconceptions and build undergraduate knowledge of evolution. This study aimed to (a) quantify knowledge and misconceptions of evolutionary processes among upper level undergraduate students and (b) analyze how knowledge and misconceptions changed throughout a semester-long, discussion-based course. Precourse assessment scores revealed that student knowledge of evolution was low, even among students who had previously taken evolution-based courses. Improvement shown on postcourse assessments suggests that classroom discussion can help strengthen student understanding of evolution and address misconceptions.

> *Nothing in biology makes sense except in the light of evolution.*
> —Theodosius Dobzhansky

This famous quote by Dobzhansky (1973) sheds light on the vital importance that biologists place on the understanding of evolutionary processes. For undergraduate biology students, a proper understanding of evolutionary processes is fundamental because evolution serves as the foundation on which all modern biological subjects (e.g., ecology, physiology) are built. However, 40 years after Dobzhansky's now-famous quote was first published, many undergraduates still struggle to grasp key concepts of evolution.

Misconceptions about evolutionary processes are commonplace in undergraduate biology classrooms (Hokayem & BouJaoude, 2008; Moore, Brooks, & Cotner, 2011; Moore et al., 2002; Nehm & Reilly, 2007). The sources of these misconceptions, although variable (Alters & Nelson, 2002), often stem from students' first encounters with evolutionary terms during their K–12 educations (Moore et al., 2011), and misconceptions are often transferred from teachers to students (Nehm, Kim, & Sheppard, 2009; Nehm & Schonfeld, 2007). These misconceptions, left unchecked, can become deeply rooted in the students' ways of thinking and continue to manifest themselves as undergraduates progress through biology curricula.

Undergraduate biology instructors are challenged to break down student misconceptions regarding evolutionary process before addressing new course topics. Correcting misconceptions is often difficult, but it is widely regarded as an important first step in building student knowledge (Bransford, Brown, & Cocking, 2000; Handelsman, Miller, & Pfund, 2007). However, given the brief time frame that instructors have to cover their course's topics, addressing students' misconceptions regarding evolutionary processes is often not a priority. Perpetuating this problem is the fact that biology curricula is generally linear in nature, with each successive course building on the foundations laid in previous courses. Thus, without addressing their misconceptions and gaining proper understanding of evolutionary processes early in their undergraduate careers, students will have difficulty understanding topics in other, more advanced courses in which they enroll (Alters & Nelson, 2002).

Active learning exercises, such as classroom discussions, have been shown to be effective teaching tools (Allen & Tanner, 2005; Alters & Nelson, 2002; Grover, 2007; Handelsman et al., 2007; Marbach-Ad & Sokolove, 2000; Nelson, 2008; Smith et al., 2009). Participation in classroom discussions helps (a) expose budding scientists to the importance of teamwork and cooperation (Handelsman et al., 2007), (b) foster the inclusion of underrepresented groups (e.g., minorities and females; Beichner et al., 1999), and (c) allow students to maintain personal contact with their instructor (Handelsman et al., 2007). Additionally, discussions in the classroom can facilitate knowledge exchange between students, helping to expose common misconceptions (Handelsman et al., 2007). This serves as the starting point for conceptual change, an approach that emphasizes students' challenging their own conceptions of a topic (Posner, Strike, Hewson, & Gertzog, 1982). This conceptual change approach is of particular value to undergraduate biology classrooms, in which evolutionary misconceptions are often rampant. To effectively uncover misconceptions, discussions must be in environments that foster communication and participation by all students, and students must understand the importance of their contributions (Handelsman et al., 2007). In large classrooms, this can be achieved by breaking students into small, heterogeneous groups of three to six students for discussion, which helps include shy students (Handelsman et al., 2007).

Extensive research has shown that students struggle with evolutionary knowledge and harbor misconceptions across education levels, including K–12 (Donnelly, Kazempour, & Amirshokoohi, 2009; Moore et al., 2011), lower level undergraduate (both biology majors and nonmajors; Anderson, Fisher, & Norman, 2002; Nehm and Reilly, 2007; Sinatra, Southerland, McConaughy, & Demastes, 2003), and upper level undergraduate (Balgopal & Montplaisir, 2011; Dagher & BouJaoude, 1997, 2005; Ingram & Nelson, 2006). Upper level biology majors are expected to have a strong grasp of evolutionary concepts because of their extensive exposure to the topic throughout their education. Because upper level biology majors represent soon-to-be biology professionals, it is of paramount importance that specific attention be paid to their understanding of evolutionary concepts.

The objectives of this study were twofold. First, we aimed to quantify the knowledge and misconceptions that upper level biology majors have regarding basic evolutionary processes. Second, we aimed to analyze whether classroom discussions could serve as pedagogical tools to increase student knowledge of evolution and address misconceptions about evolution.

Methods

Study population

Study participants were enrolled in Environmental Physiology in the spring semester 2012 at a large Midwestern university. This course is an upper level elective course, which many students take to fulfill their physiology credit requirement. The overall theme of this course is physiological adaptation to the environment, and thus students need a strong background in evolution to fully understand the course topics. Students in this course enroll in both the lecture (all students attending simultaneously, ~80 students) and one of four discussion sections (~20 students each). The course prerequisites included (a) organismal and population biology and (b) cell and molecular biology courses, both of which introduce students to fundamental evolution and genetics concepts. Additionally, some students had also taken a course solely devoted to evolutionary biology prior to enrolling in the course.

At the beginning of the semester, students were asked to give consent to participate in this study. Students who consented to participate but failed to complete the assessments in their entirety were excluded from analysis. Sixty-six students agreed to participate in this study and completed the study's assessments

TABLE 1

Self-reported class demographics.

Class level	seniors = 52, juniors = 13, sophomores = 1
Gender*	male = 22, female = 44
Previously taken a course specifically covering evolution#	yes = 35, no = 31
Taking a course specifically covering evolution concurrent with this course#	yes = 10

Note: Values represent the number of students in each category. *N* = 66 participants.

*This gender distribution is consistent with what is seen in zoology classes at this university and so is believed to be a representative population of zoology students.

#Some students reported that they were retaking evolution. These students were included as having already taken evolution in all analyses.

in their entirety. Table 1 lists the demographics of the study population.

Class discussion sections

Discussion sections consisted of one 50-minute class period per week, during which students engaged in peer–peer dialogue about course-related topics and assigned readings. Students were assigned a weekly reading assignment to complete before the discussion section. Course readings (Table 2) consisted of primary scientific journal articles (i.e., research reports) or philosophy of science articles that coincided with lecture topics covered in the main section of the course.

During discussion periods, students participated in both small group (three to six students) and large group (~20 students) discussions centered on previously constructed discussion questions (Table 3) and activities. Students tended to first answer discussion questions in self-constructed small groups and then convene to discuss their findings in the large-group setting. Other active learning exercises, including games and hands-on activities, were used to stimulate discussions within small groups; the outcomes of the exercises were later discussed in the large-group setting. Discussions were led by one of two graduate teaching assistants (TAs) who met weekly with the course instructor to brainstorm important concepts and relevant discussion questions for use that week. All discussion questions and activities were based on these meetings. Five discussion periods were led by student discussion leaders in groups of three to five students with the help of a TA (Table 2). Prior to student-led discussions, student discussion leaders met with a TA to discuss important topics and to ensure that they fully understood the discussion topics.

Discussion sections were an integral part of this course, and this study was designed to fit into the normal class structure without alteration. The discussion section grade accounted for 20% of the overall course grade and was comprised of (a) a sample discussion question submitted each week by the student, (b) a score as discussion leader, and (c) scores on reading quizzes given on 8 randomly selected weeks. Students were assigned a discussion section to attend throughout the semester. As per course policy, attendance was not strictly tracked throughout the semester. However, students were asked to report on postsemester surveys which discussion section they attended most regularly, how many sections they attended, and how many assigned readings they completed. On average, students reported attending 14.09 ± 1.30 (mean ± SD) of 15 discussions and reading 13.53 ± 1.33 of 14 assignments.

Evolution was a central or underlying topic in the classroom discussions throughout the semester and was explicitly covered in Weeks 1, 4, and 5 (Table 2). Discussion readings for these weeks were specifically chosen to stimulate student discussions on evolution. In all other weeks, evolutionary topics served as underlying topics for discussions on animal physiology, specifically the linkage between animal adaptation and the environment. Thus, evolutionary topics were covered in all discussions, in some fashion, each week.

Surveys and assessments

All students were required to complete pre- and postcourse assessments via the course's online course management system within the initial and final 2 weeks of the semester, respectively. Students were given a small amount of class credit (equal to one quiz) for the full completion of the pre- and postcourse assessments, regardless of the accuracy of their responses or decision to participate in this study. Only scores from students who consented to participation in the study were used for analysis.

Our assessments were designed by the first author of this paper with assistance from other STEM education researchers. These consisted of survey questions assessing class demographics and background with course materials, followed by a series of open-response questions (Table 4) assessing student knowledge of course-related topics. Assessment questions focused specifically on student understanding of evolutionary processes and were meant to address different levels of complexity, ranging from simple definitions to questions requiring more complex analyses. Seven of the nine questions asked were used to assess knowledge of evolutionary process. These addressed fundamental processes and were chosen because (a) the questions tested basic understanding of evolutionary processes and (b) the answers represent a knowledge base that is required for full understanding of the course's topics. The remaining two questions were nonevolutionary questions used as a quasi-control to ensure that students were learning other nonevolution topics related to this class and as a proxy to measuring student skill at reading primary literature. The nonevolution questions were chosen because (a) they represent fundamentally important methodological approaches to re-

TABLE 2

Assigned course readings.

Discussion week	Assigned course readings	Related course topics
1	Vogel, S. (1988). *Life's devices*. Princeton, NJ: Princeton University Press. Alexander, R. M. (1985). The ideal and the feasible: Physical constraints on evolution. *Biological Journal of the Linnean Society, 26,* 345–358.	Evolution, adaptation, philosophy of science
2	Frank, C. L. (1988). Diet selection by a heteromyid rodent: Role of net metabolic water production. *Ecology, 69,* 1943–1951.	Metabolic water, water physiology
3	Perrigo, G., & Bronson, F. H. (1985). Behavioral and physiological responses of female house mice to foraging variation. *Physiology and Behavior, 34,* 437–440. Schultz, L. A., Collier, G., & Johnson, D. R. (1999). Behavioral strategies in the cold: Effects of feeding and nesting costs. *Physiology and Behavior, 67,* 107–115.	Energy acquisition, ecological and physiological trade-offs
4	Jacob, F. (1977). Evolution and tinkering. *Science, 196,* 1161–1166 (pp. 1161–1165 only).	Evolution, adaptation, philosophy of science
5	Gould, S. J., & Lewontin, R. C. (1979). The spandrels of San Marco and the Panglossian paradigm: A critique of the adaptationist programme. *Proceedings of the Royal Society of London, Series B*, *205,* 581–598 (pp. 581–593). Schwalm, P. A., Starrett, P. H., & McDiarmid, R.W. (1977). Infrared reflectance in leaf-sitting neotropical frogs. *Science, 196,* 1225–1226.	Evolution, adaptation, philosophy of science
6	Lankford, T. E., Jr., Billerbeck, J. M., & Conover, D. O. (2001). Evolution of intrinsic growth and energy acquisition rates: II. Trade-offs with vulnerability to predation in Menidia menidia. *Evolution, 55,* 1873–1881.	Energy acquisition, ecological and physiological trade-offs, countergradient variation
7	Eccles, J. C. (1970). *Facing reality*. New York, NY: Springer-Verlag (pp. 102–105 and 114–117 only). Platt, J. R. (1964). Strong inference. *Science, 146,* 347–353 (pp. 347–351 only).	Philosophy of science
8*	McNaughton, S. J. (1990). Mineral nutrition and seasonal movements of African migratory ungulates. *Nature, 345,* 613–615. McNaughton, S. J. (1988). Mineral nutrition and spatial concentrations of African ungulates. *Nature, 334,* 343–345.	Mineral nutrition, Serengeti migration
9*	Mahoney, D. J., Parise, G., Melov, S., Safdar, A., & Tarnopolsky, M. A. (2005). Analysis of global mRNA expression in human skeletal muscle during recovery from endurance exercise. *FASEB Journal, 19,* 1498–1500.	Gene expression, exercise physiology, genetic techniques
10*	Piersma, T. (2011). Why marathon migrants get away with high metabolic ceilings: Towards an ecology of physiological restraint. *Journal of Experimental Biology, 214,* 295–302.	Metabolic ceilings, physiological restraint
11*	Levine, J. A., Eberhardt, N. L., & Jensen, M. D. (1999). Role of nonexercise activity thermogenesis in resistance to fat gain in humans. *Science, 283,* 212–214.	Exercise physiology, fat gain
12*	Sparling, C. E., Fedak, M. A., & Thompson, D. (2007). Eat now, pay later? Evidence of deferred food-processing costs in diving seals. *Biology Letters, 3,* 94–98.	Specific dynamic action
13	Visser, M. E., van Noordwijk, A. J., Tinbergen, J. M., & Lessells, C. M. (1998). Warmer springs lead to mistimed reproduction in great tits (*Parus major*). *Proceedings of the Royal Society of London, Series B, 265,* 1867–1870. Both, C., & Visser, M. E. (2001). Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. *Nature, 411,* 296–298.	Climate change, adaptation, reproductive biology
14	Medawar, P. B. (1984). *The limits of science*. New York, NY: Harper & Row (pp. 61–93 and 98 only).	Philosophy of Science

*Denotes that the discussion was student led.

TABLE 3

Example discussion questions used in classroom discussions.

Week	Discussion question
1	In what ways does molecular size constrain evolution? Vogel (1988) stated that "given sufficient time, all is possible through evolutionary innovation." In what ways is this statement correct/incorrect. Why?
4	How does gene duplication "help" evolution?
13	What biological factors limit the Great Tit's and the Pied Flycatcher's abilities to shift their breeding to better coincide with offspring needs? Why don't they just lay eggs earlier to adjust for the effects of climate change?

search in biology, and (b) students could not fully grasp the concepts presented in certain discussion readings without understanding these topics. Pre- and postcourse assessment questions were identical except for minor wording changes (e.g., changing organism names). Students were not given feedback on the accuracy of their responses.

All assessment responses were deidentified and scored using a defined rubric (http://www.nsta.org/college/connections.aspx). Rubric answers to definition-type questions were taken from the textbook used for this course (Hill, Wyse, & Anderson, 2008). The first author of this paper served as one of the TAs for this course and was responsible for the construction of the scoring rubrics, the scoring of all assessments, and the identification of misconceptions. Interrater reliability for quantitatively scored questions was verified by having the assessments blindly rescored by a second scorer who had no affiliation with the course, was blind to the identities of the students, and did not know which assessments were pre- and postcourse. Pearson's correlation coefficient (r) was used to assess interrater reliability for each assessment question and showed highly significant correlation between the two scorers (r = 0.720 – 0.942, $P < .0001$), and thus we concluded that the rubric and its implementation were suitable.

Three common misconceptions regarding evolution were qualitatively scored from student responses to Q1–Q5 (Table 5). These misconceptions were that (a) individual animals adapt during their lifetimes, (b) evolution is a process that takes longer than adaptation, and (c) adaptation leads to evolution. These misconceptions were chosen for analyses because they (a) have been shown to exist in other similar studies (Nehm et al., 2009), (b) frequently manifested themselves in class discussions in previous years of this course, and (c) represented strong barriers to the students' understandings of basic evolutionary processes. The number of students exhibiting these misconceptions was tallied for both pre- and postsemester assessments. Students could, and often did, show multiple misconceptions in their answers.

Statistical analyses

A significance cutoff of $P = .05$ was used for all statistical tests performed in this study. Among section variability in knowledge (total pre- and postcourse assessment scores and overall changes in total assessment scores) was analyzed using a one-way analysis of variance (ANOVA). Because the data did not conform to the distributional assumptions of parametric tests, comparisons between pre- and postcourse assessment scores were done using nonparametric tests. Pre- and postcourse scores for each question were compared using a one-sided Wilcoxon sign-ranks test for matched pairs to test the a priori hypothesis that student knowledge of evolution increases after participating in classroom discussions. The number of misconceptions per student was also compared pre- and postcourse using a one-sided Wilcoxon signed-rank test for matched pairs. Comparisons of precourse assessment scores between students who had taken versus students who had not taken a course on evolution were done using a two-sided Mann–Whitney U test because there were no a priori predictions on the directionality of the results. Occasionally, student responses were cut off by the space allotment on the online survey and were not included in analysis. This is reflected in the sample sizes listed on the graphs in the Results section.

Results

Precourse assessment

Surprisingly, students who had previously taken courses on evolution scored significantly better on only three of seven evolution questions analyzed compared with those who had not taken prior courses on evolution (Figure 1A). There was no significant difference in the ability to define the term *evolution* between students who had and those who had not taken evolution courses (Figure 1A). Although students who had previously taken classes on evolution performed better overall, they still scored below an average of 50% on all evolution questions. Students who had taken evolution scored significantly higher than those who had not on the nonevolution question regarding observational versus manipulative research methods ($P < .05$; Figure 1B).

Precourse versus postcourse assessment

Precourse assessment scores, postcourse assessment scores, and changes in scores across the semester did not differ among discussion sections in this course (ANOVA; $P > .05$). Scores on five of nine questions significantly increased over the course of the semester (Wilcoxon signed-rank test for matched pairs, $P < .05$; Figure 2). Students showed a significant increase in their ability to define the term *evolution* ($P < .0001$; Figure 2A), with mean response scores increasing from 4.35/10 on the precourse assessment to 6.42/10 on the postcourse assessment. Responses to the question asking if populations could evolve without adapting increased significantly ($P = .0093$; Figure 2A), as did responses to the question asking if populations could adapt without evolving ($P = .034$; Figure 2A). Student responses to the question regarding Francois Jacob's evolution as tinkering analogy significantly increased ($P = .0056$; Figure 2A), showing that the students identified this important evolutionary metaphor. Students also showed an increase in knowledge pertaining to distinguishing between observational and manipulative research methods ($P = .0001$; Figure 2B).

Scores on four of the nine questions assessed showed no significant increase over the course of the semester (Wilcoxon signed-rank test for matched pairs; $P > .05$; Figure 2). Response scores to the question asking students to explain the difference between evolution and adaptation showed a marginally insignificant increase ($P = .0720$; Figure 2A). This

TABLE 4

Questions asked on pre- and postcourse assessments.

Q1. In one sentence, please define the term "Evolution."
Q2. In one sentence, define the process of "Adaptation."
Q3. Explain the difference between the terms "evolution" and "adaptation" as they relate to biology.
Q4. Is it possible for a population to evolve *without* adapting? Explain why/why not.
Q5. Is it possible for a population of animals to adapt *without* evolving? Explain why/why not.
Q6. A new, highly beneficial trait is introduced into a population of wild deer. This new trait allows individuals that have it to avoid predation much better than those that do not have it. Since it is so beneficial, the new trait is selected for and spreads throughout the population of deer, becoming fixed (100% of individuals have it) after 10 generations. (A) Explain how this new trait came into existence (i.e., where did it come from?). (B) Explain how the process of natural selection drives this trait to fixation.
Q7. Suppose that I want to know the average height of our university's undergraduate students. I know from previous studies that arm lengths are directly correlated to overall height. I randomly choose 100 undergraduate students and measure their arm lengths and use those measurements to estimate the average height of our university's undergraduate students. Was measuring arm length, in this case, a *direct* or *indirect* measure of height? Explain your answer.
Q8. In less than 3 sentences, explain the difference between an *observational* and a *manipulative* research study.
***Q9.** Which statement do you find more accurate? Explain why you believe this. **Statement 1**: The process of evolution is a "tinkering" process, where existing traits are altered to best match changing environments. **Statement 2**: The process of evolution is an "engineering" process, where new traits are constantly being made to match up with changing environments.

Note: All questions were scored on a 0–10-point scale except Q6, which was scored on a 0–20-point scale.

*Q9 pertains directly to the readings in Week 5 on Francois Jacob's (1977) analogy of evolution being a "tinkering" process. Students (likely) had no knowledge of this paper prior to this course.

was not a surprising result because students continued to struggle to provide even a basic definition of the term *adaptation* at the end of the course; student scores on the define *adaptation* question did not significantly increase (P = .1315; Figure 2A) and remained very poor throughout the semester. Students showed consistent, poor responses when asked to explain the process of natural selection (Q6), with scores averaging below 9/20 points on both pre- and postcourse assessments (P = .4912; Figure 2A). Student responses to the question asking them to identify and explain direct versus indirect measurements in science also did not change significantly over the course of the study (P = .200; Figure 2B), but this may be due, in part, to strong precourse scores on this question.

On our postcourse survey, 74% of students stated that they find discussions helpful at enhancing their knowledge of a subject. Additionally, 61% of students reported they are more comfortable reading scientific literature, and 45% of students reported they are more likely to do nonassigned reading of scientific literature after taking this course.

Common misconceptions

Table 5 shows the percentages of students that harbored misconcep-

TABLE 5

Common misconceptions shown in student responses to assessment questions Q1–Q5.

	% Students showing misconception*	
Misconception	**Precourse**	**Postcourse**
Misconception 1: Individual animals adapt. Example answer: "Evolution occurs in a population while an adaptation is in an individual. Individuals do not evolve, they adapt."	All students = 54.54 taken evolution[#]: Yes = 54.29 No = 54.84	All students = 33.33 taken evolution[#]: Yes = 35.56 No = 28.57
Misconception 2: Evolution takes longer than adaptation. Example answer: "Evolution occurs over a much greater time and is present within the genome. Evolution can and has resulted in brand-new species. Whereas adaptations can occur when an obstacle is placed in an organism's life and they change to deal with it. Adaptations occur at a quicker pace than evolution."	All students = 28.79 taken evolution[#]: Yes = 25.71 No = 28.57	All students = 27.27 taken evolution[#]: Yes = 31.11 No = 19.05
Misconception 3: Adaptation leads to evolution. Example answer: "Adaptation is the changes that occur over a shorter period of time and could lead to evolutionary traits."	All students = 27.27 taken evolution[#]: Yes = 22.86 No = 32.26	All students = 16.67 taken evolution[#]: Yes = 17.78 No = 14.29
	Misconceptions per student	
	Precourse	**Postcourse**
Number of students showing 0, 1, 2, and 3 misconceptions in answers	0 misconceptions = 19 1 misconception = 25 2 misconceptions = 18 3 misconceptions = 4	0 misconceptions = 30 1 misconception = 21 2 misconceptions = 15 3 misconceptions = 0
Mean ± SD number of misconceptions per student	1.106 ± 0.8966	0.7727 ± 0.7999

*Students could be included in any or all categories of misconceptions depending on their responses to the assessment questions asked. Many students showed two or more misconceptions in their responses.

[#] For presemester assessments: "Yes" represents students who had previously taken evolution prior to this course (N = 35), and "No" represents students who had not (N = 31). Students who reported they were retaking evolution were categorized as having taken evolution. For postsemester assessments: "Yes" represents students who had previously taken evolution prior to taking this course plus the students who were taking evolution concurrently with this course (N = 45) and "No" represents students who had neither taken evolution before this class, nor took it concurrently with this class (N = 21).

tions during the study period. Misconceptions were rampant in student responses in both the pre- and postcourse assessment, although some improvement in the percentage of students showing these misconceptions was seen over the course of the semester. We found that the number of misconceptions per students decreased significantly over the course of the semester (Wilcoxon signed-rank test for matched pairs; $P < .01$). On precourse assessments, a lower percentage of students who had completed an evolution course showed Misconception 3 than those who had not. The percentage of students showing Misconceptions 1 and 2 were similar between the two groups precourse. On postcourse assessments, misconceptions were found at a lesser rate for students who had not completed an evolution course compared with those who had.

Discussion

Overall, our results suggest that classroom discussions can help increase student knowledge of evolution. Students entered this upper level zoology course with a poor overall knowledge of evolutionary processes, with the majority of students not being able to provide an accurate definition of the term *evolution*. Even students who had previously taken courses that specifically covered evolution as the main focal topic performed poorly on precourse assessments, showing that they still harbored misconceptions regarding evolution. The improvement in score over the course of the semester is promising. It is acknowledged that changes in student scores cannot be directly attributed to their participation in these classroom discussions because the students were taking other courses simultaneously. However, the results of this study offer promising avenues for future research.

Postsemester survey results suggest that students found our discussions to be intellectually stimulating and increased their interest levels in science. This increase in interest level may have contributed to the learning gains shown on content-based questions, as engagement may increase students' attainment and retention of knowledge (Handelsman et al., 2007). Like any pedagogical technique, discussions may not engage every student, which may have contributed to the somewhat modest learning gains as a class. If some students were not engaged during discussions, they may have missed content that more-engaged students noted and subsequently reduced the average learning gains shown by the class overall. In the future, it may be beneficial to provide "minilectures" before discussions to help students more accustomed to and stimulated by lecturing to acquire knowledge possibly missed during discussions.

Over the course of the semester, students showed statistically significant increases in their scores on four of seven evolution-based questions. Despite learning gains, postsemester assessment scores were still below what would be expected from upper level biology undergraduates. One possible explanation for these low scores is the design of the scoring rubric used to assess student responses. Although the rubric was designed to award credit for "textbook" definitions (Hill et al., 2008), definitions often consisted of multiple subparts, and students often lost credit for omitting one or more subparts. For example, in our rubric, we defined *evolution* to be the change in a population's allele frequency from one generation to the next. Although we were lenient on exact wording of answers, to receive full credit on this definition the student would need to accurately identify (a) the genetic component (allele frequency), (b) that evolution occurs at the population level, and (c) that it occurs over generational timescales. Because the assessments were used solely for research purposes and were not tied to student grades, we were obliged to be rigorous in our formulation of acceptable answers.

Our results suggest that students have difficulty understanding the process of adaptation, even after repeated readings and discussions focused specifically on this topic. Although scores on the define *evolution* question significantly increased over the course of the semester, scores on questions asking students to define *adaptation* and to contrast between evolution and adaptation showed no significant increases. These results suggest that specific attention needs to be directed toward ensuring that undergraduate students taking foundational courses understand what *adaptation* truly means and that they can distinguish between *evolution* and *adaptation*.

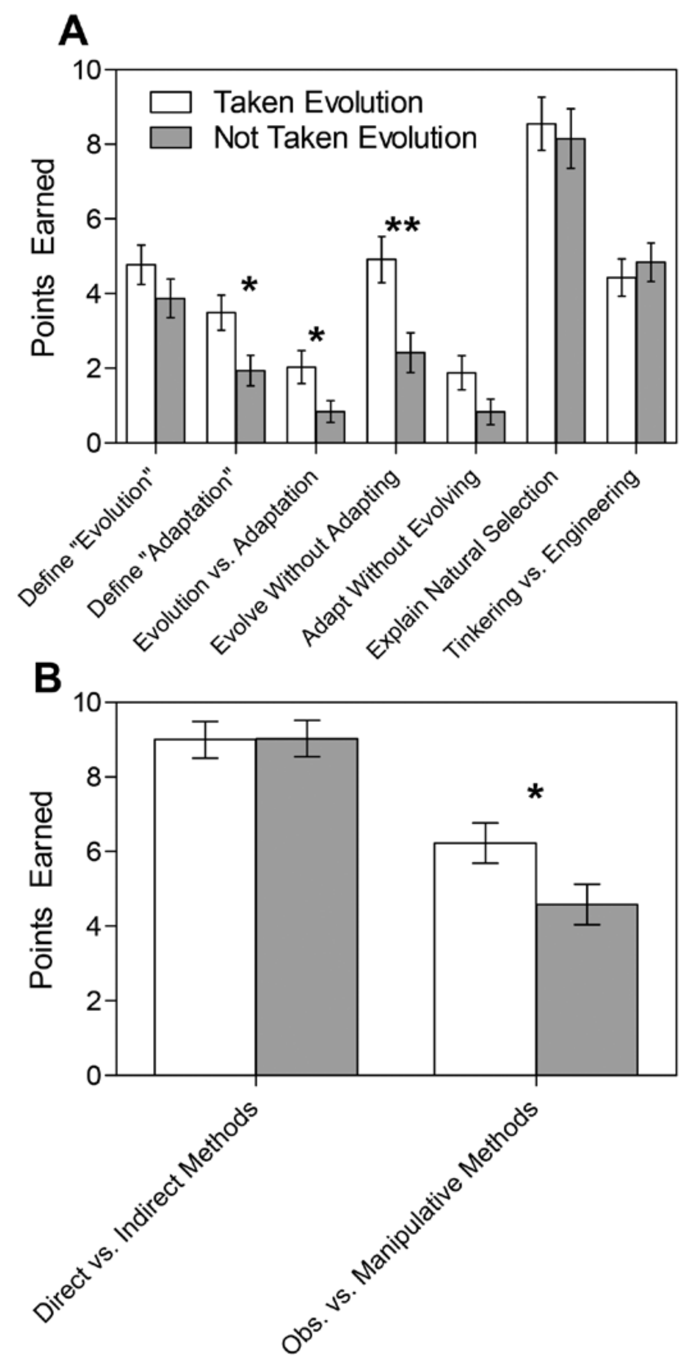
Qualitative analyses uncovered a number of common misconceptions about evolutionary processes. The prevalence of these misconceptions suggests that students can often become confused by misuse (or alternative use) of terminology (Moore et al., 2002). For example, in evolutionary biology, *adaptation* is defined as the process of acquiring fitness-enhancing traits via natural selection (Hill et al., 2008), whereas sensory biologists often use the term *adaptation* as a synonym for physiological *acclimation* or *acclimatization*. An example of this is that pupils in the eye undergo “sensory adaptation” to adjust to various light conditions. Although the term *sensory adaptation* is widely used in sensory biology, the dual use of the term *adaptation* can easily confuse biology students. Indeed, this misconception manifested itself routinely in student responses when asked to define *adaptation* (Table 5). Parallel misconceptions shown by students in our study were the beliefs that changing phenotypes via phenotypic plasticity or animals altering behaviors dependent on environmental scenarios represent individuals “adapting” within their lifetimes. Students struggle to grasp that changes of this nature are not true adaptation in the context of evolutionary biology, but instead represent physiological processes of acclimation or acclimatization.

Surprisingly, students who had never taken a course solely devoted to evolution showed a lower percentage of misconceptions on postcourse assessments than students who had. This suggests that taking an evolution course may not be enough to dispel evolutionary misconceptions and may actually make it harder to dispel misconceptions in the future. Our results suggest that discussions helped students in this regard, but that discussions may work best for early-career students before they take courses specifically covering evolution.

Our classroom discussions were particularly helpful at exposing students’ misconceptions. We found that, in general, students were very willing to express their ideas to the class, as long as the TA diligently ensured that all classroom discussions were encouraging, rather than cynical, of students’ opinions and beliefs. In creating this open forum, our dis-

FIGURE 1

Comparisons of precourse assessment scores between students who had versus had not previously taken a course on evolution. Mean ± SEM shown. All questions were scored on a 10-point scale, except for the Explain Natural Selection question, which was scored on a 20-point scale. (A) Evolution questions. (B) Nonevolution questions. Sample sizes: Evolve Without Adapting, $N = 34$ taken, $N = 31$ not taken; Adapt Without Evolving, $N = 34$ taken, $N = 30$ not taken; Explain Natural Selection, $N = 31$ taken, $N = 27$ not taken; for all other questions, $N = 35$ taken, $N = 31$ not taken. Astrisks indicate that differences between groups were significant in a Mann–Whitney *U* test. *$P < .05$, ** $P < .01$.



cussions were able to get students to openly discuss their beliefs without fear of reprimand or failing grades, which allowed TAs to identify common misconceptions and center the discussions on those topics. The fluid design of our discussions was crucial because it allowed the TAs to address these misconceptions as they arose, rather than having to stick to predetermined discussion questions.

The results of this study highlight the need for biology instructors to address their students' preconceived ideas about evolution to dispel misconceptions at the start of courses. Further, these results highlight the need for such instructional practices in high school and introductory biology classrooms, so that misconceptions are addressed early in students' scientific careers. Misconceptions are often strongly held, and while simply addressing misconceptions may sometimes not be enough to dispel them, classroom discussion can serve as venues for exposing students to alternate conceptions (Posner et al., 1982). Thus, classroom discussions can serve as important pedagogical tools for addressing these misconceptions via the exchange of ideas among students at all levels of education. ■

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FIGURE 2

Comparisons of pre- and postcourse assessment scores. Mean ± SEM shown. All questions were scored on a 10-point scale, except for the Explain Natural Selection question, which was scored on a 20-point scale. (A) Evolution questions. (B) Nonevolution questions. $N = 66$ for all questions except: Evolve Without Adapting, $N = 65$; Adapt Without Evolving, $N = 64$; Explain Natural Selection, $N = 58$. Astrisks indicate that differences between groups were significantly different in a one-sided Wilcoxon signed-rank test for matched pairs. $^{*}P < .05$, $^{**}P < .01$, $^{***}P < .001$.