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Correcting misconceptions about evolution: an innovative, inquiry-based introductory biological anthropology laboratory course improves understanding of evolution compared to instructor-centered courses

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Abstract

Comprehensive understanding of evolution is essential to full and meaningful engagement with issues facing societies today. Yet this understanding is challenged by lack of acceptance of evolution as well as misconceptions about how evolution works that persist even after student completion of college-level life science courses. Recent research has suggested that active learning strategies, a focus on science as process, and directly addressing misconceptions can improve students' understanding of evolution. This paper describes an innovative, inquiry-based laboratory curriculum for introductory biological anthropology employing these strategies that was implemented at West Chester University (WCU) in 2013–2016. The key objectives were to help students understand how biological anthropologists think about and explore problems using scientific approaches and to improve student understanding of evolution. Lab activities centered on scenarios that challenged students to solve problems using the scientific method in a process of guided inquiry. Some of these activities involved application of DNA techniques. Formative and summative learning assessments were implemented to measure progress toward the objectives. One of these, a pre- and post-course evolution concepts survey, was administered at WCU (both before and after the implementation of the new curriculum) and at three other universities with more standard introductory biological anthropology curricula. Evolution survey results showed greater improvement in understanding from pre- to post-course scores for WCU students compared with students at the comparison universities ($p < .001$). WCU students who took the inquiry-based curriculum also had better understanding of evolution at the post-course period than WCU students who took the course prior to implementation of the new curriculum ($p < .05$). In-class clicker assessments demonstrated improved understanding of evolution concepts ($p < .001$) and scientific method ($p < .05$) over the course of individual labs. Two labs that involved applying DNA methods received the highest percentage ratings by students as 'very useful' to understanding important concepts of evolution and human variation. WCU student ratings of their confidence in using the scientific method showed greater improvement pre- to post-course during the study period as compared with the earlier, pre-implementation period ($p < .05$). The student-centered biological anthropology laboratory curriculum

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developed at WCU is more effective at helping students to understand general and specific concepts about evolution than are more traditional curricula. This appears to be directly related to the inquiry-based approach used in the labs, the emphasis on knowledge and practice of scientific method, directly addressing misconceptions about evolution, and a structure that involves continual reinforcement of correct concepts about evolution and human variation over the semester.

Keywords: Evolution education, Biological anthropology, Inquiry-based laboratory, Misconceptions, College level, Student-centered learning, Human examples

Background

Understanding the reality of evolution is fundamental to science education. However, many Americans deny the theory of evolution despite overwhelming evidence and uniform support from the scientific community (Nadelson and Hardy 2015). In 2006, Miller et al. published an enlightening study demonstrating the low acceptance of evolution in the United States compared to 34 other countries, with the US ranking second to last in acceptance of evolution. Data from the Pew Research Center's (2015) Religious Landscape Study show that these results had not changed very much in the intervening decade; at that time, 34% of Americans reported that they reject evolution and believe that humans arrived on earth in their present form. Recent work by Miller et al. (2021) suggests this may be changing, with increased public acceptance of evolution in the last decade. Even though acceptance of evolution increases with level of education, from 20% in high school to 52% and 65% among college or postgraduates, respectively, the rejection rate of evolution from students in introductory biology classes can reach up to 50% (Brumfield 2005; Rice et al. 2010; Paz-y-Miño-C and Espinosa 2016). Even college-level instruction in evolution, then, may not increase students' acceptance of evolution.

Perhaps more surprisingly, even when acceptance of evolution is not a factor, college-level instruction does not necessarily result in full understanding of evolution either, and numerous studies identify multiple evolution-related misconceptions held by different groups of students. For example, Cunningham and Wescott (2009) identified and evaluated biological anthropology students' misconceptions about evolution and found that, despite acceptance of evolutionary theory, students lack understanding of the process of evolution. Tran et al. (2014) also identified similar misconceptions among advanced undergraduate biology majors. And Beggrow and Sbeglia (2019) reported that despite some differences in evolutionary reasoning and in the specific types of evolution misconceptions held by biology and anthropology majors, both populations performed poorly on a measure of evolutionary knowledge (Conceptual Inventory of Natural Selection [CINS]; Anderson et al. 2002). Several other instruments to assess both student misconceptions about evolution and student understanding of evolution have been developed, including the Measure of the Acceptance of Evolutionary Theory (MATE; Rutledge and Sadler 2007) and the Inventory of Students' Acceptance of Evolution (I-SEA; Nadelson and Southerland 2012) with different student populations (see also Nehm and Mead 2019; Furrow and Hsu 2019). Results of multiple studies using these instruments show that student misconceptions continue despite college-level classroom instruction (e.g., Beggrow and Sbeglia 2019). Use of these types of assessment instruments aids in understanding and addressing student misconceptions, but there clearly remains a need to find the most effective teaching and learning strategies for evolution education (Glaze and Goldston 2015).

Pobiner (2016) recently reviewed the current state of evolution teaching and learning and concluded that focusing on human examples, such as in biological anthropology courses, is an effective way to enhance student understanding and acceptance of evolution. Based on results of the "Teaching Evolution through Human Examples" project (Pobiner et al. 2015, 2018), these authors suggest that the use of human examples is helpful because human examples are relevant, they increase students' acceptance and understanding of evolution, and they help students to appreciate historical science. Numerous other investigators have supported this suggestion (e.g., see Beggrow and Sbeglia 2019) and some research suggests that students across multiple disciplines (majors and non-majors) actually prefer the use of human examples when learning about evolution (e.g., Pobiner et al. 2018; Paz-y-Miño-C and Espinosa 2016). However, even with a focus on human evolution, misconceptions continue to exist (e.g., Cunningham and Westcott 2009; Beggrow and Sbeglia 2019).

Some research suggests that instructor-centered pedagogy (lecture) is less successful in helping students recognize and correct their misconceptions about evolution (Bishop and Anderson 1990; Gregory 2009) compared to historically rich, problem-solving methods of instruction that appear to significantly improve student understanding of evolution (Jensen and Finley 1996). Nehm and

Reilly (2007) directly compared pedagogical approaches using pre- and post-course tests and found that students taught using active-learning techniques performed better than those using a more traditional approach.

Pittinsky (2015) further suggests that firsthand experience with scientific methods, as well as interactions with real scientists, would help address some of the problems in teaching evolution. It seems that when students learn to think like a scientist and use the same actions that led to original discoveries, they gain insight into the strategies and techniques used by scientists studying evolution (Passmore and Stewart 2002). Scharmann et al. (2018) and Nelson et al. (2019) also suggest that Nature of Science (NOS) principles should be covered before even introducing the theory of evolution. Some research supports this suggestion. For example, DeSantis (2009) reported that introduction of a curriculum module that included inquiry-based activities that model the work of paleontologists increased interest in and acceptance of the theory of evolution among middle- and high-school age students. Might the inclusion of similar inquiry-based laboratory activities also reduce the evolution misconceptions held by students (at all levels)?

Other research suggests that the order in which concepts are introduced makes a difference in students' understanding of evolution, at least among high school students. For example, Mead et al. (2017) reported that teaching genetics first (before evolution) improves student understanding of evolution. And, Alters and Nelson (2002) as well as Beggrow and Sbeglia (2019) further suggest that targeting naïve ideas about evolution should be an instructional goal, particularly in anthropology education. Research by Bishop and Anderson (1990) and Jensen and Finley (1996) support this suggestion, reporting that confronting students' misconceptions directly before introducing correct conceptions is associated with significant gains in student understanding of evolution. Wingert et al. (2022) show that employing instructional activities that directly challenge students' teleological concepts about natural selection improves their acceptance and understanding of evolution.

Taken together, these results support Nelson's (2008) recommendation of three learning strategies to improve student understanding of evolution: (1) extensively using active learning strategies; (2) focusing on science as a process and way of knowing; and (3) identifying and directly addressing student misconceptions. We report on the effectiveness of an inquiry-based laboratory curriculum that incorporates all of these strategies in an undergraduate biological anthropology course.

Evolutionary theory is central to the discipline of biological anthropology, which is fundamentally about human evolution. At West Chester University (WCU), Biological Anthropology (ANT 101) is a general education, introductory course taken by majors and non-majors that had, traditionally, been taught using a teacher-centered approach. In 2010, assessment data indicated that many students retained common misconceptions about evolution after completion of the course. For example, responses to the question "What is evolution?" included replies such as: "…survival of the fittest, species do what they need to do to pass their genes on"; "the change that occurs in an environment over time from a change in species"; "the way an organism changes to survive in a changing environment." Clearly course changes were needed to address these misconceptions, and it seemed a good idea to attempt to do so by actively engaging students in understanding the concepts of evolution as well as the tools used by researchers to solve problems using scientific methods. Based on previous work emphasizing the need to employ human examples using active, hands-on pedagogy that emphasizes the scientific process, we developed an innovative biological anthropology laboratory course that merges these three important components of effective teaching of evolution. Based on our results, this course not only improves overall performance in correcting misconceptions when compared to other biological anthropology courses, but it also significantly improves understanding in specific areas.

Methods

Introduction to Biological Anthropology (ANT 101) has been offered annually or more frequently at WCU for nearly two decades. It is a required course for anthropology majors, and for most of that time period non-majors have been permitted to take it to meet a general education distributive requirement. Until the fall semester of 2013, it was configured as a three-hour per week lecture course with no hands-on lab component, and the department had no access to laboratory classroom facilities. For several of those years, the instructor incorporated 3–5 virtual laboratory experiences over the semester using one lecture hour for each. While students said they enjoyed these experiences, assessment data indicated that they still had persistent misconceptions about evolution at course completion.

In fall 2013, a project team at WCU, including the course instructor (a biological anthropologist), a human physiologist experienced in inquiry curricula, an evolutionary biologist, and a psychologist with expertise in assessment and program evaluation were awarded a three-year TUES (Transforming Undergraduate Education in STEM) grant from the National Science Foundation (NSF). The purpose of this award was to develop an innovative, inquiry-based laboratory curriculum targeting student misconceptions about evolution, student ability to use the scientific method, and student understanding of the investigative tools used by biological anthropologists. To accommodate this new curriculum, the course was redesigned to meet four hours per week in an integrated lecture-lab format, with roughly half of that time devoted to laboratory activities and the other half to lecture and/or discussion.

The project was submitted to the West Chester University Human Subjects Committee and received expedited approval in the summer 2013. Informed consent was obtained each semester from students enrolled in the course who wished to participate. Over the period of the project, this was all but one or two students.

During each lab period, brief instruction on methodology was provided, as appropriate to the lab, and students were presented with a challenge scenario that asked them to apply the scientific process to solving that problem using the relevant method (with the challenge scenario providing a structured context in which to do so). In a standard biological anthropology lab curriculum, students might be asked to describe and identify various casts of hominin fossil skulls using characteristics they had learned about, associate these traits with dietary differences, and receive verification of their assessments by the instructor. In the inquiry-based, structured challenge approach developed at WCU, students were given a problem to solve that required them to hypothesize the likely diet of the various hominins or hominids. They were instructed in a technique that allowed them to test one of their hypotheses, then required to state their results in an organized manner, evaluate them, indicate next steps, and so on. Thus, each lab in the curriculum is configured to (1) help students understand how biological anthropologists think about and explore problems using relevant techniques and (2) gain experience with the scientific process. The lab curriculum includes some instruction and application of basic molecular techniques (e.g., constructing simple primate phylogenies based on morphological v. genetic variation and doing a DNA fingerprinting exercise to attempt to identify a hypothetical hominin fossil), since the curriculum is also designed to help students make connections between phenotypic observations and the molecular level in service of the project goal of helping students to better understand evolution. Table 1 provides a list of the labs with descriptions of the inquiry learning activities performed.

The full lab manual can be accessed at: https://digitalcommons.wcupa.edu/anthrosoc_facpub/72.

Standard assessments, including periodic exams and laboratory reports, were utilized to measure student learning. Responses to lab challenges at multiple time points were evaluated at the end of each semester using a rubric to measure individual students' abilities to define the problem, to develop a plan to solve the problem, to analyze and present information, and to interpret findings and solve the challenge problem. Student lab teams also developed a project that they designed and implemented (from hypothesis to interpretation) using one of the methods they learned, and gave group presentations to the class. Other, more formative, measures of student learning were also introduced. For example, during each lab, students completed a pre-post assessment tool which was a modified version of the RSQC2 (Recall, Summarize, Question, Connect, and Comment) classroom assessment technique developed by Angelo and Cross (1993). Beginning in the second year of the project, pre- and post-lab clicker questions were incorporated for rapid assessment of the lab impact.

Several global surveys were administered at the beginning of each course, prior to any instruction, and again (for all but one survey) on the last day of the course. These included a survey focusing on evolution (17 items in year one, revised to 25 items in the second year) as well as surveys assessing students' familiarity and comfort level with the scientific process, their level of motivation, and, at the end only, their overall assessment of their course experience. The evolution survey was also administered at WCU for 2 years prior to the course reorganization and lab implementation; data from this period are used for an internal comparison with survey results obtained during the implementation of the new curriculum. Biological anthropology colleagues at three other US universities (reported here as A, B, and C) also administered the evolution concepts survey to their students in introductory courses in biological anthropology, during the grant period, for comparison purposes. All of these courses were taught with some version of a more standard laboratory curriculum for this discipline (example of a standard approach described above). University 'A' is a large, midwestern state school (approximately 40,000 students); University 'B' is a sizable state school located in the south (approximately 30,000 students). University 'C' is a large, northeastern state school (approximately 30,000 students). At all three, introductory biological anthropology is taught in large lecture context with smaller recitation sections that meet one hour per week (i.e., two hours lecture, one hour of recitation or lab). At A and C, these recitations were used for weekly laboratory activities throughout the semester; at B, there were seven labs during the semester. Prior to 2013, the course at University A had no lab at all—only lecture.

The current report first describes the results of the evolution concepts instrument administered at the very beginning of the course and at the end of the course at WCU and across universities. Following a presentation

Table 1 Schedule of lab topics and inquiry-based learning activities

Lab	Lab topic	Example of inquiry-based challenge activity (all performed by students in groups)
1	Evolution and scientific thinking	Sex identification of two complete skeletons (male and female). Students are challenged to hypothesize how sexes differ skeletally, determine how they would collect relevant data, do so, then report results and interpret. Provides opportunity to reinforce scientific method and way of knowing.
2	Genes and variation	Challenges include problem solving related to Mendelian and population genetics. Students do paternity determination using Punnett Squares and prediction of class allele and genotype frequencies for simple Mendelian trait using Hardy–Weinberg.
3	Tree-building and primate classification (taught over two weeks)	Week 1: Students are challenged to examine three primate skulls and hypothesize how they are related. They learn to build trees, draw a tree to represent their anatomically-based hypothesis, then are instructed in locating and counting pairwise differences in gene sequences. They receive a gene sequence for three primate species to count pairwise differences as homework. Week 2: Students use their base pair counts from the homework to test their anatomically-based phylogenetic hypotheses, compare their anatomy- and gene-derived trees, and discuss the differences.
4	Primate anatomy and locomotion	Challenge is to determine the locomotor pattern of a mystery primate whose limb bones are provided. Students develop hypotheses, list methods, collect data, then work through guided steps about constructing limb ratios and using those to predict locomotor pattern. These secondary hypotheses are evaluated in relation to body mass.
5	Human osteology and forensics	Challenge is to determine sex of unidentified skeletal remains using qualitative and quantitative methods. Students work through hypothesis, methods, data collection, and discussion.
6	Hominin identification 1: bipedalism	Challenge is to determine the locomotor pattern of a mystery fossil (hominin) species using comparison with known quadruped and biped. Students work through hypothesis, methods, data collection, and discussion using comparative skulls, pelvises, femurs, and feet.
7	Hominin identification 2: skulls, teeth, diet	Challenge is to determine likely diets of hominids based on a comparative study of skulls and teeth of four species. Students work through hypothesis, methods, data collection, and discussion, including learning about the relationship of cheek teeth size with body mass and diet.
8	DNA fingerprinting	Students learn to perform DNA fingerprinting in the context of a scenario that challenges them to predict and then test the hominin group affiliation of a fossil finger bone discovered in a Siberian cave.
9	Population history and ancestry	Students learn to use a bioinformatics database to examine relationships among living human populations based on mitochondrial DNA. They are then challenged to generate their own research question and hypothesis about population relationships, collect the data, and organize and present their explorations to the class orally with slides.
10	Human genetic adaptation: ELISA	Students learn to perform ELISA technique in the context of a scenario that challenges them to determine the likely allele frequency distribution at the CCR5 locus of a population of European ancestry exposed to HIV.
11	Human variation: anthropometry	Students learn basic anthropometric techniques and then employ them to predict and test the relationship between brain and body sizes and brain size and sex. They have to decide which of the measures/indices they have learned would be best suited to evaluate their hypotheses, then follow through with organizing and discussing their results.

of the results regarding changes in misconceptions we turn our attention to an examination of the specific areas of learning that we believe may have contributed to the reduction in misconceptions, including a look at specific assessments of students' growing understanding of science as a process throughout the course.

Evolution misconceptions

Two versions of the evolution concepts instrument were used, one prior to the start of the grant period and throughout the first year following the grant award and a revised version used beginning in fall 2014. Each version included statements that students responded to on a 5-option Likert-type scale ranging from strongly agree to strongly disagree, or having no opinion. This instrument was based on a published and freely available tool used by other researchers (Cunningham and Wescott 2009). For purposes of analysis, each item was agreed by the project team to be either true or false, such that strong agreement with a true statement and strong disagreement with a false statement were considered to be 'correct' responses. A scale ranging from $+2$ to -2, including 0 for 'no opinion' was constructed, and several variables were computed from these scores, including total score (pre, post), percent of total points earned (pre, post), number of items correct (pre, post), and percent of items correct (pre, post). The use of percent variables was necessitated by a revision of the survey after the first year of curriculum implementation (2013–2014). The initial version of the survey included 24 items, but a qualitative analysis by study consultants resulted in a set of only 17 items deemed usable for the purposes of our study. This initial survey was then revised for use beginning in fall 2014 to include the 17 items kept from the original survey with the addition of 8 new items, resulting in a set of 25 usable items. The 25-question survey can be found in Additional file 1.

Several questions were addressed using the results of the evolution concepts instrument. First, we compared WCU student survey responses to responses from the three other institutions whose students completed the survey. We asked if student performance on the evolution concepts instrument improved from pre- to post-course for all institutions and whether the amount of improvement varied by institution. Second, we examined WCU student survey responses (both pre and post surveys) over time, asking if student performance on the evolution concepts instrument improved both prior to and during the grant implementation period. Next, we asked whether the degree of improvement changed following implementation of our new inquiry-based curriculum, relative to the academic years prior to implementation of the grant. Finally, in an attempt to understand the specifics of what evolution-related misconceptions might have improved and which did not, we conducted a qualitative analysis of survey items and compared student performance on sets of related items across universities.

WCU course assessments

A variety of measures were used to assess student learning throughout each semester at WCU and to evaluate the effectiveness of particular pedagogical approaches as well as the overall curriculum. Some of these measures were objective and direct measures of student learning. Some were indirect measures, student perceptions of what they learned and/or which laboratory sessions they believed were most helpful in their learning. In this report, we provide results of four of these measures—in-class clicker questions, laboratory challenges, RSQC2 responses, and student confidence ratings—to provide insights about the effectiveness of the curriculum in meeting its primary objectives.

In-class clicker questions

Students were presented with a set of true/false statements or multiple choice questions at the beginning and end of multiple laboratory sessions. Some items were tied directly to misconceptions about evolution, others to students' understanding of the scientific method, while others were designed to measure more general understanding of the topics covered by the individual laboratory modules. Students responded, via clickers, to these statements presented visually in class. Responses served as an important source of formative assessment but also provided information on the effectiveness of each of the laboratory modules in correcting student misconceptions about evolution and student understanding of the scientific method.

Laboratory challenges

Laboratory modules included "challenge" activities, designed specifically to enable students to apply problem-solving skills within a structured context (Knabb and Misquith 2006). In each of these laboratory challenges, students were asked to state research questions or generate hypotheses, collect data, draw conclusions, report/graph their results, and reflect on those results. Each student completed a laboratory worksheet during each lab module and all worksheets were submitted as part of student lab notebooks at the end of each semester. Selected lab worksheets were reviewed by faculty involved with the grant project at the end of each semester using a developmental assessment screening tool developed by all project faculty. This screening tool underwent its own developmental process, resulting in a final tool that included four measures of scientific thinking (i.e., students' ability to use the scientific method): Defining the Problem, Developing a Plan to Assess the Problem, Analyzing and Presenting Information, and Interpreting Findings and Solving the Problem. Each of these four areas was assessed on a scale of four developmental levels: beginning, developing, appropriately developed, and exemplary. A copy of this scoring rubric can be found in Additional file 2. Developmental changes in these four areas of scientific thinking were assessed by comparing assigned developmental levels following an early semester laboratory module with assigned developmental levels following a later semester laboratory module.

RSQC2 (Revised)

A modified version of the RSQC2 classroom assessment technique (Angelo and Cross 1993) was completed by students during each laboratory session. Complete details about the multiple sections of this activity can be found in Additional file 3. For the current report, we present data on one of the sections completed by students at the end of each laboratory session. Students were asked to rate the usefulness of each laboratory session in reaching learning outcomes. Ratings were made on a 4-point Likert scale: 4 = very useful; 3 = somewhat useful; 2 = minimally useful; 1 = not useful. Questions included: *How useful was today's laboratory session in helping you to understand the important concepts of evolution and human variation discussed in this course and used by biological anthropologists? How useful was today's laboratory session in helping you to understand the tools used by biological anthropologists to understand the concepts of evolution and human variation?*

Student confidence in using scientific method

WCU students completed a 10-item survey at both the beginning and the end of each semester asking them to rate their level of confidence in their abilities and/or understanding of several pieces of the scientific process. All items were rated on a 5-point Likert scale: 1 = completely doubtful; 2 = somewhat doubtful; 3 = neutral; 4 = somewhat confident; 5 = strongly confident. A copy of this survey is available in Additional file 4.

A variety of both univariate and multivariate linear model procedures were used to address questions of interest involving all student assessments, both within and across time periods and universities (where appropriate). Specifics regarding these analyses are discussed within the Results section.

Results

Evolution misconceptions at WCU and other institutions

WCU evolution surveys were collected across all six semesters of the grant implementation period (fall 2013 through spring 2016), with a total of 105 complete survey sets (pre- and post-course). Survey responses from students at the three other universities were provided by institution instructors whenever possible: University A provided 469 complete survey sets across five terms; University B provided 273 complete survey sets across six terms; and University C provided 200 complete survey sets across three terms. Comparisons across universities were made across only the three terms for which data was provided by each university (fall 2014, spring 2015, and fall 2015). Figure 1 shows pre-course and post-course percent items correct at each university (WCU, University A, University B, and University C), collapsed across these three semesters.

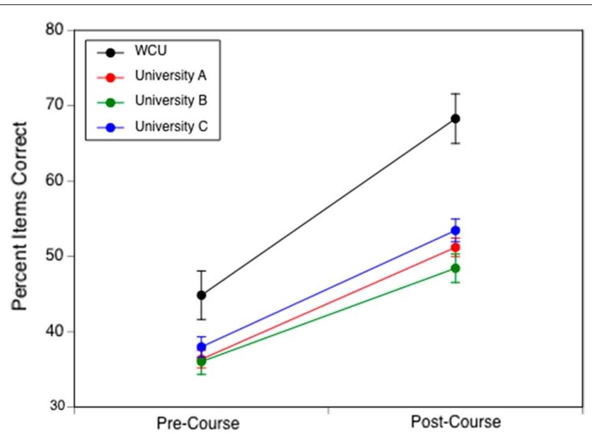

Fig. 1 Pre-course and post-course evolution concept survey ‘percent items answered correctly’ across 4 universities: WCU (n = 43); University A (n = 308); University B (n = 143); and University C (n = 200)

Significant change from pre- to post-course percent items correct was found within institutions for each of the three terms individually [as assessed after each term] and across all terms combined. Furthermore, significant change from pre- to post-course percent items correct was found across all three terms and 4 institutions, collapsed [$t(693) = 25.762$, $p < 0.001$]. Thus, significant improvement in overall performance on the evolution misconceptions instrument occurred at every institution and during each of the three terms considered here.

While there were no significant differences by term, institution, or term x institution in pre-course percent items correct, we did note a near significant effect of institution [$F(3, 690) = 2.548$, $p < 0.10$]. An informal review revealed that WCU pre-course scores were higher than pre-course percent items correct at all three other universities. Thus, comparison of post-course percent items correct included the pre-course percent items correct scores as a covariate. ANCOVA results support a significant effect of institution on post-course percent items correct, after controlling for pre-course percent items correct [$F(3, 689) = 8.345$, $p < 0.001$]. Post-hoc tests show significant differences between post-course scores at WCU and at all three other institutions. In addition, post-course percent items answered correctly at University B was significantly lower than percent items answered correctly at University C.

Internal WCU comparisons

The results reported above support statistically significant improvement in evolution misconception scores among students at all participating universities but further suggest that post-course scores are significantly higher at WCU than at any of the other three universities, even after controlling for potential differences in pre-course scores. WCU differs from these other institutions in terms of the curriculum focus (our inquiry-based approach versus other, more standard approaches), but WCU also differs from the other institutions in terms of class size. Individual class sections are smaller at WCU, resulting in smaller sample sizes both within and across semesters. If class size is the factor that explains the difference in post-course performance across universities, it should also be the case that post-course performance at WCU would not change following the introduction of the new inquiry-based curriculum. To evaluate this possibility, we compared WCU evolution survey results for pre-grant terms to evolution survey results following implementation of the inquiry-based curricular approach. Survey results are reported here for pre-grant (fall 2011 and fall 2012, N = 22 and 26, respectively), and

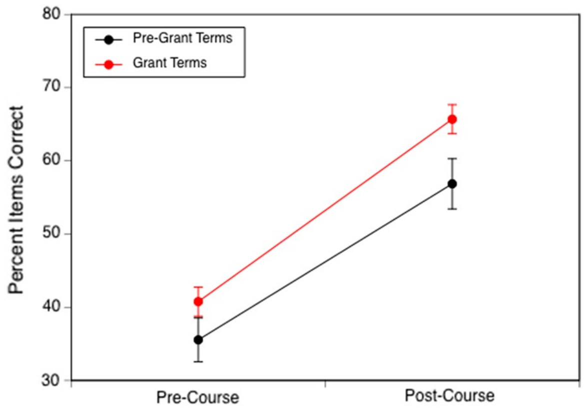

Fig. 2 WCU pre- and post-course 'percent items answered correctly' by project phase: pre-grant (n = 48) and post-grant (n = 105)

grant implementation (fall 2013, spring 2014, fall 2014, spring 2015, fall 2015, and spring 2016; Ns = 18, 23, 12, 12, 19, and 21, respectively) (Fig. 2).

There were no significant differences by term in pre-course percent items correct or post-course percent items correct during the pre-grant period (fall 2011 and fall 2012) or during the grant implementation period (fall 2013 through spring 2016). Significant change from pre- to post-course percent items correct was found across the pre-grant period [$t(47) = 7.387$, $p < 0.001$] and across the grant implementation period [$t(104) = 14.871$, $p < 0.001$]. Thus, significant improvement in performance on the evolution conceptions instrument was found both prior to and during the implementation of the grant. There were no significant differences in pre-course percent items correct between pre-grant and grant implementation periods [$F(1, 151) = 2.145$, $p = 0.145$]. But, a significant group difference was found in post-course percent items correct [$F(1,151) = 5.600$, $p < 0.05$], with students answering a larger percentage of items correctly (i.e., earning full 2 points) across the grant implementation period than during the pre-grant period.

Evolution concepts

The results reported above support the conclusion that our new laboratory curriculum may be more effective in improving student understanding of evolution and evolutionary concepts and may be more effective in reducing student misconceptions of evolution than the curriculums utilized at the other universities. In addition, significantly more WCU students answered certain survey items correctly at the post-course assessment than did students at any of the other three institutions (see Table 2), but a clear pattern was difficult to identify. Thus, we conducted a qualitative analysis of the 25 survey items that made up the revised version of the survey (the one implemented beginning fall 2014). We examined the survey results for the three terms for which data were available for all four institutions (fall 2014, spring 2015, fall 2015). This analysis resulted in four groups of items, each addressing one broad theme: (1) understanding of basic scientific evidence and the process of science (5 items); (2) understanding of evolution (from a general or "big picture" perspective) (7 items); (3) understanding of the mechanisms of evolution (i.e., natural selection, mutation, genetic drift, gene flow) (8 items); and (4) understanding of the evidence for evolution (5 items). Table 2 provides a list of all survey items and identifies which theme each item falls into.

A significant multivariate effect of institution was found when we included the four concept scores (i.e., percent of items within each concept grouping answered correctly) in a MANOVA procedure with both pre-course scores and post-course scores included as dependent variables. Univariate follow-up tests suggest a significant institution effect for Concepts #1, and #4. In both cases, pre-course scores were higher for WCU students than for students at other institutions. Thus, a set of Analysis of Covariance (ANCOVA) procedures were conducted, one for each set of post-course concept scores (i.e., percent of items within each concept grouping answered correctly at post-course time period), with institution included as a between-subjects factor and pre-course scores for that concept included as a covariate. Results suggest a significant institution effect for three of the four concepts (#1, #2, and #3). With regard to Concept #1 (understanding of basic scientific evidence and the process of science) post-hoc tests following an overall significant effect of institution [$F(3,689) = 3.919$, $p < 0.05$] show significantly higher post-course concept scores at WCU than at any of the other three institutions. A similar result was found for Concept #2 (understanding of evolution from a general/big picture perspective) [$F(3,689) = 12.899$, $p < 0.001$]. Again, post-course scores for WCU were significantly greater than those for the other three institutions. In addition, University A post-course scores were significantly greater than those for University B. A significant effect of institution was also found for Concept #3 (understanding of the mechanisms of evolution) [$F(3,689) = 7.278$, $p < 0.001$]. Post-hoc tests reveal that WCU post-course scores are significantly greater than those of University A and University B. WCU scores are higher than those of University C but that difference did not reach statistical significance. No significant effect of institution was found for Concept #4 scores (understanding of the evidence for evolution) [$F(3,689) = 1.643$, $p = 0.178$]. But, despite the lack of an overall significant effect, WCU post-course scores are greater than those of

Table 2 Evolution survey item list, by concept, with significance test results (Response options for each: Strongly Agree; Agree; Disagree; Strongly Disagree; No Opinion (undecided/never heard of it))

Item #	
2*	Dinosaurs and humans lived at the same time in the past.
5*	There is sufficient cause for doubt about evolution because it is "just a theory."
17*	You cannot demonstrate that evolution happens.
20*	A scientific theory is a set of hypotheses that have been tested repeatedly and have not been rejected.
24*	Evolution is a fact.
*3**	Humans and chimpanzees share a common ancestor that is neither a human nor a chimpanzee.
*9**	A species evolves because individuals want to.
*15**	Evolutionary change in a population is irreversible.
18	Evolution cannot work because one mutation cannot cause a complex structure (e.g., the eye).
*19**	There is an inevitable direction in evolution.
*22**	Evolution has made living things perfectly adapted to their environment.
*25**	Based on current function in humans, grasping hands must have evolved to facilitate tool use.
6	Population size has little or no effect on the evolution of a species.
7*	If two light-skinned people moved to Hawaii and got very tan their children would be born tanner than the parents were originally.
8	Variation among individuals within a species is important for evolution.
11	From an evolutionary perspective, a 25-year-old Olympic gymnast obviously has a higher fitness than an obese 60-year-old grandmother of 10.
13*	New mutations occur within a population when they are needed.
14*	If two distinct populations within the same species begin to breed together this can influence the evolution of that species.
16*	Evolution only occurs through natural selection.
21	Changes in the environment can drive adaptation.
1*	There is a lot of evidence against evolution.
4*	The theory of evolution correctly explains the history and diversity of life.
10*	Humanity came to be through evolution.
12	Evolution is such a slow process that it is impossible to witness in action.
23	Humans are more evolved than other forms of life.

Concept #1 (in bold): Understanding of basic scientific evidence and the process of science

Concept #2 (in italics): Understanding of evolution (from a general/big-picture perspective)

Concept #3 (in bold italics): Understanding of the mechanisms of evolution (i.e., natural selection, mutation, drift, and gene flow)

Concept #4 (in underline): Understanding of the evidence for evolution

*A significantly higher percentage of WCU students answered correctly post-course than at other institutions

the other institutions for this concept. Descriptive statistics for the concept scores across universities can be found in Additional file 5.

WCU course assessments

How might this inquiry-based course have aided in the reduction of evolutionary misconceptions? In an attempt to gain insight about which course components or processes were effective in this regard, we examined student responses to in-class clicker questions about evolution concepts and scientific method, their development of scientific thinking skills over the term via lab worksheets, their perceptions about each lab's effectiveness in helping them to learn about evolution and human variation concepts, and their confidence in using the scientific method. These results are presented below.

In-class clicker questions

Clicker questions were developed over the course of the second year of the grant, then revised slightly for use across the final year of the grant (Fall 2015–Spring 2016). Questions were developed for eleven laboratory modules (see Table 1). Some items were included within each module to measure understanding of specific laboratory content. Items measuring evolution misconceptions were also included for all modules (1, 2, or 3 items). Items measuring scientific thinking (i.e., understanding of the scientific method) were included for only three modules (1 or 2 items): Evolution and Scientific Thinking, Primate Anatomy and Locomotion, and Human Osteology and Forensics. Clicker questions were presented at the beginning and at the end of each laboratory module session. Data for the final year of grant implementation are presented here. Complete data (across all laboratory modules) were available for 24 students across both semesters.

Overall student performance (as measured by % total items answered correctly) increased significantly from 78.64% at pre-module assessment to 91.06% at post-module assessment (across all items and all laboratory modules) [t (23) = 10.89, p < 0.001]. Performance also increased within each of the laboratory modules.

Student performance also increased significantly on the items specifically designed to measure previously identified misconceptions about evolution, with percent total items answered correctly across all laboratory modules increasing from 83.85% correct to 91.93% correct (across all items and all laboratory modules) [t (23) = 4.992, p < 0.001]. Given that evolutionary misconceptions were addressed most steadily during the early part of the semester, we examined the degree to which improvement on misconception items might be different across the semester. Table 3 shows measures of student performance on evolution misconception in-class clicker items during three time periods of the semester: Early Semester (3 modules focused on basic evolutionary concepts); Mid Semester (4 modules focused on non-human primates and human evolution); and Late Semester (4 modules focused on living human biology). While some slight improvement was noted across all time periods, the only period during which a statistically significant improvement occurred was the early semester time period.

Student performance on the items specifically designed to measure student understanding of the scientific method increased significantly from 90.00% to 97.50% (across all items and all three laboratory modules that included those items) [t (23) = 2.584, p < 0.05]. When broken down by individual laboratory module, the greatest improvement in student performance appears in the later modules but is only statistically significant in the Primate Locomotion module (see Table 4).

Laboratory challenges

Two laboratory sessions (one early- and one mid-semester) were chosen for comparison: (1) the Evolution and Scientific Thinking laboratory module was chosen for the early-semester session; and (2) the Primate Anatomy and Locomotion module was chosen for the mid-semester session. The Evolution and Scientific Thinking laboratory module was the first laboratory

Table 3 Mean (± S.E.) percent correct on clicker items designed to measure evolution misconceptions by course phase

Semester phase	Total # Items	N (# Students)	Pre-module % correct	Post-module % correct	Average change in % correct
Early Semester 3 Modules focused on basic evolutionary concepts	6	24	70.14 (S.E. = 4.48)	86.81 (S.E. = 3.01)	16.67***
Mid Semester 4 Modules focused on non-human primates and human evolution	5	24	91.67 (S.E. = 2.06)	95.00 (S.E. = 2.17)	3.33
Late Semester 4 Modules focused on living human biology	5	24	92.50 (S.E. = 2.35)	95.00 (S.E. = 2.17)	2.50

***p < .001

Early Semester: 3 laboratory modules: Evolution and Scientific Thinking; Genes and Variation; Tree Building and Primate Classification

Mid Semester: 4 laboratory modules: Primate Anatomy and Locomotion; Human Osteology and Forensics; Hominin ID 1: Bipedalism; Hominin ID 2: Skulls, Teeth and Diet

Late Semester: 4 laboratory modules: Forensics 2: DNA Fingerprinting; Population History and Ancestry; Human Genetic Adaptation: ELISA; Human Variation: Anthropometry

Table 4 Percent correct on clicker items designed to measure understanding of the scientific method by laboratory module

Laboratory module	Total # Items	N (# Students)	Pre-module % correct	Post-module % correct	Average change in % correct
Evolution and Scientific Thinking	2	24	91.67 (S.E. = 3.89)	97.92 (S.E. = 2.08)	6.25
Primate Anatomy and Locomotion	2	24	87.50 (S.E. = 4.51)	97.92 (S.E. = 2.08)	10.42*
Human Osteology and Forensics	1	24	83.33 (S.E. = 7.77)	95.83 (S.E. = 4.17)	12.50

*p < .05

Table 5 Mean (±S.E.) developmental level scores on selected laboratory challenges

Laboratory challenge variables	N (# Students)	Early Semester Lab Module (Evolution and Scientific Thinking)	Mid Semester Lab Module (Primate Anatomy and Locomotion)	Change in Mean Developmental Level
Defining the Problem	42	2.05 (S.E. = 0.08)	2.00 (S.E. = 0.12)	−.05^
Developing a Plan to Solve the Problem	42	1.83 (S.E. = 0.07)	2.10 (S.E. = 0.09)	+0.27*^
Analyzing and Presenting Information	42	2.07 (S.E. = 0.07)	2.52 (S.E. = 0.08)	+0.45***^
Interpreting Findings and Solving the Problem	42	2.17 (S.E. = 0.08)	2.33 (S.E. = 0.11)	+0.16^

*p < .05;

***p < .001;

1 = Beginning; 2 = Developing; 3 = Appropriately Developed; 4 = Exemplary

^Repeated Measures: Within subjects = pre- vs post-course, significant for Developing a Plan to Solve to the Problem [F (1,41) = 5.340, p < .05] and for Analyzing and Presenting Information [F (1,41) = 17.271, p < .001]; Between subjects = fall term vs spring term, no significant effects; No significant interaction

Table 6 Student ratings of individual laboratory modules as useful to understanding important concepts of evolution and human variation

Laboratory module	Lab #	# Ratings	% "Very Useful" ratings
Tree Building and Primate Classification	3	41	73.17
Forensics 2: DNA Fingerprinting	8	41	70.73
Human Variation: Anthropometry	11	36	66.67
Human Osteology and Forensics	5	43	65.12
Hominid ID 1: Bipedalism	6	40	62.52
Genes and Variation	2	45	62.22
Human Genetic Adaptation: ELISA	10	40	60.00
Evolution and Scientific Thinking	1	46	58.69
Hominin ID 2: Skulls, Teeth and Diet	7	36	50.00
Primate Anatomy and Locomotion	4	43	48.84
Population History and Ancestry	9	36	36.11

Table 7 Student ratings of individual laboratory modules as important to understanding tools used by biological anthropologists to understand concepts of evolution and human variation

Laboratory module	Lab #	# Ratings	% "Very Useful" ratings
Forensics 2: DNA Fingerprinting	8	41	82.93
Human Variation: Anthropometry	11	36	77.78
Human Genetic Adaptation: ELISA	10	40	75.00
Tree Building and Primate Classification	3	41	73.17
Osteology and Forensics	5	43	65.12
Genes and Variation	2	45	62.22
Hominin ID 2: Skulls, Teeth, and Diet	7	36	55.56
Primate Anatomy and Locomotion	4	43	51.16
Hominid ID 1: Bipedalism	6	40	50.00
Population History and Ancestry	9	36	47.22
Evolution and Scientific Thinking	1	46	34.78

module students participated in and occurred during week two of the semester. The Primate Anatomy and Locomotion session occurred at about week six of the semester. Four variables were scored from the laboratory worksheets of each of these sessions across the final two semesters of the grant implementation period, fall 2015–spring 2016: Defining the Problem; Developing a Plan to Solve the Problem; Analyzing and Presenting Information; and Interpreting Findings and Solving the Problem. All were rated on a scale of 1 to 4 (Beginning, Developing, Appropriately Developed, and Exemplary). Three faculty scorers worked together to determine final scores by consensus for each variable in each laboratory worksheet. Complete data were available for a total of 42 students across both semesters (21 each semester) (see Table 5).

RSQC2

Student responses to all items of the RSQC2 classroom assessment tool were collected across the final two semesters of the grant implementation period, fall 2015–spring 2016. As outlined earlier, students were asked to rate the usefulness of each laboratory session in helping them to understand (1) the important concepts of evolution and human variation discussed in the course, and (2) the tools used by biological anthropologists to understand the concepts of evolution and human variation. Students ranked each laboratory session, as it ended, on a 4-point scale, ranging from Not Useful to Very Useful, on each of these items. Table 6 lists the laboratory session topics and the percent of students who rated each one as "Very Useful" to their understanding of the important concepts of evolution and human variation. Table 7 lists the percent of students who rated each one as "Very Useful" to their understanding of the tools used by biological anthropologists (i.e., to their understanding of the scientific method as practiced by biological anthropologists). Some differences in student ratings across the two areas of understanding are apparent.

Student confidence in using scientific method

Student ratings of their confidence in using the scientific method are reported here for the pre-grant period (fall 2011 and fall 2012 combined), and the grant implementation period (fall 2013, spring 2014, fall 2014, spring 2015, fall 2015, and spring 2016 combined) (see Table 8). Student ratings increased from pre- to post-course during both time periods, but improvement was greater during the grant implementation period than during the pre-grant period.

Discussion

The laboratory curriculum developed and evaluated at WCU increases students' understanding of evolution in introductory biological anthropology compared with other institutions using more standard approaches. While students taking the evolution concepts survey demonstrated improved understanding of evolution at all of the schools that employed this instrument (WCU and comparisons) from the beginning to the end of each semester, WCU students demonstrated a greater increase in percent items answered correctly from pre- to post-course (see Fig. 1). Significantly more WCU students answered 18 (of 25) survey items correctly at the post-course assessment than did students at any of the other three institutions (see Table 2). Given that WCU class sizes are smaller than those at the three comparison universities, WCU student performance on the evolution survey before the new curriculum was implemented was compared with performance during the first three years of the new, grant-funded curriculum. Students taking the survey during the grant period answered a statistically greater percentage of items correct at the post-survey than students in the pre-grant period, with pre-survey response levels showing no significant difference across these two phases (see Fig. 2); class sizes were comparable across the entire time frame.

Thus, we demonstrate the impact on improved student understanding of evolution is related to the new curriculum itself. In the remaining discussion, we focus on the question of what aspects of the new curriculum may be contributing to this improvement, detailing how this curriculum incorporates all three of the key learning strategies outlined by Nelson (2008): (1) extensive use of active learning approaches; (2) focus on science as a process and way of knowing; and (3) identification and direct targeting of student misconceptions.

First, the WCU curriculum is inquiry-based, engaging students actively and directly with the process of "doing science". Active learning (also known as student-centered learning) strategies, such as problem- or inquiry-based approaches, have been shown to be superior to instructor-centered approaches (e.g., lecture) in promoting student learning about evolution (e.g., Jensen and Finley 1996; Nehm and Reilly 2007). One of the stated learning goals of this course is to help students come to understand how biological anthropologists investigate questions. We strive to accomplish this by having them learn and actually use some of the tools scientists in this field employ—both at the 'outward' physical (e.g., skeletal, body shape and size, etc.) and molecular/biochemical

Table 8 Mean (± S.E.) student ratings of confidence in using the scientific method pre- and post-course by grant phase (total possible scores range from 0 to 50)

Project Phase	Pre-Course Average Confidence Rating	Post-Course Average Confidence Rating	Change in Average Confidence Rating
Pre-Grant Terms (N = 46)	40.80 (S.E. = 0.75)	42.91 (S.E. = 0.70)	+ 2.11*** [t (45) = 3.797)
Grant Implementation Terms (N = 104)	41.08 (S.E. = 0.48)	44.73 (S.E. = 0.41)	+ 3.65*** [t (103) = 7.984]
Difference: Pre-Grant vs Grant Implementation Periods	+ 0. F (1,148) = 0.096]	+ 1.82* [F (1,148) = 5.600]	+ 1.54*^ [F (1,148) = 3.910]

*p < .05; **p < .01; ***p < .001

^Repeated Measures: Within subjects = pre- vs post course, significant effect [F (1,148) = 54.39, p < .001]; Between subjects = pre-grant vs grant implementation, no significant effect [F (1, 148) = 2.067, p > .10]; Interaction significant [F (1, 148) = 3.910, p = .05] levels (e.g., gene sequence readouts, DNA fingerprinting)—in a problem-solving context. Student lab teams receive a challenge scenario and have to come up with a methodological approach (usually using techniques they have just learned, and occasionally employing techniques learned earlier in the course), collect data, and then interpret those data—in every lab. This is fundamentally different than the typical approach in an introductory biological laboratory setting, such as those used in the comparison institutions and described earlier in this paper.

We think that this bi-level approach to teaching and using relevant methods in problem-solving helps students connect the evidence for evolution and human variation with the underlying molecular basis of that variation and change over time. Student ratings of each lab on the RSQC2 question pertaining to effectiveness in helping them to learn concepts of evolution and human variation were highest for Tree-Building and Primate Classification and DNA Fingerprinting (Table 6). We think it telling that both of these labs involve genetic as well as phenotypic variation linked with evolution. Ratings for the question concerning lab effectiveness in helping students to learn to use the tools biological anthropologists employ to understand evolution and human variation were highest for Forensics 2: DNA Fingerprinting, followed by Human Variation: Anthropometry, Human Genetic Adaptation: ELISA, and the Tree-Building and Primate Classification labs (see Table 7); all but the anthropometry lab address directly both genetic/biochemical and physical traits.

Second, the WCU curriculum focuses on the scientific way of knowing and the scientific process from the first week, in both lecture and lab contexts. The first topic after the students are introduced to the discipline is the nature of science: how science seeks to understand phenomena, the meaning of 'fact', 'hypothesis', and 'theory' in a scientific inquiry, and how the scientific approach to understanding natural phenomena differs from others. The first lab, which occurs early in the second week, then provides an opportunity for students to try out the scientific method and to learn, in context, about generating hypotheses, developing methods, collecting data, and interpreting those observations. They also learn about bias caused by preconceptions, measurement error, and different approaches to understanding the world (e.g., science and religion). Each lab module thereafter requires students to methodically think through and structure their work using the standard methodological sequence: question/hypothesis, explication of methods, data collection and reporting, discussion, and interpretation (see Table 1). Further examples of how the process of science is addressed in the curriculum are described below in the discussion about addressing evolution misconceptions.

The effectiveness of this approach is supported by the qualitative evolution concepts analysis that we undertook to look for thematic patterns in the evolution survey statements (see Table 2 and associated text). Three broad concepts showed a significant effect of institution, with WCU student post-course scores being higher than those at the other institutions; the first of these was understanding of basic scientific evidence and the process of science. The in-class clicker data we analyzed (see Table 4) support the idea that students gained knowledge about the scientific method during lab classes. Analysis of the change in student performance on lab challenges relevant to steps of the scientific process from early to mid-semester (see Table 5) also supports improved student ability to develop a plan to solve the problem (Methods) and to analyze and present information (Results) from the early time point to the later one. Additionally, students' report of their confidence in using the scientific method (see Table 8) indicated greater improvement from pre- to post-course during the grant implementation period than during the pre-grant period at WCU. Firsthand experience with the scientific method and opportunities to 'think like a scientist' have been linked with improved ability of students to understand and accept evolution (see, e.g., Pittinsky 2015; DeSantis 2009; Robbins and Roy 2007; Nelson 2008).

Third, the WCU curriculum is designed to identify and directly address student misconceptions about evolution, and it does so from early in the course (Nelson 2008). Students take the evolution concepts survey on the first day of class, before any instruction about evolution. This provides a baseline of their understanding, and the concepts included in the survey are among those that the curriculum proceeds to address. The order of the labs over the semester (Table 1) ensures that basic concepts of evolutionary theory and mechanisms, genetics, and classification/phylogeny are covered early. As part of this attention to foundational ideas, class discussions during and at the end of labs include a focus on misconceptions about evolution and, indeed, about how scientific inquiry is conducted. For example, in the Evolution and Scientific Thinking lab (the first one), students nearly always assume the male skeleton will be the taller of the two—whether or not they overtly state that as a hypothesis. This and other ideas that students mention lead to a discussion of assumption bias and how we try to avoid that in the process of "doing" science. This is followed by a dialogue (sometimes precipitated by a student-expressed view, but more often introduced by the instructor as a story) focused on the idea some people hold that the male should have one less rib than the female. We talk through whether this is a scientific hypothesis (yes, because it can be tested); how they would test it (go count the ribs); what kind of evolution mechanism this idea reflects (Lamarkism, i.e., inheritance of acquired characteristics); and what genetic assumption is also being made (that rib number is sex-linked). We also tell students that, in reality, there is a range of variation in number of rib pairs in humans. In fact, the male skeleton is shorter than the female, and this fact also fosters a framework in which to look at what kinds of factors may affect variation in height in humans, besides sex (e.g., population or individual ancestry, various environmental influences, age). In the Tree Building and Primate Classification two-part lab, we address directly the relationship among monkeys, apes, and humans. At the outset, most students think that monkeys and apes are more closely related evolutionarily than either group is to humans; this is also typically how they interpret the anatomic evidence of the comparative skulls and build their initial trees. However, when they do the counts of pairwise differences in the gene sequence for the three primate groups, they come to understand that the genetic evidence is indicating that apes and humans are more closely related than either group is to monkeys. The discussion in this lab is also focused on the conduct of science inquiry (e.g., can we say a hypothesis is "proven" based on one gene sequence or a limited set of anatomic traits?) and evolution misconceptions (e.g., that extant species differ from each other in "how evolved" or better adapted they are, based on body size or some other assumption).

In addition, we assess student understanding about common misconceptions in all labs directly via some of the in-class clicker questions administered as a formative assessment at the beginning and end of each lab module. Use of clickers allows us to assess immediately, at the conclusion of a lab module, how well students grasped the key concepts and techniques on which the lab was based, including evolution concepts. In the data presented in this paper, scores on evolution concept clicker questions improved significantly in the early lab modules analyzed as a group compared with mid-semester and later semester groupings of lab modules (see Table 3). In the later phases, the baseline (pre-lab) scores were higher, reflecting student mastery of evolution concepts generally over course duration. Finally, evolution misconceptions were also addressed in 'lecture' class discussions as well as queried on exams. In other words, the focus on correcting misconceptions occurred at multiple levels and time points in the course.

The kind of repetition and reinforcement that we describe here has been termed "spaced practice" or "varied practice" and is documented as improving student conceptual learning (Brown et al. 2014; Cepeda et al. 2006; Lang 2016). Spaced practice improves learning for a variety of reasons and in a variety of ways, but one thing that spaced practice supports is long-term consolidation of information; practice over time and in various forms allows for the connection of new information to existing knowledge and for the strengthening of memory traces over time (Brown et al. 2014; Cepeda et al. 2006; Goode et al. 2008; Moulton et al. 2006). We think that reinforcing on a weekly basis both the scientific method and correct general and specific concepts about evolution (including the mechanisms of evolution) represents this kind of spaced and varied practice and may well be contributing to the comparative success of this curriculum. The close integration of lecture and lab is likely also a factor.

Following the project, the course instructor, in consultation with the project team, made a number of changes to the curriculum based on the promising findings described above. The steps of the scientific method were more explicitly built into all of the lab worksheets, for emphasis. Opportunities to emphasize key evolution concepts within particular labs were enhanced during post-lab discussions. Clicker questions were revised to incorporate more statements reflecting science process and understanding, as well as additional repetitions of evolution concepts (with altered wording each time). Eventually, two new labs were developed related to human physiological adaptability. The first of these was added in spring of 2017 and focused on blood pressure response to stress; this lab, done late in the semester, then became the basis for the students' final group project (instead of the population ancestry lab). After the students conduct a pro-forma experiment assessing cardiovascular response to a stressor using the blood pressure sensor and software, they design and conduct their own experiments, which they then present orally the following week. In fall 2017, a second physiology lab was added in the first half of the course, focused on skin temperature response to cold, and provided another, and earlier, opportunity for students to develop their own experiments once they learned the technique, with an emphasis at this early stage on hypothesizing. Students present these first 'mini' projects briefly (focusing on hypothesis and results) the following week. We felt that it was important to provide students with two experiences that allow them to ask and answer research questions of their own, under guidance. In fall 2017 the course topic order was also altered, bringing most of the human biology material previously covered at the end (biological variability and adaptation) into the sequence immediately after evolutionary theory and genetics—thus the relevance of a temperature adaptability lab in week 5.

Conclusions and suggestions

The student-centered biological anthropology laboratory curriculum developed at WCU is more effective at helping students to understand general and specific concepts about evolution than are more traditional curricula. We argue here that this is not just a function of small class size, but is directly related to the inquiry-based approach used in the labs, the emphasis on knowledge of science and practice applying the scientific method regularly, the very intentional confronting of misconceptions about evolution starting early in the course, and the structure that allows for 'spaced practice', i.e., continual reinforcement of correct concepts about evolution and human variation. Inquiry-based approaches can be incorporated in lab sections of otherwise large lecture courses (Casotti et al. 2008) or as small-group activities within lecture-only science courses. Evidence suggests that these student-centered approaches also work well for diverse learners (Tuan et al. 2005).

We encourage instructors of introductory biological anthropology and other life science courses to incorporate these key elements in their curricula to support improved student understanding about science process and evolution. Three general suggestions that might be applied fairly readily based on our study would be: (1) assess students' level of understanding of evolution and how science proceeds right at the beginning of the course or relevant unit, and again at the end—to take stock of the impact of the curriculum on student learning; (2) provide hands-on problem-solving opportunities, such as case studies, guided challenges, or self-designed experiments, that iteratively emphasize scientific method and correct understanding of evolution; (3) use human examples where possible, and look for opportunities to help students connect the phenotypic changes reflecting evolution with the underlying genetic changes. The WCU curriculum is freely available to those who are interested in more detail or who may wish to adapt and incorporate components of what we have discussed here in their own courses—e.g., specific labs, etc.—at the following link (https://digitalcommons.wcupa.edu/anthrosoc_facpub/72); inquiries or requests for additional information may be sent directly to the first author.

Abbreviation

WCU: West Chester University.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12052-022-00164-4.

Additional file 1. Revised version of the evolution survey that includes 25 items; administered at WCU and three other universities from Fall 2014 on.

Additional file 2. Rubric used to review student laboratory worksheets. Includes 4 measures of scientific thinking (defining the problem, developing a plan to assess the problem, analyzing and presenting information, and interpretating findings and solving the problem), with each assessed on a scale of 4 developmental levels (beginning, developing, appropriately developed, and exemplary).

Additional file 3. A modified version of the RSQC2 classroom assessment technique (Angelo and Cross, 1993), completed by students during and after each laboratory module.

Additional file 4. A 10-item survey completed by WCU students at both the beginning and the end of each semester asking them to rate their level of confidence in their abilities and/or understanding of several pieces of the scientific process. All items were rated on a 5-point Likert scale: 1 = completely doubtful; 2 = somewhat doubtful; 3 = neutral; 4 = somewhat confident; 5 = strongly confident.

Additional file 5. Evolution survey, concept scores: descriptive statistics by institution

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Author contributions

SLJ, MK, and JA designed the curriculum. SLJ is the instructor of record for the course and was responsible for obtaining informed consent and for implementing the curriculum. LR-D served as the project evaluator and conducted all analyses. All authors read and approved the final manuscript.

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Availability of data and materials

The lab manual can be accessed at the open source link: https://digitalcommons.wcupa.edu/anthrosoc_facpub/72. Other materials can be obtained from the first author on request.

Declarations

Ethics approval and consent to participate

As reported in Methods section.

Consent for publication

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Competing interests

The authors have no competing interests.

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