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Clearing the highest hurdle: Human-based case studies broaden students' knowledge of core evolutionary concepts

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Abstract

An anonymous survey instrument was used for a ten year study to gauge college student attitudes toward evolution. Results indicate that students are most likely to accept evolution as a historical process for change in physical features of non-human organisms. They are less likely to accept evolution as an ongoing process that shapes all traits (including biochemical, physiological, and behavioral) in humans. Students who fail to accept the factual nature of human evolution do not gain an accurate view of evolution, let alone modern biology. Fortunately, because of students' natural curiosity about their bodies and related topics (e.g., medicine, vestigial features, human prehistory), a pedagogical focus on human evolution provides a fun and effective way to teach core evolutionary concepts, as quantified by the survey. Results of the study are presented along with useful case studies involving human evolution.

Keywords: Survey, pedagogy, biology, evolution, Darwin.

All science educators face pedagogical difficulties, but when considering the social ramifications of scientific ideas, few face as great a challenge as biology teachers. Studies consistently show more than half of Americans reject any concept of biological evolution (Harris Poll, 2005, Miller et al., 2006). Students embody just such a cross-section of society. Much ink has been spilled explaining how best to teach evolution, particularly to unwilling students (Cavallo and McCall, 2008, Nelson, 2008). In this paper I argue that use of basic, widely recognized case studies involving human evolution can make a difference. Fortunately, because people are naturally most curious about themselves, this is easy and fun to do.

My experience after twenty years of teaching general and advanced biology courses with an evolutionary emphasis (including human evolution, evolutionary theory, vertebrate paleontology, and comparative anatomy) is that acceptance of biological evolution is not an all-or-nothing proposition. Not only are most classes a mixed bag in terms of student acceptance of evolutionary thinking, but even among students who end up accepting the factual nature of evolution, views are often severely limited or constrained. Students may agree with the basic notion of biological evolution, but their understanding may be far from what their instructor has in mind. In particular, I have found (via the statistical study

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described in this study) that students are most willing to accept biological evolution as 1) an historical explanation for 2) physical features of 3) non-human organisms. In other words, it produced dinosaur bones long ago. In addition, students often develop 4) teleological, Lamarckian notions. Most students emerge from my general classes with a thorough, modern view of evolution, but where some get hung up it is likely to involve acceptance of evolution as (in contrast to the numbered points above) 1) an ongoing process that involves 2) non-physical (e.g., biochemical, physiological, or behavioral) traits, and most of all as a process that 3) affects humans. Students generally accept evolution of peppered moths. As Allchin (1999) has argued, the "hang-up" typically involves human evolution. Regarding acceptance of evolutionary science, this is for most people the final, highest hurdle. Yet as Darwin himself wrote in his "C" notebook (1838) more than twenty years before the publication of his landmark *On the Origin of Species* (1859a), when he was just beginning to piece together his ideas on natural selection, man "is no exception" to evolution. Barely a month before the publication of *Origin*—in which Darwin hinted at but was unwilling to spell out the explicit claim of human evolution—he wrote in a letter (1859b) about evolution that there is "no possible means of drawing [a] line & saying here you must stop."

Like Tycho Brahe, the 16th century Danish astronomer who, after observing planetary motion, aligned his observations with his prevailing geocentric worldview by positing that extraterrestrial planets do indeed orbit the sun but the entire solar system then orbits Earth (Barash, 2007), people often attempt to confront the concrete empirical evidence for evolution by meeting it halfway. In essence, they admit it as a powerful explanatory force but only up to a point, invariably with the proverbial line drawn in the sand up to but not including human beings, as Darwin implied in the letter cited above. The result is a partial acceptance: wrong in that it is not wholly right. As Barash puts it (2007), "Give ground in response to undeniable facts, but if those facts conflict with your more cherished beliefs, hold fast to the latter."

Given the ubiquity of religious, philosophical, and other social objections to evolution, this is not surprising. Many people mistakenly believe acceptance of evolution will shatter their faith or lead to moral nihilism (Brem et al., 2003). They are wary of strict philosophical naturalism. They find the idea that humans can be studied as biological creatures—as animals—alarming, and worry that such investigation degrades and demeans us. They forget that evolution depends on environmental context, and thus they fear, wrongly, that genes fully predetermine rather than predispose. Despite the fact that no legitimate scientific evidence has been found which contradicts evolution, even with tremendous scrutiny, and that instead a huge weight of consilient scientific evidence (multiple independent lines of data) supports the factual nature of human evolution, these social objections carry the battle for a large number of people. Given that many young people whose minds are not yet made up are willing to give fair hearing to objective evidence, it behooves biology teachers to face these issues squarely, clearly, and effectively.

Sadly, educators must not only confront social dimensions of science but must, in many cases, undo years of misinformation or neglect. Students must recognize that evolution is not merely another chapter or section of their textbook: it is the essential, fundamental, unifying theme of all life science. In Dobzhansky's famous words, "Nothing in biology makes sense except in the light of evolution" (1973). Students must see that although evolutionary theory remains a field of vigorous debate, its central, factual nature is not in dispute among scientists. Once students have a clearer grasp of the nature and scope of science and a better comprehension of what evolution does and does not entail, instructors must not retreat in the face of student fears about human evolution. They must confront such qualms head on.

I recommend that instructors, especially at the college level where students are more mature, not shy away from the contentious topic of human evolution, which is the primary reason people are often unwilling to accept the possibility of evolution. Such peoples' "understanding" of evolution is usually grossly misinformed, but it is typically dependent on bones and fossils. Further, I contend that when guided by the skilled hand of a dedicated, well-informed instructor, discussion of human behavior, including thorny new fields of evolutionary psychology and sociobiology, will have greater impact than traditional exposition of paleoanthropology (of which see the excellent review in Alles and Stevenson, 2003). Not only does exploration of human evolution satisfy curiosity, but it is likely to dispel myths and misconceptions and ultimately leave students with a purer, broader understanding of the thriving, dynamic disciplines comprising modern biology.

Here I provide specific ideas for human-based teaching of evolutionary concepts. Second, to demonstrate that such teaching makes a difference, I present results of extensive student surveys. Third, I offer time-tested suggestions, gleaned from this study, for teaching evolution (human and otherwise). Students who flat out refuse to consider the possibility of evolution may never be persuaded, but then they probably don't belong in the classroom in the first place. If students are willing to listen and engage in open dialogue, my tips offer a high likelihood of success.

Materials and Methods

Pedagogical emphasis

In terms of pedagogy, the general Biology 110: Principles of Biology course has been revised at my institution such that evolution is the first topic and a consistent, ever-present theme. The course is required for biology majors and fulfills a basic laboratory science general education requirement for all students; typically half to two-thirds of enrolled students are non-majors. Instead of merely describing a history pageant, I explain evolution as an ongoing process. I present results of evolutionary studies in many species but dwell especially on humans. In lieu of bones and fossils I devote more time to behavior, including complex systems such as language, ethics, and aesthetics. I eschew delineation of various lines of evidence supporting evolution, which are readily found in every biology text and many excellent websites, and focus instead on discussion of what kinds of empirical evidence might constitute evidence *against* evolution (which fits better with the nature and methodology of science). In addition I concentrate on examples of evolution in everyday life, including human social evolution, disease, and "Darwinian medicine" (Williams and Ness, 1996; Burnham and Phelan, 2001; Dawkins, 2004; Cochran and Harpending, 2009).

Case studies are an effective way of teaching evolutionary concepts (Goldstein, 2008), and it is absurdly easy to find human-based studies of evolution, which are available in most modern biology texts and a staple of popular television documentaries, science magazines, and websites. Here are fifteen examples of case studies I have found effective, whose use I heartily endorse:

1) **Metabolic-based cases**, such as why humans (unlike most mammals and some other primates) cannot synthesize Vitamin C and must therefore ingest it, due to mutation in the now inactive human GULO pseudogene, make fascinating stories. Another simple case involves lactose tolerance, which is the exception rather than the rule, and how it may have evolved in populations in concert with domestication of livestock. **Population differences** in alcohol dehydrogenase enzyme is another student favorite.

2) Everyone knows of the sickle cell anemia vs. malaria trade-off, but recently proposed hypotheses suggest similar **stabilizing compromises** such as cystic fibrosis vs. tuberculosis, hemochromatosis vs. bubonic plague, and even high blood sugar levels (leading to diabetes) vs. hypothermia in people, including ancestral Europeans, living at very high latitudes. Such cases offer speculative evolutionary explanations for the **persistence of debilitating genetic conditions** (Moalem and Prince, 2007).

3) **Adaptation to altitude and climate** is a core anthropology topic and thus widely available. Although skin color, folic acid, and Vitamin D make an intriguing story of natural selection (sunlight is needed to create Vitamin D, yet destroys stores of folate), teachers are cautioned not to raise the issue of skin color unless they are prepared to devote much attention to it. Students like to discuss **racial concerns** (especially genetic variation and IQ) yet these often yield more disadvantages than benefits in class. The Vitamin D story is compelling (Jablonski, 2004). Moalem and Prince (2007) point to seasonal variation in cholesterol levels as well as overall high levels of cholesterol (a precursor of Vitamin D synthesis) in some populations, as another evolutionary tradeoff.

4) Quirky **physiological responses** and reflexes, such as the photic sneeze reflex (sneezing after exposure to bright light, especially after emerging from darkness), which some claim offered a benefit to clearing upper respiratory passages from potential pathogens encountered by ancestors in musty caves, offer fun opportunities to discuss human physiology as well as prospective dangers of eager over-reliance on evolutionary "just-so stories."

5) Evolution of **resistance in pathogenic organisms** (such as bacteria responsible for tuberculosis, or mosquitoes and DDT) to antibiotics and other compounds is a widely-known topic, so students are likely to have heard of it, but often they have

basic facts and principles confused, and may not appreciate connections to humans (Levy, 1998).

6) **Host manipulation** by parasites and other pathogens offers an intriguing evolutionary perspective on disease. Paul Ewald (1994) has generated provocative ideas about, for example, why colds are less virulent than other pathogens (so we remain mobile and spread the rhinovirus), whereas pathogens transmitted by non-human vectors (e.g., mosquito-spread malaria-causing *Plasomodium*) keep us in one place, where vectors can find us. Ewald suggests we can influence pathogen evolution toward less virulence , e.g., "selecting" for less virulent cholera by cleaning up water supplies and ensuring infected people don't contaminate them, forcing cholera to become less harmful in order to spread.

7) Predisposition to cancer or heart disease, or other **genetic bases of disease**, are widely discussed in the popular press and hence easy to find and familiar to students. College-age men and women may feel invulnerable, but they will be interested as elder family members manifest health concerns.

8) **Imperfections** are everywhere in the natural world; students are sure to know of many in the human body, including various **adaptive compromises**: pelvis adapted for upright stance and bipedal locomotion yet poor for childbirth; spine from quadrupedal ancestors, leading to back problems; lowered larynx allowing for vocalization yet letting us choke on food. There are also numerous **vestigial features**, including but not limited to the vermiform appendix, coccyx, wisdom teeth, extrinsic ear muscles, "goosebumps" to fluff fur for insulation, and nipples and rudimentary uterus of males. Shubin (2008) is a great source for such examples involving the human body, as is Chapter One of Darwin's *The Descent of Man* (1871).

9) Students enjoy pondering the role of **genes and basic human behavior**, such as thrill-seeking behavior or assertiveness, or autism and schizophrenia (Holden, 2009). But make sure students are aware of epigenetic and environmental effects (e.g., from studies of identical twins, and from behavioral changes with age, and so on).

10) However, students find the rapidly emerging fields of **sociobiology** and evolutionary psychology, which present broader behavioral implications, controversial and inflammatory. These topics may shed more heat than light, but create a smoldering spark that can lead students to see human behavior in evolutionary terms. Two popular areas are human **mating strategies** and **altruism/evolutionary ethics** (Allchin, 2009).

11) A current hot topic is the role of methylation in **epigenetic imprinting of genes**. For example, some biologists argue (Jirtle and Skinner, 2007; nice review in Moalem and Prince, 2007) that the current rise in obesity stems from a "thrifty" gene which helped ancestral humans survive lean times, yet now leads to over-

weight people in cultures where low-nutrition, high-calorie food is abundant. Similar stories implicate smoking in health woes of children and even grandchildren via methylation of the fetal genome. Students enjoy discussing the extent to which their physiology and health are due, or not, to their own lifestyle choices. Study of epigenetic changes suggests something akin to "on-demand" mutations, which should lead to discussion of Lamarck vs. Darwin and inheritance of acquired variation.

12) **Non-coding "junk" DNA** and transposons ("jumping genes," which may have a higher incidence in African primates, including humans) can lead to all sorts of novel variations. High levels of HERVs (human endogenous retroviruses) in the human genome might have provided our ancestors with increased fodder for phenotypic variation, and thus might have been critical in human evolution. This also ties in to concepts of coevolution, such as the origin of eukaryotic organelles via endosymbiosis.

13) The topic of **aging**, and why humans live so long (and with what social costs and benefits) is, to young people, a fascinating but non-threatening way to study evolution.

14) The **Human Genome Project** offers many opportunities to discuss genetic variation (e.g., haplotype mapping) within and between populations and species, as well as the relationship between genetics and health, and the growing possibility of tailored pharmacogenomic drugs.

15) Gene and stem cell therapy and the specter of **genetic manipulation** or "enhancement" in humans is guaranteed to provoke discussion, much of it invariably veering off topic, but one can steer the dialogue toward the human evolutionary past, present, and future.

Suffice to say one could fill a book listing examples of human-based evolution studies. As time permits (or as supplementary readings and fodder for discussion) I recommend use of these and countless other "anthropocentric" studies. Any biology topic is best viewed through an evolutionary lens.

Survey methodology

For ten years (1994-2003 inclusive) I utilized a 25 question anonymous, pre- and post-semester survey to gauge student attitudes about evolution (Werth, 2009), as well as to provide feedback for outcomes assessment and thereby improve teaching in this Principles of Biology course. Results presented here derive from a spin-off of this study, with a shorter, modified questionnaire used for three years (2000-2003) in this course as well as to freshmen and sophomores in a basic Organismal Biology course (primarily plant and animal structure and function), including six cohorts of students (total N=166). [The survey was also attempted in two sections of a human evolution class, but results of such administration are not presented here, as the sample size was small and the self-selected students who enrolled in that course all began highly accepting of evolutionary principles.] Each class was surveyed at the start of the semester (on or around the second day of classes, after the roster had stabilized) and again, using the same questionnaire, during the final class of the semester. Although this longitudinal study followed each student cohort, no attempt was made to track changes in responses of individual students, as all responses were anonymous. No credit was given for this survey; participation was optional, but students were told it was part of a pedagogical study and urged to respond seriously.

The survey involved 12 statements to which students were asked to respond using a simple seven-point Likert scale of agreement or disagreement (1=agree completely; 4=unsure or don't know; 7=disagree completely). The five statements most relevant to the study presented here are:

1. Evolution is a purely historical phenomenon (i.e., all in the past).
2. Evolution applies only to non-human species.
3. Evolution applies only to physical features, like bones.
4. Evolution does not affect complex behavioral systems such as ethics.
5. Evolution works toward a purpose or goal.

The wording of these non-normative statements did not change over the three years of the study. Statements were counterfactual; objective, empirical evidence strongly supports rejection rather than acceptance in all cases. Presuming an effective pedagogical approach, students who initially accept such claims should move toward rejection over the course of the semester. In other words, the null hypothesis is that scoring on the seven-point scale should increase. Note that one of the five statements (#2) deals specifically with evolution of our species, but the expectation is that by teaching human-based evolution students will better understand multiple integrated core concepts of evolutionary theory, not merely human evolution. Also note that instead of harping explicitly on the five points embodied by these statements, my teaching via case studies addressed them indirectly rather than directly.

In addition to this formal survey, I rely on data from an assessment instrument used by my department for all sections of our Principles of Biology course, which involves a brief (approximately twenty minute) "exit interview" with individual students at the conclusion of the course to assess how well we are teaching basic concepts. Although this session is not required, I explain its value as a review session before the final examination, and hence have excellent (~85%) participation. The interview involves five questions, all scored by the instructor on a four point scale to assess student mastery of the material, and in this way I gain even more quantitative and qualitative feedback from my teaching regarding the effectiveness of my emphasis on human evolution.

The Principles of Biology textbook for this 2000-2003 study was *Discover Biology* by Cain, Damman, Lue and Yoon (Sinauer/Norton 2000, first edition, and in the third year the second edition, published 2002), and for the Biology 202 Organismal Biology course the text was *Life: The Science of Biology* (6e), by Purves, Sadava, Orians and Heller (Sinauer/Freeman 2001).

Results

Responses to the five statements, indicated as percentage of students (data from all classes combined; N=166 students) responding in each category (1-7), are shown in Figures 1-5. In general, a majority of students accepted each of the five statements at the start of the semester yet rejected them at the end. The total percentage of students agreeing with each statement (from "agree completely" [response 1] to "agree somewhat" [2] and "agree a little" [3]), as opposed to the percentage of students disagreeing with each statement (from "disagree a little" [response 5] to "disagree somewhat" [6] and "disagree completely" [7]) are displayed in Table 1 (all years combined). Since percentages in Table 1 exclude response 4 (unsure/don't know), they do not total 100%. Notably, whereas a majority of students agreed with all five statements at the outset of the course, only one quarter to one third of them agreed at the end (summarized in Table 1).

Table 1. Results of anonymous survey (2000-2003) on student attitudes toward evolution.

Statement#	*Pre-Semester* Percentage agreeing/disagreeing		*Post-Semester* Percentage agreeing/disagreeing
1. Evolution is a purely historical phenomenon (i.e., all in the past).			
	64 / 25	→	9 / 84
2. Evolution applies only to non-human species.			
	52 / 32	→	20 / 71
3. Evolution applies only to physical features, like bones.			
	53 / 28	→	27 / 61
4. Evolution does not affect complex behavioral systems such as ethics.			
	50 / 30	→	40 / 44
5. Evolution works toward a purpose or goal.			
	52 / 33	→	41 / 48

The biggest change engendered by the shift to a clear evolutionary focus with an emphasis on human evolution concerns the historical versus current nature of evolutionary change (Figure 1).

At the start of the semester, nearly two-thirds of students (64%) agreed that evolution is a thing of the past; at the end, only 9% agreed with this claim and 84% disagreed with it. Likewise there was a significant, substantial shift with regard to whether evolution applies only to non-human species or affects humans as well (Figure 2), as disagreement (at all levels) with this statement jumped from fewer than a third of students to over 70% of them.

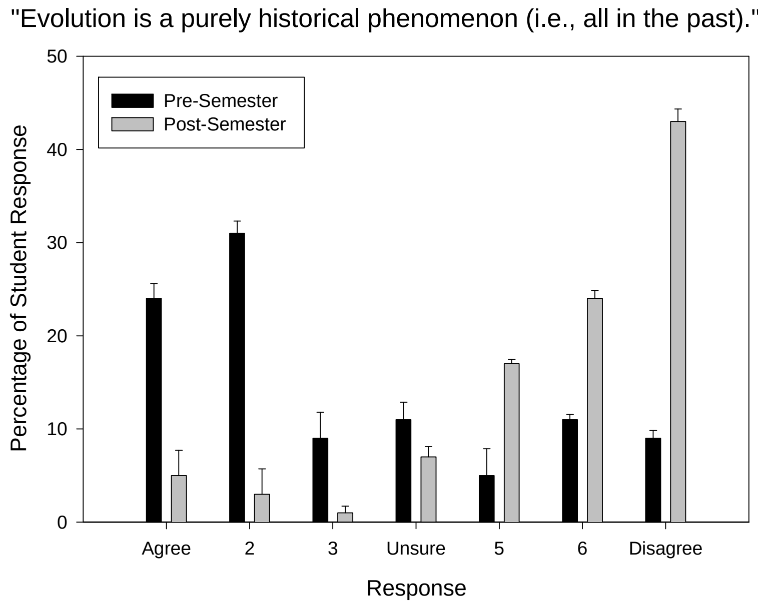

Figure 1. A concerted pedagogical focus on human evolution led students to see evolution as an ongoing process. This and all figures are from an anonymous four-year classroom survey (2000-2003, results from all years pooled), with error bars representing one standard deviation.

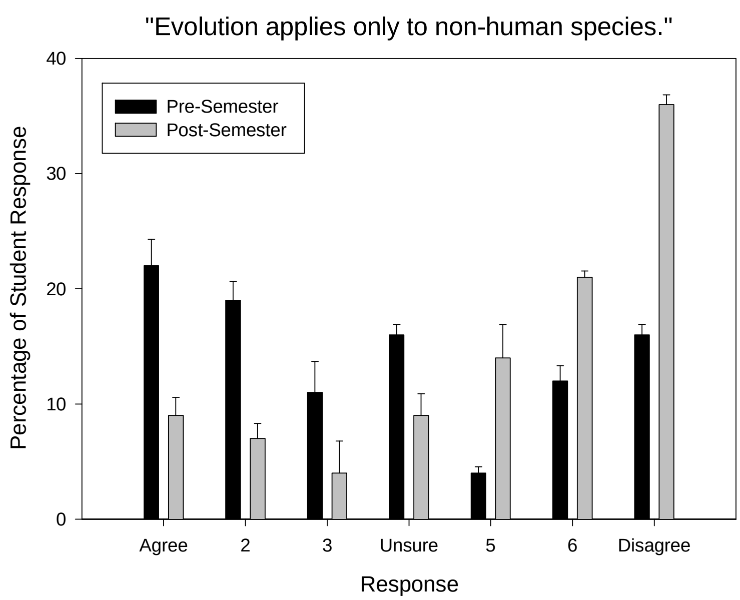

Figure 2. Results show students in the study became more likely to accept evolution of humans.

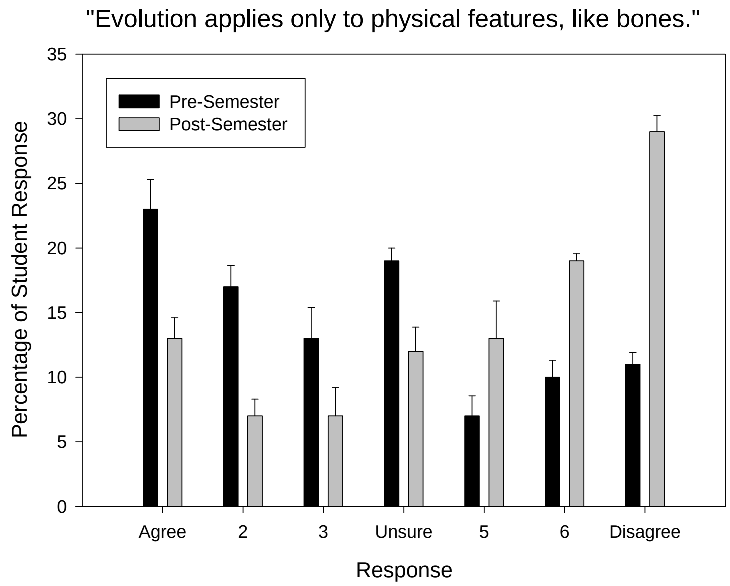

Figure 3. Students became more likely to accept non-physical (e.g., biochemical) evolution.

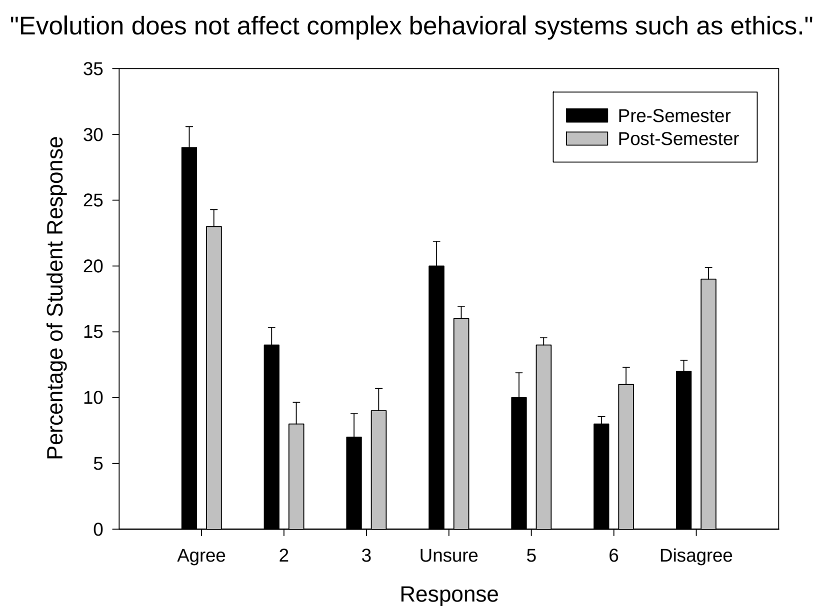

Figure 4. Students also became more accepting of evolution of complex behaviors, but less so.

As Figure 3 shows, slightly fewer students ended up rejecting the claim (#3) that evolution applies only to physical features. Fewer still changed their minds about the likelihood of involvement of evolution in complex behavioral systems (Figure 4), although admittedly this topic was dwelled upon to a lesser degree in class and not dealt with in the text or other course materials. Unlike Statements 1 & 2, both 3 & 4 had a sizable number of students choosing "don't know/unsure" even at the end of the course, although less so than at the beginning.

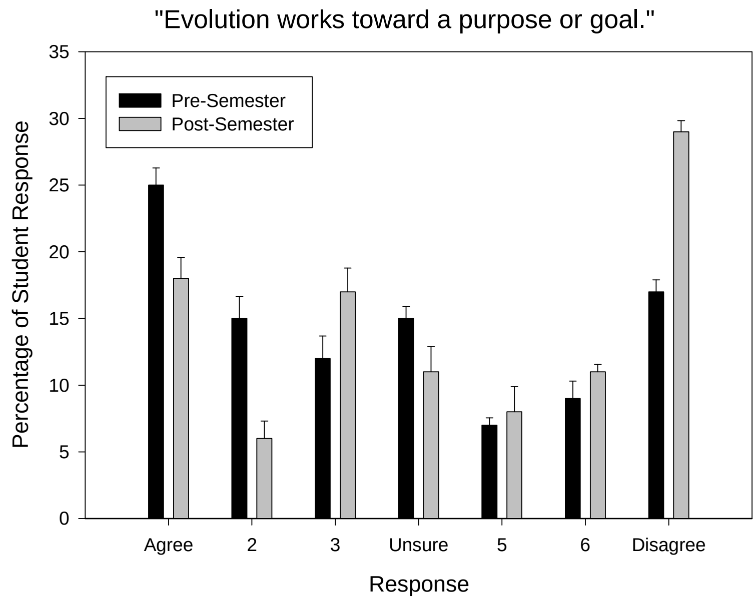

Figure 5. Students were more equivocal about teleological versus mechanistic explanations of evolution. Responses show opinions shifted, though not as strongly as with other statements.

As for Statement 5, which asserts that evolution works toward a goal, there was as in all cases described here a clear shift in opinion, yet a smaller shift. At the end of the semester 33% of students still agree with the claim that evolution is purposeful, although 17% agree only a little, and 29% disagreed completely at the end of the course.

Qualitative non-numeric findings yield similar results as gauged by student responses to classroom questions and comments in discussions, by responses to questions on exams and quizzes (particularly essay or short written answers), and from the end-of-semester oral quizzes and other dialogue outside class.

Discussion

Not all students ended up rejecting these claims as a result of their enrollment, but whereas a majority of students accepted them at the start, most students' views on evolution shifted dramatically. A general finding is that student attitudes vary widely. Initially, many accept evolutionary explanations yet the big "hang-up" clearly appears to be admitting evolution of humans, especially human behavior. In addition to the five points specifically addressed in this paper, other attitudes changed as well. For example, even at the beginning of the course students were much more willing to accept adaptation within species (i.e., "microevolution") than they were speciation or even adaptive radiation (i.e., "macro-" and "megaevolution" involving appearance of new species), but this too changed during the course.

How can I be sure that the changes I found in student attitudes result from my new pedagogical focus, specifically my increased case study-based emphasis on human evolution? Most of all, I can compare results with those from my broader unpublished study (Werth, 2009), which followed students in the same course over a ten year period, the first half of which preceded my shift to an evolutionary focus. Results of similar teacher surveys have been published by Osif (1997), Rutledge and Mitchell (2002), Rutledge and Warden (2000), and Lovely and Kondrick (2008). My data indicate that a broadly-based general biology course is likely to change student attitudes toward evolution, but much more so if evolution is made a central, unifying theme of the course, and if the dynamic nature of human evolution is made a center point (Linhart, 1997).

One of the most basic precepts of evolution is that it is an ongoing process—that it is insufficient merely to claim that all organisms have evolved, since all species are still evolving and moreover doing so in relation to one another in an intricate coevolutionary dance. Results (Figure 1) indicate that at the end of the course students clearly understand this concept. Even if evolution were a purely historical phenomenon it would of course still be amenable to scientific study by the hypothetical-deductive method (Cooper, 2002, 2004). The fact that humans are biological creatures and as such exempt neither from laws of nature nor the process of evolution was likewise grasped by most students. Yes, we are unique—indeed, all species are unique, otherwise they would obviously not be distinct species. Still, we recognize that in many ways, most notably cognitively and culturally, humans stand apart from other species, yet this does not diminish us. In contrast, the fact that we are related to all other living things yet have made great strides on our own might be seen both to ennoble and elevate us.

My results, both quantitative and qualitative, indicate that although a majority of students ultimately accept the evolution of behavioral traits and the non-teleological nature of evolution, they are more conflicted about these concepts, with fewer students changing their views or more adopting an uncertain one. Our teleological nature is indeed deep-seated. As Richard Dawkins (1995) notes, humans have "purpose on the brain." Michael Shermer explains (2006) that we see design everywhere because nature has in fact been designed, yet from a bottom-up rather than top-down process. He advises that we should "quit tiptoeing around" and admit that forms follow function "because evolutionary design is based on functional adaptation." In my experience our default anthropocentric, teleological worldview is firmly entrenched and very difficult to modify. As for the role of genes underlying evolutionary change, students may counter that genes are mere molecules. As Colin Tudge (2000) points out for those who deny the influence of genes, why else do dogs behave like dogs and birds like birds? Of course genes influence behavior, and since evolution is change in gene frequency, behavior evolves. Still, teachers must explain the role of genetic drift and evolutionary byproducts. Every facet of an organism (including behaviors) need not be adaptive. Instructors will rightly complain that their schedule is already stretched so thin, especially in a general biology course, that there is little "flex" time in which to introduce new material. However, human-based case studies need not occupy an entire class to make evolution more relevant and meaningful. They can be inserted as brief examples into lectures or discussions, using examples I have provided here.

Conclusions and Recommendations

Ironically, much of the difficulty in teaching human evolution stems from the fact that humans are naturally predisposed to think in teleological terms (Shermer, 2006; Kelemen and Rosset, 2009). Design that evolved in nature in a bottom-up sense, rather than divine design (imposed in a top-down way; Dennett, 1995), is thus a counterintuitive view that often meets resistance. As E.O. Wilson explains in *Consilience* (1998), the human mind "did not evolve to believe in biology." Darwin himself saw that the deck was stacked against him. As he wrote in *The Descent of Man* (1871), "A belief in all-pervading spiritual agencies seems to be universal." Nonetheless it is paramount to explain that acceptance of evolution does not equal rejection of religious beliefs. It is essential to explain that scientific and spiritual ideas need not conflict, and that science does not address supernatural claims (Meadows et al., 2000).

Throughout this paper I do not refer to "belief" in evolution but rather acceptance of empirical statements. As Shermer (2006) writes, "evolution is not a religious tenet, to which one swears allegiance or belief as a matter of faith." Evolution is an idea, not an ideology, which is why biologists often advocate rejection of the term "Darwinism" (Scott and Branch 2009). Religious objectors may not change their minds easily, if at all, but my aim is to reach undecided fence-sitters who are willing to listen and make up their own minds. Maturing college students generally fall into this camp. Many older adults are unswayable, yet a good number of students are grappling with new ideas and willing to see the world from a fresh perspective. As noted earlier, those who enter college resisting evolutionary teachings often have been misinformed and possess a skewed view of science. Patient, polite, and non-confrontational, non-threatening instructors who are nonetheless clear and firm in their teaching likely bear the best chance of successfully leading students to view evidence objectively. It would be interesting to monitor student attitudes years later, to see if seeds planted in the mind bear fruit years later. Yes, it is true that some reluctant students will not accept evolution no matter what tack teachers take nor how hard they try, but in other cases students will accept a balanced, realistic view of evolution if their concerns are addressed squarely, surely, and sincerely, as a central pedagogical focus on human evolution does.

It is essential to maintain a proper attitude. The approach should always be firm but never confrontational or condescending. The goal is to open minds, not to close them off. As noted above, most classes include a great diversity of views on evolution. I have found that many students who resist evolutionary thinking remain silent and keep concerns to themselves. Not only do they fear their beliefs are threatened, but they do not want to expose themselves to potential criticism from classmates or, worse, instructors. The teacher's tone is paramount in allaying fears and reminding students that there is a place for all beliefs, but that science class is a place to discuss scientific explanations. Never belittle or blame students for not immediately accepting evolution. In addition to demeanor, the language one employs is of utmost importance. The terminology used to present, explain, or even ask questions about evolution makes a huge difference. Myths and misconceptions persist even among students who acknowledge evolution from what they have heard or been mistaught (McComas, 1997). There remains in the minds of college students much confusion about whether evolution is merely one of many equally valid views or if it is scientific "truth." Just as genes are "linked" on chromosomes, views on evolution are often linked to each other as well as, more obviously, to religious faith and views on the compatibility of science and religion.

Finally, as a result of my survey of student attitudes and experience focusing on human case studies as a means of teaching evolution, I can offer a few additional words of guidance for teachers. It is imperative that students understand the nature and scope of science (Alles, 2001; Farber, 2003). The easiest way for them to understand what evolution is all about is to be assured of what it is not about. Students often erroneously equate "Social Darwinism" with Darwinian evolution. Also, teachers must stay current with evolutionary explanations. The field has changed greatly in the past two decades, especially with a proliferation of books on evolutionary ethics, evolutionary psychology, and sociobiology (Allchin, 1999), and with new ideas in molecular and evolutionary developmental ("evo-devo") biology, and hence the possibility of major morphological "leaps" via minor mutations in regulatory genes. As Kirschner and Gerhart (2005) note, the origin of novel structures need not involve "irreducible complexity," as critics of evolution frequently assert. Explanation of epigenetic in addition to genetic inheritance is also essential (Jirtle and Skinner, 2007). I recommend that instructors correct fallacious ideas (e.g., we did not evolve from monkeys or chimpanzees) yet not get bogged down in discussion of the origin of life and chemical evolution. Point out that Darwin was a proponent of hypothesis-based science. Long before hominid fossils were discovered in Africa he claimed it as the likely site of human origins: a testable, falsifiable hypothesis.

Evolutionary biology has changed profoundly in the century and a half since Darwin published *On the Origin of Species* (1859), but his approach remains relevant. He saw that rejection of evolution largely stems from its implications for humans (hence his follow-up work, 1871's *The Descent of Man*), and he recognized that scientists must not stray from science. In his words (Darwin 1880), "Freedom of thought is best promoted by the gradual illumination of men's minds which follow[s] from the advance of science." My advice is to continue on the path Darwin blazed, drawing examples from human biology to teach basic principles of evolution.

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