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Interactive Effects of Diagrammatic Format and Teleological Beliefs on Tree Thinking

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Abstract

A common misconception regarding evolutionary history is that the tree of life depicts the progression of species over time from least complex to most complex, ending with our own species at the pinnacle of evolution. The current study examined the diagrammatic factors that may impact the effect this misunderstanding has on students' ability to correctly interpret evolutionary trees. Students with weaker and stronger backgrounds in biology were presented with two cladograms, each featuring a different focal taxon (human or honeybee). The evolutionary relationships among the taxa were presented in four diagrammatic formats. Students reasoned in qualitatively different ways when asked about the human species as opposed to the honeybee, with specific diagrammatic formats facilitating anthropomorphic views, particularly among weaker background students.

Keywords: spatial cognition, teleological explanations, evolutionary diagrams, evolutionary misconceptions, cladograms, macroevolution

Introduction

There is a wealth of evidence that indicates students have great difficulty acquiring evolutionary concepts, particularly concepts regarding macroevolution and the origin of species. These studies have demonstrated that misconceptions are prevalent even among students with substantial training in the biological sciences (Ferrari & Chi, 1998; Greene, 1990; Samarapungavan & Weirs, 1997). A pertinent question is whether the tools that scientists use to study macroevolution are cognitively accessible and transparent to students of varying abilities, and whether there are perceptual or diagrammatic factors that potentially impede students' understanding of these tools in the absence of explicit instruction.

Tree thinking is a tool that professional biologists use to describe and classify species according to patterns of *most recent* common ancestry and to make inferences in the absence of data (e.g., Angielczyk, 2009). Evolutionary trees, or cladograms, are based on hypotheses regarding the distribution of derived characters among a set of taxa; they provide biologists with a conceptual framework for understanding the historical processes that promote and maintain the biodiversity of our planet. Although intensive instruction on macroevolution and tree thinking is largely absent from high school and college biology classes (Catley, 2006), a recent analysis of textbooks indicates that biology students at both levels are exposed to cladograms (Catley & Novick, 2008). This poses a potential problem if students reason incorrectly about the evolutionary relationships depicted in those diagrams.

Researchers have only recently begun to examine what information students are able to extract from these diagrams, both in the absence of explicit instruction as well as after instruction. This research has focused on assessing tree-thinking skills when cladograms are drawn in the familiar hierarchical tree format or in an alternative ladder format (Catley, Novick, & Funk, accepted; Meir, Perry, Herron, & Kingsolver, 2007; Novick & Catley, 2010; Sandvik, 2008). The results indicate that students, regardless of instruction, find the tree format much easier to understand.

The current study builds upon this prior research by examining how the particular taxa depicted in the cladograms, and especially students' knowledge and/or beliefs about those taxa, affects tree thinking (i.e., cladogram interpretation). We used the simpler-to-understand tree format and manipulated how the cladograms were oriented and how the taxa were arranged (keeping the underlying structure—evolutionary relationships—constant across cladogram versions). In particular, this study explores the misconception that the tree of life depicts the progression of the evolution of taxa over time from least complex to most complex. If students reason incorrectly about the evolutionary relationships among taxa, they may state that the most cognitively complex taxon (i.e., the human) is the most highly evolved. Feeding into this misconception is the widely held belief that humans are not subject to the same evolutionary pressures as other organisms because we were created intentionally by an outside agent (Evans, 2001; Greene, 1990) or created intentionally to fulfill a purpose (Kelemen, 1999; Kelemen & Rosset, 2008).

These considerations raise several questions: In the absence of explicit instruction, are students likely to perceive the evolution of specific taxa, such as the human, in teleological, or goal-directed, terms? Do students' responses differ depending on their biology background? Additionally, are students more likely to provide teleological responses when the focal taxon is located at the end of the cladogram versus when it is located in the center position? How does the vertical or horizontal orientation of the cladogram influence students' judgments?

Study Overview

The data presented here are part of a larger study that was designed to assess college students' reasoning about evolutionary history among several different subsets of taxa from the tree of life. The questions assessed, in several different ways, students' understanding of the evolutionary relationships among hierarchically nested sets of taxa. We limit our presentation here to one question that examined whether students' misinterpreted the information depicted in the cladograms by stating that the focal taxon was the most highly evolved. This question was asked about two cladograms, which differed in the focal taxon highlighted for subjects (human or honeybee).

The cladograms were drawn in four different ways: The cladogram itself was oriented either horizontally or vertically, and the focal taxon was situated either at one end of the cladogram (top or right) or in the center position among the set of nine taxa. Given students' teleological beliefs and misconception that humans are evolutionarily special, we predicted that students would be more likely to state that the focal taxon was the most highly evolved taxon when it was the human rather than the honeybee (see Figures 1 and 2). We also predicted that students would be more likely to make this claim when the focal taxon occupied the end (top or far right) rather than the middle position because a teleological construal would lead one to expect the most complex taxon to be at the end. Finally, because Franklin and Tversky (1990) have found that the vertical dimension is the most salient of the three spatial dimensions, we predicted that responses indicating that the human is the most highly evolved taxon would be most prevalent for the vertical orientation when human was situated at the top.

The main study included a sample of college students with weaker and stronger backgrounds in biology. In a follow-up study, a subset of the stronger background students received two days of instruction on phylogenetics (i.e., understanding evolutionary trees). They were tested before and after instruction.

Method

Subjects

The subjects in the main study were 112 Vanderbilt University undergraduates. Most students (34 females, 33 males, 2 unknown sex) were recruited from a paid subject pool in the psychology department. The remaining students (23 females, 20 males) were currently enrolled in the evolution class at Vanderbilt (taught by the fourth author).

We divided the subjects into two groups based on their background in biology: Students who had completed at least the two-semester introductory biology sequence for biology majors and pre-med students were assigned to the stronger background group; the remaining subjects were assigned to the weaker background group. The 52 stronger background students (28 females, 24 males) completed an average of 3.09 semesters of biology classes that were chosen from a list of classes presented on a background questionnaire. The 60 weaker background students (29 females, 29 males, 2 unknown sex) had completed an average of only 0.40 semesters of such coursework. This is nearly an 8:1 difference in coursework between the groups.

Materials and Procedure

All students received a 4-page booklet that included one cladogram and two to three questions about the information in that cladogram on each page. The presentation order of the cladograms was counterbalanced. Students completed this booklet, as well as several other booklets, in one session that took approximately 50-75 min.

Each cladogram included nine taxa. One taxon was the focal taxon, so named because the first question for each cladogram asked students what the diagram shows about the evolution of that taxon. (Subjects provided a written response to that question.) We limit our discussion here to the third question that was asked about the two cladograms for which human and honeybee were the focal taxa. This question asked students which taxon/taxa was/were the most highly evolved. (The second question asked students to evaluate the relative evolutionary distance between pairs of taxa. This question did not reference the focal taxon and did not bear on the present results).

Design

We examined three factors in the present study. One factor was weaker versus stronger biology background. We were interested in whether a year-long introductory class (and perhaps subsequent biology coursework) would countervail stronger background students of a teleological perspective on evolution.

The remaining two factors pertained to the visual presentation of the cladograms. The first of these factors was the orientation of the cladogram, which was manipulated between subjects. The terminal branches were either located at the right side of the cladogram (vertical orientation, Figure 1) or at the top of the cladogram (horizontal orientation, Figure 2). The second factor was the rotation of the branches of the cladogram. The branches were rotated, without altering the depicted relationships (i.e., the underlying topology), so that the focal taxon was located either at the end (far right or top, depending on the orientation; see Figure 1) or at the center position (see Figure 2). In Rotation Set 1, human was located at the end position whereas the honeybee was in the middle. In Rotation Set 2, the human was in the middle and honeybee was at the end. Rotation set was manipulated between subjects. We fully counterbalanced the orientation and rotation of the cladograms (see Figures 1 and 2 for two of the four possible combinations).

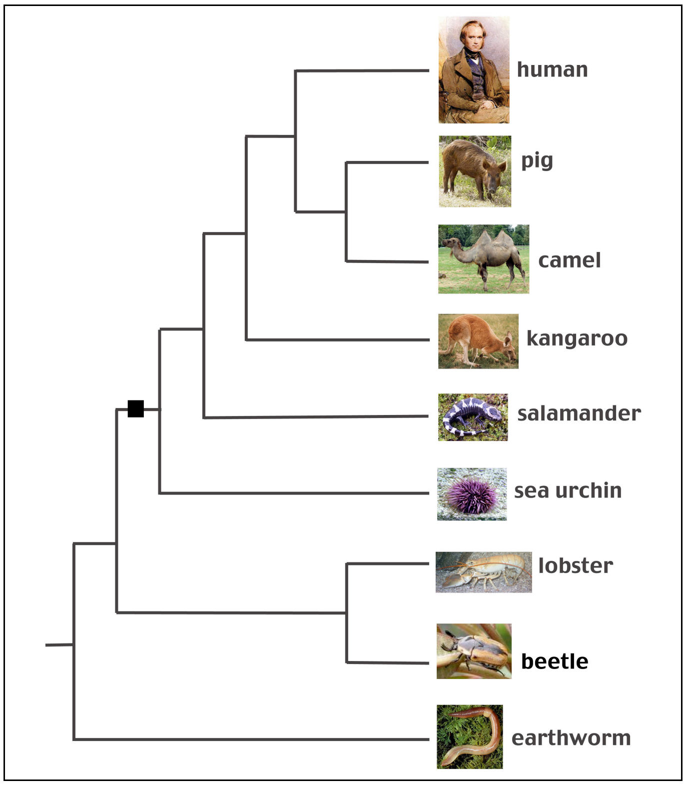

Figure 1: Human cladogram—vertical orientation, focal taxon at the end.

Follow-Up Study

We also examined whether students' evolutionary concepts were amenable to instruction by providing a subset of the students in the stronger biology background group (N = 42) with two days of instruction in phylogenetics (i.e., understanding cladograms). These students were recruited from their evolutionary biology course and completed the cladogram booklets at mid-semester (Time 1) and again 4.5-5 weeks later (Time 2). Students received the same booklet at both times.

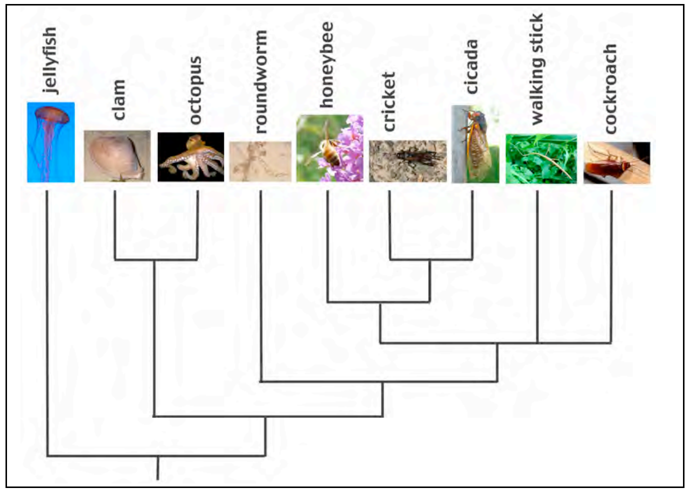

Figure 2: Honeybee cladogram—horizontal orientation, focal taxon in the middle.

Results

Are Humans Most Highly Evolved?

Students received a score of 1 if they indicated that the focal taxon (i.e., human or honeybee) was the most highly evolved species or a score of 0 for any other response. Overall, only 6% of students (all stronger background) responded correctly that the human cladogram did not reveal that any taxon was more highly evolved than any other taxon. In comparison, 5% of students (all stronger background) provided a correct response to this question regarding the honeybee.

As discussed earlier, we expected more responses that the focal taxon was most highly evolved when that taxon was the human as opposed to the honeybee. The results support this prediction, with 35% of students providing this response for the human cladogram, compared with only 2% (2 students, both from weaker backgrounds) for the honeybee cladogram, (χ^2=42.32, p <.001). Because students essentially never said that the honeybee was the most highly evolved taxon, we restricted our analysis of the effects of the diagrammatic factors on these responses to the human cladogram.

We conducted a 2 (biology background; between) x 2 (orientation; between) x 2 (rotation set = human at the end vs. in the middle; between) analysis of variance (ANOVA) on the responses that the human was the most highly evolved taxon. The main effect of biology background, $F(1, 104) = 17.20$, $p < .001$, $MSE = 0.17$, partial $\eta^2 = .14$, indicated that weaker background students were more likely to make this incorrect claim than were stronger background students (M = 0.50 vs. M = 0.19, respectively). The main effect of focal taxon location (rotation set), $F(1, 104) = 20.17$, $p < .001$, partial $\eta^2 = .16$, indicated that a higher proportion of students made this claim when the human was positioned at the end of the array than at the center (*M* = 0.52 vs. *M* = 0.20, respectively).

There was also a biology background x orientation interaction, *F*(1, 104) = 6.55, $p < .05$, partial η^2 =.06 This interaction was subsumed by a three-way interaction between biology background, focal taxon location, and orientation, *F*(1, 104) = 4.02, $p < .05$, partial η^2 = .04 (see Figure 3). When the human was located in the middle of the cladogram, weaker background students said humans are most highly evolved 35% of the time, compared with 0% of the time for stronger background students. Cladogram orientation had little effect. When the human was located at the end, however, both groups of students said that the human was most highly evolved, with such responses being especially prevalent for weaker background students who received the vertical orientation. Indeed, 92% of these students said that humans were most highly evolved, compared with only 40% for the other three groups combined.

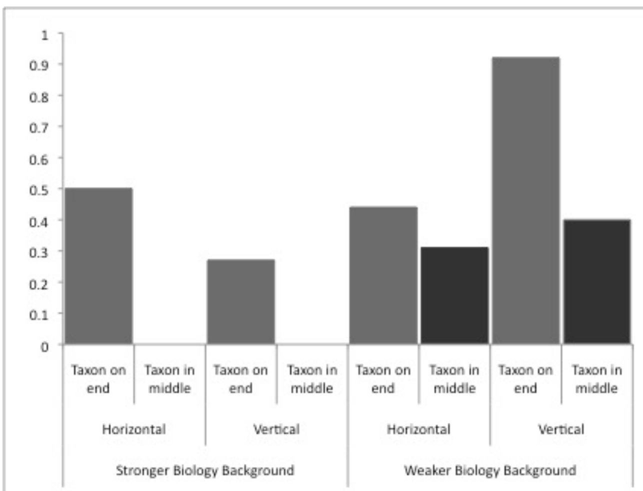

Figure 3: Proportion of students who claimed the human was the most highly evolved taxon as a function of biology background, focal taxon location, and cladogram orientation.

To examine the effects of instruction on students' phylogenetic conceptions, we conducted a 2 (orientation; between) x 2 (rotation set = human at the end vs. in the middle; between) x 2 (test: Time 1 vs. Time 2; within) mixed ANOVA on the responses that the human is the most highly evolved taxon. These students comprised a subset of the stronger background students from the main study. The analysis revealed a main effect of time of test, *F*(1, 38) = 6.18, $p < .05$, *MSE* = 0.05, partial η^2 =.14. Students were less likely to claim that the human is the most highly evolved taxon after having received two days of instruction on phylogenetics (*M* = 0.17 vs. *M* = 0.05, respectively, for before vs. after instruction). There was also a time of test x focal taxon location interaction, *F*(1, 38) = 6.18, $p <.05$, *MSE* = 0.05, partial η^2 =.14. Students only claimed that the human was the most highly evolved taxon when it was presented at the end (top or right) of the cladogram. Under these conditions, students were less likely to state that the human was the most highly evolved taxon after instruction (*M* = 0.10) than before (*M* = 0.33). Students never responded that the human was the most highly evolved taxon when it was presented in the middle position.

Students' Justifications

After indicating which taxon was most highly evolved, students were asked to provide an explanation for their response. We are in the process of devising a coding scheme to examine these qualitative data. In the following paragraphs, we provide a subset of the responses students wrote for the explanation question for illustrative purposes.

Consistent with our hypotheses, students who indicated that the human was the most evolved taxon frequently stated that a) the cladogram presented the progression of evolution across species and time, and b) presented an array of organisms, from least complex to most complex. For example, students provided statements such as, "The general assumption is that with every further deviation from the evolutionary chain, organisms develop more complete biological systems (esp. nervous systems)", "We have complex language & highly developed social systems", or "we are the only sentient beings on earth." Students also made comparative statements such as "I'm arogant [*sic*] enough to believe [that] I'm more evolved than livestock" or "they are the last animal in the chart. I am, as a person, more evolved than a pig."

Students also provided evidence that they were reasoning about phylogenetic concepts, albeit incorrectly: "humans have diverged from the most basic common ancestor the most times out of all the animals shown", "humans are at the top of the diagram and they display the most specified method of evolution in the diagram", or "humans are the organism which most recently evolved." Interestingly, sometimes students provided conflictive statements such as, "from the chart I would say pig & camel, but I'm biased to say human" or "humans have to be the most highly evolved (regardless of the structure of the diagram)." Additional analyses will examine whether stronger and weaker background students provided different types of justifications for incorrect responses.

The aforementioned statements were qualitatively different from those that students provided for correct responses. For example, students who indicated that no taxon was more highly evolved than any other taxa made statements such as, "the diagram only shows the evolutionary relationships not how much each species has changed over time" or "these trees just show genetic similarity and hypothetical common ancestors. All the organisms have radiated into different niches, from the labeled hypothetical common ancestor." As stated previously, only a very small minority of students with stronger backgrounds in biology provided correct responses.

Discussion

The current study provides critical information regarding the use of cladograms for educational purposes. In the absence of instruction, both students with weaker and stronger backgrounds in biology misinterpreted the information depicted in cladograms when asked to evaluate which taxon was the most highly evolved. An important finding is that the cladograms had different effects on students' reasoning depending on the format in which they were presented and the biology background of the students.

As expected, students provided more teleological responses and explanations for the human cladogram than the honeybee cladogram. In fact, students essentially never stated that the honeybee was the most highly evolved taxon despite the fact that the two taxa occupied identical locations in their respective cladograms. Students provided justifications that indicated that they perceived the human as the most complex organism in the array, and therefore the most highly evolved.

Previous research has found that college students endorse scientifically unwarranted explanations for the occurrence of natural phenomena (e.g., "Finches diversified in order to survive"), especially when placed under a high cognitive load (Kelemen & Rosset, 2009). These studies indicate that adults, like children (see Carey, 1985; Keil, 1994; Kelemen, 1999), ascribe to teleological explanations for the existence of biological natural kinds and prefer these explanations to physical-causal explanations. These beliefs are suppressed under certain conditions, such as when students are provided with alternative explanations and are provided with ample time to think about the phenomena in question. However, under cognitively demanding circumstances, these unwarranted scientifically beliefs prevail.

Our results are consistent with these earlier studies and provide new information concerning the perceptual or diagrammatic factors that either promote or lessen students' appeal to teleological interpretations of evolutionary diagrams. We reasoned that students who conceived of evolutionary processes as goal-directed would expect the most complex taxon to occupy an end position. As predicted, students were more likely to state that the human was the most evolved taxon when it occupied the end position rather than the center position. Students with stronger backgrounds in biology only said that the human is the most highly evolved taxon when it was depicted at the end of the set of taxa. Instruction in phylogenetics reduced such responding to only 10% of students.

Teleological responses were most prevalent for weaker background students when interpreting the vertically oriented cladogram with the human located in the top position. One possible interpretation of these results is that students used spatial location to evaluate evolutionary relatedness; that is, they inferred the taxon at the highest vertical point was the most complex. These results are consistent with the embodied cognition perspective that states that individuals orient themselves vertically in reference to elements of the environment, such as the sky and ground (Franklin and Tversky, 1990).

Given that high school and college students in the United States are currently exposed to cladograms in their biology textbooks, and perhaps from their instructors in class as well, our results indicate that it is essential that textbook illustrators and instructors consider the perceptual or diagrammatic factors that impact students' understanding of evolutionary processes. In particular, our results indicate that the horizontal cladogram format is preferable to the vertical format. Moreover, because cladogram branches can be rotated without changing the underlying structure (i.e., the evolutionary relationships depicted; just as the turning branches of a mobile in the wind do not change the structure of the mobile), when cladograms include taxa that may play into students' teleological misconception of evolution, it is critically important to present those taxa in a horizontal order that suppresses activation of this misconception. For example, more complex taxa should be located in the middle rather than the end, and there should be little or no correlation between the linear ordering of the taxa across the terminal branches of the cladogram and students' conceptions of complexity.

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