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Using Manipulative Models to Develop Tree-Thinking

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Abstract

It is well known that students often struggle with tree-thinking, a core aspect of evolutionary education. Scientists consider phylogenetic trees multidimensional hypotheses of evolutionary relationships. However, student view textbook diagrams as static, two-dimensional images. Physical manipulatives have been used to facilitate learning science content in areas such as genetics, but these instructional tools have not yet been tested in tree-thinking. In order to circumvent students' tree-thinking struggles, I investigated the use of manipulative, three-dimensional tree models in an introductory biology course designed for non-science majors (n=163). Specifically my research questions included: What are the differences in tree-thinking learning gains when exposed to one of three instructional treatment groups?; How do students interact with manipulative tree models? I compared three treatment groups across three semesters: 1) control; 2) multichromatic model; and 3) monochromatic model. I used a mixed methods approach gathering data from pre/post assessments, course observations, and student reflections to measure student tree-thinking learning gains and interactions. I found that students had the highest tree-thinking learning gains when given explicit instruction tied with a multichromatic model ($F(2,160)=15.608$, $p < 0.001$). Students reported most challenges in the Control Treatment and the Monochromatic Treatment groups because they had difficulties distinguishing which branch represented which taxa when manipulating branches. The use of multiple colors aided students understanding of the major components of trees and facilitated easy distinction among the taxa represented. This investigation supports the use of manipulative models as interdisciplinary tools that provide a tangible, effective alternative for teaching abstract concepts.

Key Terms

Branch – the portion of a phylogenetic tree that connects tow nodes or one node and a tip (Baum and Smith, 2013)

Monochromatic manipulative – a phylogenetic tree manipulative model composed of only one color of pipe cleaners (Baum and Smith, 2013)

Multichromatic manipulative – a phylogenetic tree manipulative model composed of differently colored pipe cleaners (Baum and Smith, 2013)

Node – a branching point in a phylogenetic tree (Baum and Smith, 2013)

Phylogenetics - the field of study concerned with inferring the evolutionary relationship of living and extinct taxa and using this information to learn about patters and processes of evolution (Baum and Smith, 2013)

Phylogenetic tree – a visualization illustrating evolution as descent from common ancestors (Baum and Smith, 2013)

Representations – a visual illustration or diagram symbolizing conceptual meaning of a phenomenon or process.

Speciation event - formation of a new species due to genetic and/or reproductive isolation

Taxa (taxon) – a formally named group of organisms. The groups of organisms represented by the tips of a phylogenetic tree (Baum and Smith, 2013)

Tree-thinking - the ability to conceptualize evolutionary relationships (Meisel, 2010)

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Chapter I: Introduction

Illustrations are commonly used to aide in teaching evolution. One of the most commonly used and recognized illustrations is a phylogenetic, or evolutionary, tree. Phylogenetic trees capitalize on the visualization that physical trees represent, a series of lineages that branch from one another. Symbolically, phylogenetic trees use a branch system to represent occurrences of speciation. These depictions prove to be integral in education but only have value when utilized correctly. The term “tree-thinking” has been coined to describe a person’s ability to conceptualize evolutionary relationships (Meisel, 2010). Unfortunately, students often struggle with interpreting phylogenetic trees (tree thinking) because of pre-existing misconceptions or limited mental rotation abilities Halverson, Piers, & Abell, 2011; Gregory, 2008). One way to help students overcome misconceptions in tree-thinking is by using representations.

Representations have been proven to enhance learning across various disciplines of academia, improve problem solving and creativity, and facilitate developing connections between new and prior knowledge (Cook, 2006; Peterson, 1994). Representations provide different methods of presenting information than traditional lectures and are critical to effectively communicate abstract science concepts (Gilbert, 2005; Mathewson, 1999; Patrick, Carter, & Wiebe, 2005). Phylogenetic trees are representations that can help students understand evolutionary relationships. Like a map key, the only way to understand a phylogenetic tree is to understand all of its parts (Tversky, 2005). However, if a student does not understand the fundamental basis of phylogenetic trees, the illustration is useless.

Phylogenetic trees are intended to represent multidimensional hypotheses about the nature of relationships among taxa, with branches being able to “swivel” around nodes and not alter the relationships represented by the topology (Halverson, 2010). However, textbook representations of phylogenetic trees are fixed and restricted to two dimensions. Subsequently, the nature of these images can limit the information represented in trees and requires students to rely upon mental rotation skills to interpret and compare information across these representations (Maroo & Halverson, 2011). Students with poor mental rotation abilities may use alternative justifications for interpreting phylogenetic trees.

Students’ rationales when evaluating phylogenetic trees are often non-scientifically based (Halverson, Piers, & Abell, 2011). For example, previous studies indicate some students base taxa relationships on the distance between the branches tips of evolutionary trees, with closer tips being inaccurately interpreted as closer relationships (Halverson, Piers, & Abell, 2011; Baum, Smith, & Donovan, 2005). However, taxa relatedness is inferred by interpreting the patterns of nodes (the point organisms diverge) on phylogenetic trees. Halverson (2010) suggested that using a physical, three-dimensional, manipulative tree model will facilitate learning tree-thinking by allowing students to physically see branch rotations rather than relying solely on mental rotation.

Manipulative models have been shown to enhance students’ learning outcomes in multiple science disciplines. Krontiris-Litowiz (2003) found that the use of manipulatives allowed students to gain a deeper understanding of neurophysiology concepts but only when used in conjunction with explicit classroom instruction.

Additionally, Grumbine (2006) found that instructors who used manipulatives as instructional aids in introductory genetics courses reported that students found the manipulatives helpful and those students had an increase in learning outcomes. For students to become experts with representations, they must use representations correctly and as a reasoning tool when investigating problems (Halverson, 2013). I investigated the use of a manipulative tool to facilitate students' representational competence development in tree thinking.

Research Questions

- What are the differences in tree thinking learning gains when using a traditional tree thinking approach versus using a multichromatic or monochromatic manipulative?
- How do students interact with manipulative tree models with learning tree thinking?

Chapter II: Literature Review

Visualizations are pertinent to understanding scientific concepts and are often central to instruction, comprehension, and creating scientific ideas (Tversky, 2005). Gilbert (2005) suggests that representations found in print media offer the fewest cognitive gains for learners, whereas visual models and simulations offer the greatest. Visual models are able to illustrate a concept and can make abstract science ideas more accessible to learners. These visual tools are often used to simplify complex problems and present them in a manner aids in problem solving. For example, maps are highly utilized visual tools that illustrate information needed for navigation. If the map becomes slightly disoriented to better represent the information, the content remains the same and users are still able to navigate (Tversky, 2005). Visualizations can take two-dimensional or three-dimensional forms, and can be computer simulated. The key to a successful visual representation is that is explains the content in such a manner that the user can still interpret the meaning.

Although it is accepted that visualizations are important to science education, there are challenges incorporating them into learning environments (Rapp, 2005). One challenge is the practice of simply including visualizations into instruction as a remedy for teaching difficult topics. Poor visualizations are as ineffective as poor text or poor lecture and may inhibit learning. Additionally, previously held beliefs are particularly resistant to change (Posner, Strike, Hewson, & Gertzog, 1982). A students' prior knowledge can influence how they approach visualizations (Rapp, 2005). Gomez, K., Lyons, L., and Radinsky, J. (2010) suggest that many times problems arise because students' prior knowledge is incorrect or incomplete. It is challenging to create visualizations that address specific education concerns because some students have strong, but incorrect beliefs. However, some students have a better frame of reference about the topics that new, innovative visualizations convey. Therefore, results that come from testing visualizations may be attributed to both the model and students' prior knowledge.

As a central focus of biology education is learning basic evolutionary principles, students should be able to understand evolutionary relationships between taxa. Phylogenetic trees are the most conventional visualization tool for displaying evolutionary relationships, and "tree-thinking" has been coined as a term to describe the ability to conceptualize evolutionary relationships (Meisel, 2010). Catley, Novick and

Shade (2010) found that a person's knowledge of life sciences is based largely on understanding of evolution, yet misconceptions persist particularly with tree-thinking. Baum et al. (2005) and Sandvik (2008) reported that phylogenetic trees are commonly misunderstood by students, leading to confusion about the concept of common ancestry.

These misconceptions about evolutionary trees can be very detrimental to understanding the patterns and processes which occurred in evolutionary history (Gregory, 2008). Evolutionary trees are visual representations that depict evolutionary relationships among taxa based on the distribution of derived character states. Additionally evolutionary trees are used to show evolutionary relationships among genes in multi-gene families (Omland, Cook & Crisp, 2008). Scientists interpret phylogenetic trees by identifying groups of taxa that share common ancestry. Taxa branch off from one another at nodes (intersections representing hypothetical common ancestors). Taxa sharing the most recent hypothetical common ancestor are most closely related to each other than any other taxa represented on the tree.

Research has inferred that students misinterpret trees because of flawed reasoning, associating species proximity to each other as relatedness. For example, when tips of the branches are close to each other, students assume that this indicates a closer relationship among the taxa represented even when this is not an accurate interpretation. Gregory (2008), Meir, Perry, Herron, and Kingsolver (2007), and Meisel (2010) have identified many additional common misconceptions such as incorrect mapping of time, node counting to determine relationships, and confusing straight lines as equating no evolutionary change after the point of divergence. Additionally, students tend to read trees from left to right assuming that more primitive organisms are on the left. This is problematic in that students are interpreting phylogenetic trees as ladders of progress (Omland et al., 2008). Understanding the core features and key information represented by phylogenetic trees is the key to developing ones tree-thinking ability (Halverson, 2011). Improved tree-thinking will not only help us better understand the evolution of character states and improve our fundamental understanding of evolution (Omland et al., 2008). Therefore, fostering tree-thinking skill development is a critical component of biological education.

Phylogenetic tree visuals are included in biology textbooks at both the secondary and post-secondary level (e.g., Figure 1). However, students struggle with correctly interpreting and understanding these trees, especially given the varying styles used (e.g., Baum, et al., 2005; Catley & Novick, 2008; Catley et al., 2010; Gregory, 2008; Halverson, Piers, & Abell, 2011). Sandvik (2008) found that not one single student was able to answer tree-thinking questions correctly when analyzing a traditional textbook images of phylogenetic trees. Flawed understanding and inaccurate rationales used by students when tree-thinking has prompted a need for to revise how Evolutionary Biology textbooks illustrate the relationship among lineages of species (e.g., Cately & Novick, 2008; Halverson, Piers, & Abell, 2011; Omland et al., 2008).

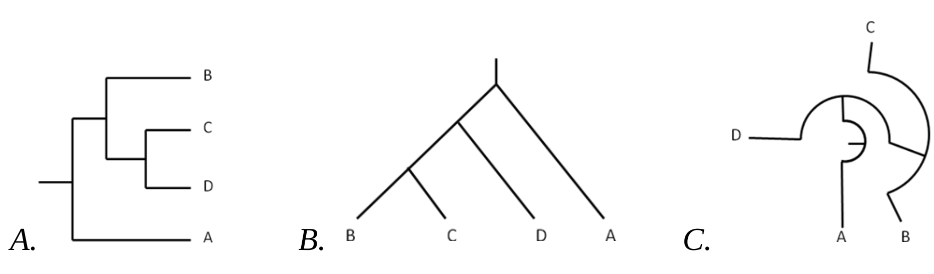


Figure 1. Alternative phylogenetic tree representations. Tree ‘B’ and ‘C’ show equivalent relationships while Tree ‘A’ shows an alternative set of relationships.

Symbolically, phylogenetic trees use a branch system to represent occurrences of speciation. The science textbook representation of a phylogenetic tree is restricted to two dimensions, which can hinder full understanding of the relationships these trees represent and limit real time interaction (Ruths, Chen, & Ellis, 2000). In phylogenetic tree representations, it is understood among scientists that the branches can swivel around a node without altering the monophyletic groupings (or the relationships illustrated). Thus, interpreting traditional textbook image of phylogenetic trees relies heavily on students' ability to mentally swivel the branches of phylogenetic trees around its node, the axis that shows its point of divergence, on the phylogenetic tree.

Halverson (2010) suggested that a three-dimensional, visual, manipulative model would allow learners to physically rotate tree branches rather than relying only on their mental rotation ability. Manipulative models may supply alternative means of phylogenetic tree representation that facilitate the development tree-reading skills (Meir et al., 2007). Phillips and Novick (2010) found that students perform better in tree-thinking when they use three-dimensional models compared to two-dimensional models. However, the factors that contribute to the increased effectiveness have yet to be explored. Additionally, some students have problems developing and utilizing mental rotation skills when tree-thinking (Maroo & Halverson, 2011), thus inhibiting their tree-thinking ability. However, regardless of students' individual mental rotation abilities, tree-thinking skills were enhanced with use of a manipulative model (Maroo & Halverson, 2011). Thus, tools that go beyond standard textbook-based techniques for teaching tree-thinking are sorely needed (Meir et al., 2007).

Manipulative models are used across numerous disciplines to illustrate various fundamental concepts. Manipulative models prove to be quite useful in transforming ideas that rely primarily on mental rotations to those that can be assessed physically. For example, Organic Chemistry courses use model kits to depict the physical structure of molecules. However, not all research supports the use of manipulative models in science education. For example, Jungk et al. (2010), provided two concerns that faculty have with use of manipulative in science: physical manipulatives are often outdated and students are already skilled with abstract thinking. Conversely, classroom use of manipulatives helps demonstrate the importance of structural models in scientific discovery and communication (Jungk, 2010). Belenky and Nokes (2009) investigated the use of manipulatives in a math class. In the class, subjects were subjected to three treatments: an abstract manipulative, concrete manipulative, and no manipulative. The results showed an improvement of student learning from pretest to posttest with the use of manipulative, but there was no significant difference between the abstract manipulative and concrete manipulative.

This project aims to improve undergraduate biology instruction by using a novel, low-tech, three-dimensional, tactile, manipulative model of a phylogenetic tree (Figure 2) to help students overcome known challenges associated with tree-thinking. This manipulative model will allow students to physically interact with evolutionary relationships represented in phylogenetic trees. Students will be able to manipulate the tree by flipping branches, comparing topologies, identifying informative features of a phylogenetic tree, and identifying evolutionary relationship patterns.

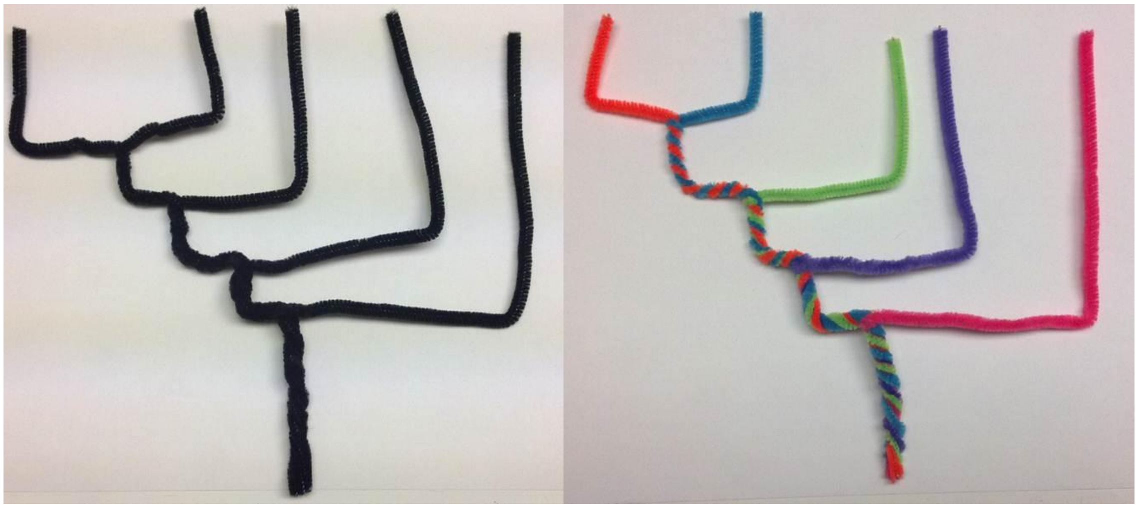


Figure 2. Two versions of a manipulative tree model: one monochromatic and one multichromatic.

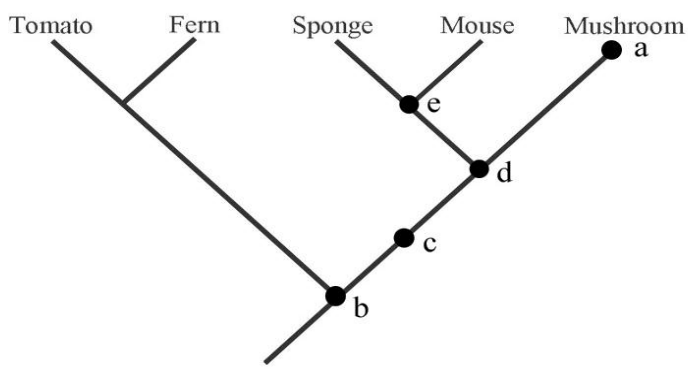
Undergraduate learning outcomes were tested using three types of representations during tree-thinking instruction: a two-dimensional textbook image, a three-dimensional multichromatic manipulative and a three-dimensional monochromatic manipulative. Additionally, this study explored the superficial aspect of color layered into the multichromatic model. The monochromatic model mirrors the multichromatic model in shape and orientation of the branches, the only difference was the use of one color, black, rather than the five colors used in the multichromatic model. Rapp (2005) found that without the use of appropriate cues such as, color, design, and organization, students are less likely to know what is being conveyed by the visualization. I hypothesize that the multichromatic model will elicit greater learning outcomes than the monochromatic model.

Chapter III: Methodology

Data was collected in a lower division, non-majors Biology course and included 163 student participants over three years. Any identifying student information was replaced with an alphanumeric code to ensure the anonymity of the participants.
The course is divided into four topics: Unit One – Nature of Science; Unit Two – Environment; Unit Three – Genetics; Unit Four – Evolution. The first three units were taught with a foundation in evolution in an effort to help students be less resistant to instruction on evolution. The Evolution unit (Unit Four) is comprehensive, bringing information from previous units together, and uses a tree-thinking approach to teach evolution content. There were three treatment groups, each from a different section of the same course: Control, Multichromatic and Monochromatic. In the Control treatment group, the instructor taught students how to read phylogenetic tree using only traditional textbook images (n=21). In the Multichromatic treatment group, the instructor taught students how to read phylogenetic trees using a supplemental multicolored, manipulative tree model (n=129). In the Monochromatic treatment group, the instructor taught students how to read phylogenetic trees using a supplemental single colored, manipulative tree model (n=13). All three treatment groups were exposed to identical instruction aside from the supplemental manipulative. All groups were taught by the same instructor and grade distributions were consistent across all course sections.

Data was collected from tree-thinking, multiple choice pre/post-assessments (Halverson, Piers, & Abell 2011) and course observations during tree-thinking instruction. For the quantitative portion of my study, I calculated students' scores on the pre/posttest measuring tree-thinking accuracy. This assessment was modified from the tree-thinking challenge test (Baum et al., 2005) and then tested to measure student learning gains when taught tree-thinking through a traditional approach (see Figure 3 for sample question). I reported differences in mean scores based on treatment groups and conducted a Mixed-Methods Repeated Measures ANOVA to determine if there were significant differences in student responses within and between the three treatment groups. I assigned statistical significance when $p < 0.05$. For the qualitative section of data analysis, I conducted classroom observations while students used the each of the two manipulative models (multichromatic and monochromatic). I used observations to provide additional evidence regarding how students interacted with each model type.

Look at the tree below to answer this question. Which of the five marks in the tree above corresponds to the most recent common ancestor of a mushroom and a mouse?



a) a
b) b
c) c
d) d
e) e
f) the mushroom and mouse do not share a common ancestor

Provide an explanation for why you chose your answer.

Figure 3. Example question from Pre/posttest.

Student learning outcomes were measured by scoring the scientific accuracy of student responses on the two-tiered tree-thinking pre/posttest. I assigned a score (0 or 1) based on the multiple choice answer selected and students' explanation of the answer selected. After scoring student responses on both the pretest and posttest, data was stored and analyzed in SPSS. I ran a paired t-test to identify significant differences in student responses. Next, I compared the results from the monochromatic model to those collected from the monochromatic model and textbook images of phylogenetic trees. I ran an ANOVA to analyze the pre/posttest results between and within the three representation types. I highlighted the differences in student learning outcomes between the instructional models to identify the most effective tree-thinking instructional intervention.

Chapter IV: Findings

I hypothesized greater earning outcomes with the use of manipulative models than traditional textbook instruction. Additionally, I hypothesized that the multichromatic model would develop a greater learning gain than the monochromatic model.

Students' Learning Outcomes with Manipulative Models

I graphed student mean scores on the pre/posttest measuring tree-thinking accuracy to identify learning gains. Student scores improved from the pretest to the posttest in all treatment groups (Figure 4). The gain scores from pretest to posttest were statistically significant (test factor $F(1, 160) = 50.27$, $p < 0.001$) for all instructional approaches.

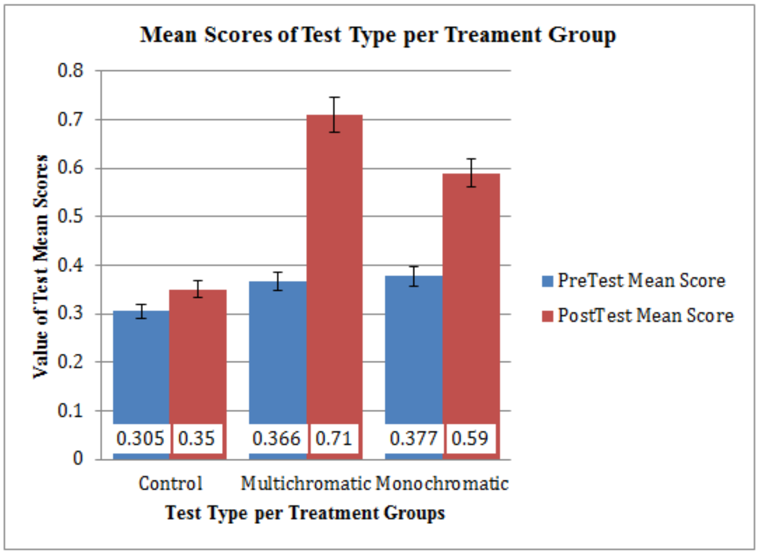


Figure 4. Changes in mean pre/post scores by treatment group

When using an ANOVA to measure differences, if the F-ratio value is significantly greater than 1 it is very unlikely that the result is due to chance (Field, 2009). Therefore, the p-value would be less than 0.5 in these instances. The multichromatic treatment group had higher gains than both the monochromatic and control groups (test * treatment interaction $F(2,160)=15.608$, $p < 0.001$; Table 1). Additionally, the monochromatic treatment group had higher gains than the control (treatment $F(2, 160) = 28.17$, $p < 0.001$; Table 2). Thus, the multichromatic model had the most significant learning gains of all the treatments.

Table 1

Tests of Within-Subjects Effects

	Type III Sum of Squares	df	Mean Square	F	Sig.
Test	1.346	1	1.376	50.272	0.000
Test * Treatment	0.854	2	0.427	15.608	0.000
Error (test)	4.378	160	0.027		

Table 2

Tests of Between-Subjects Effects

	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	27.52	1	27.52	959.463	0.000
Treatment	1.616	2	0.808	28.17	0.000
Error	4.589	160	0.029		

Interactions in the Classroom

Through the instructional intervention using the manipulatives, students altered the shape and style of the tree to mirror that of the instructor's. Students responded positively to the use of manipulative models when learning tree-thinking. One student stated that using the manipulative model helped her, "think of the sister branches as a propeller on a helicopter." Another student stated that using the tree manipulative helped him see that tree-thinking was similar to decorating a Christmas tree, "If you could take your decorated Christmas tree, hold the bottom and turn the top until the tree looked like a corkscrew, then turn it upside down without all the decorations falling off, it would certainly look different but everything within the tree would still have the same configuration.

The monochromatic model presented some challenges for students. The most common challenge students reported was tracking which branch represented which taxa. One student resorted to tracking the location of each taxa on the tree on a separate piece of paper. This issue was compounded further when students began rotating branches around nodes. While all students that used the manipulative models recognized that monophyletic groups were not changed during this process, students using the monochromatic model struggled with remembering what taxa each branch represented. However, with the multichromatic model, each taxa was represented by a unique color and students could easily distinguish and track the different taxa. I found this identical trend when students tried to identify the lineage of a single taxa.

In the multichromatic model, the *trunk* is comprised of intertwined colors and when a specific lineage diverges, the color differentiation is apparent visibly. Students using the multichromatic model accurately understood and identified a lineage as extending from root to tip, while students that used the monochromatic model more often stunted the lineage and only thought it extended from the tip to the first node (or intersection). The lack of color distinction made interpreting when lineages share evolutionary history more difficult with the monochromatic model.

Chapter V: Discussion

Communicating phylogenetic hypotheses using trees , even within the scientific community, can be a difficult task due to the complex relationships being distilled through the visual representations. Helping non-science majors understand the meaning in these trees is substantially more difficult because some students have strong, but incorrect beliefs about evolution (Halverson, Boyce, & Maroo, Under Review). Compounding the problem of communication difficulties due to flawed prior ideas, two-dimensional text book diagrams cannot represent the dynamic nature of evolutionary relationships between taxa. Furthermore, accurately using tree representations in the classroom can be a difficult task for instructors, particularly if they are also unfamiliar with these models (Rapp, 2005). If the tree representations are not used accurately, students may leave the classroom more confused than when they arrived. Therefore, rather than decrease misconceptions regarding phylogenetic trees, the use of these representations may increase students' misconceptions. However, when used effectively, representations can increase student learning of scientific concepts (Gilbert, 2005; Mathewson, 1999; Patrick et al., 2005).

The misconceptions students build about phylogenetic tree-reading will have negative repercussions on how students understand evolutionary history (Gregory, 2008). Students develop alternative modes of tree-reading which often results in inaccurate conclusions from representations. Studies report that students often form their rationales on the distance between the tips of phylogenetic trees, the orientation of the taxa on the branches, and ecosystem variables which are not the most scientific approaches to interpreting phylogenetic trees (Gregory, 2008, Meir et al., 2007, Meisel, 2010, and Omland et al., 2008). These misconceptions are directly related to students' tree-thinking abilities and their ability to understand evolutionary relationships.

Evolution is the basis for modern biology, and as such, students should be able to interpret evolutionary histories depicted by phylogenetic trees (Baum et al., 2005). Traditional textbook images of phylogenetic trees require students to mentally swivel branches around nodes. However, Maroo and Halverson (2011) found that when students used only text-based representations to learn tree-thinking, they were unable to translate the two-dimensional representations to mental images. Alternative instruction tools and techniques that feature physical manipulatives are needed to foster stronger tree-reading abilities in students.

There is a growing body of evidence that shows using manipulatives can increase students understanding of abstract and concrete topics, such as organic chemistry and evolutionary relationships (Halverson, 2010; Belenky & Nokes, 2009; Stieff, Bateman & Uttal, 2005). These studies propose that when manipulative models are used correctly, they can increase students' understanding of evolutionary relationships represented by phylogenetic trees, thus becoming better tree-readers. This study provides a different way for students to consider tree-thinking. Specifically, I investigated how students used two types of manipulative models.

The use of physical, tactile models allowed students to develop more concrete ideas about tree-thinking concepts represented in abstract ways. Similar to reports from Krontiris-Litowiz (2003) and Grumbine (2006), my findings demonstrate that using a manipulative tree model with explicit tree-thinking instruction is an effective intervention tool for improving learning gains. Of the two models I tested, I found that while both increased learning gains, the multichromatic model was the most effective model for increasing students' posttest scores, but there was a greater increase using the monochromatic model than no model at all. However, there was an increase in scores from pretest to posttest for students in the control group. This suggests that explicit tree-thinking instruction helped students understand the traditional textbook images of phylogenetic trees more so than they would without explicit instruction.

After exposure to both models, I found that students used trees as reasoning tools to explore evolutionary relationships based on clades (descendants of shared common ancestry) rather than rely upon tip proximity (e.g., Baum et al., 2005). Both models were effective in demonstrating the ability of branches to swivel around the nodes eliminating the need for mental rotation that is required by traditional textbook illustrations of phylogenetic trees. Students were better able to understand that evolutionary relationships between taxa did not change when the branches were rotated. Students also discovered that no matter which direction the tips point, the evolutionary relationships are still the same.

Past research has found that superficial features, such as color, often hinder students learning outcomes when using visual representations (Kozma & Russell, 2005; Patrick et al., 2005). My study indicates that color plays an important role in learning tree thinking with my manipulative model. My study demonstrates when used with a clear purpose, some superficial features (e.g. color) can increase student learning outcomes rather than hinder them. In my model, the use of multiple colors facilitates communication of distinct lineages, shared histories, and points of divergence. During course observations, students tracked lineages more easily because of the differentiation of colors in the multichromatic model. Students were able to follow the taxa divergences because some colors branched off while others remained intertwined.

In comparison, the students found it harder to use the monochromatic model. The biggest challenge for students was keeping track of which branch represented which taxa when they rotated the branches. The monochromatic model did not allow for students to be able to track taxa by looking at the tree alone. It required students to create a mental map of where each taxon was located before and after each rotation to remember how they were related. This confusion is what is similarly seen in textbook images. Students have to mentally keep track of information which can lead to misconceptions. However, a monochromatic manipulative still provides a better alternative to traditional textbook images by reducing the amount of information students need to track mentally. With these manipulatives, students can rotate the branches of the models and the models themselves.

This investigation supports the use of manipulative models as interdisciplinary tools that provide a tangible, effective alternative for teaching abstract concepts. This project determined one contributing factor that increases the effectiveness of manipulative models is color. This is supported by Rapp (2005) who found that some superficial features are necessary for students to understand what is being represented. My study found that for any manipulative to be effective, it must be combined with explicit instruction and only have superficial characteristics that enhance the model rather than take away from it. This idea is supported by research by Kozma & Russell (2005) who found that visualizations do not need to be exceptionally realistic to help students learn, and by adding too many details, student learning is inhibited. By exploring the mechanics of different models, researchers are one step closer to developing a refined model that enhances evolutionary biology instruction.

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