Evolution, Hypermedia Learning Environments, and Conceptual Change: A Preliminary Report

Michael J. Jacobson
Learning Technology Center
Vanderbilt University
United States of America
jacobsmj@ctrvax.vanderbilt.edu

Akiko Sugimoto
Department of Educational Psychology
University of Illinois at Urbana-Champaign
United States of America
sugimoto@uiuc.edu

Anthi Archodidou
Department of Educational Psychology
University of Illinois at Urbana-Champaign
United States of America
archodid@vmd.cso.uiuc.edu

Abstract: This paper describes a study of high school students using a case-based hypermedia learning environment, the *Evolution Thematic Investigator*, to help learn a neo-Darwinian model of evolution. This hypermedia program has a number of features based on recent cognitive learning theory and research, such as: a conceptual change lesson, multiple cases of evolutionary biology, case-theme commentaries to make explicit the situated variability of the neo-Darwinian mental model, on-line scaffolded problem-solving modules, and guided thematic criss-crossing of knowledge synthesis study questions. The experiment collected written assessment measures, detailed verbal protocols, and interviews of eight students using the program and solving evolutionary biology problems. The main experimental findings indicated that there was a significant change in the students' mental models about evolution. The implications of this research for learning about evolution, and for the design of hypermedia environments that promote learning and conceptual change of complex knowledge, are also considered.

Biology is a complex and difficult domain for students to learn at a variety of educational levels. There are a number of important aspects of modern biology (e.g., genetics, metabolism/energy transformation, homeostasis), but of particular centrality is the neo-Darwinian theoretical foundation of evolutionary biology (i.e., the twentieth century synthesis of Darwinian theory of evolution by natural selection and Mendelian genetics) [Dobzhansky, 1973; Mayr, 1991]. Given the critical importance of neo-Darwinism to modern biological thought and practice (and the increasing social implications of biological research in areas such as biotechnology, genetic engineering, etc.), it is disturbing that research to date has shown the majority of students acquire but a poor understanding of the neo-Darwinian theory of evolution even after completing various programs of instruction [Bishop & Anderson, 1990; Brumby, 1984; Greene, 1990; Settlage, 1994].

The purpose of this research project was to explore how a case-based hypermedia learning environment, the *Evolution Thematic Investigator*, might be used to help students learn central components of neo-Darwinian evolutionary biology. This paper provides an overview of recent research into the difficulties associated with learning neo-Darwinism, discusses the main features of the Evolution Thematic Investigator, and reports on the major findings of a conceptual change study involving the use of this case-based hypermedia learning environment.

Learning Evolutionary Biology

Distinct differences between naive and expert mental models about evolution have been found [Bishop & Anderson, 1990; Brumby, 1984; Greene, 1990; Settlage, 1994]. Students with a naive mental model of evolution tend to view evolution as consisting of a single process in which characteristic traits of species gradually change (e.g., necks gradually lengthen) and believe the environment, use/disuse, or the species "trying to evolve" causes these traits to change (rather than random processes and natural selection). The naive view is also implicitly Lamarckian as these learners believe traits acquired by an organism during its lifetime can be passed on to the offspring. Furthermore, students with a naive view of evolution do not see population variability as important in evolution and they frequently hold a teleological bias that ascribes purpose to evolutionary developments (e.g., ancient giraffes *needed* long necks to reach food, so they *evolved* longer necks). In contrast, a neo-Darwinian view of evolution has the following core components: evolution is defined as the changing proportion of individuals in a population with discrete traits; the origin and survival of new traits in populations results from random changes in genetic material due to mutation or sexual recombination; the survival or disappearance of traits is due to selection associated with environmental factors (i.e., natural selection); and variation within a population is critical for evolution through natural selection. Overall, populations evolve because some individual members possess a reproductive advantage over other individual members in a particular environment.

The naive Lamarckian and expert neo-Darwinian models of evolution thus differ along a number of important dimensions. The simplicity of the naive Lamarckian model, and the surface level plausibility of the model (e.g., passing on acquired traits *seems* reasonable), evidently makes this a difficult model to change in conventional instructional and even in most research settings [Bishop & Anderson, 1990; Brumby, 1984; Cummins, Demastes, & Hafner, 1994; Greene, 1990; Settlage, 1994].

Evolution Thematic Investigator

A general goal of our overall research program is the principled exploration of ways that hypermedia learning environments can be designed to help students learn complex knowledge. Specifically, this study developed features for a case-based hypermedia learning environment, the *Evolution Thematic Investigator* (TI), that were grounded in current cognitive learning theory and research [Brown, Collins, & Duguid, 1989; Cognition and Technology Group at Vanderbilt, 1992; Collins, Brown, & Newman, 1987; Glaser, 1991; Posner, Strike, Hewson, & Gertzog, 1982; Spiro, Feltovich, Jacobson, & Coulson, 1992; White, 1993]. Several features of the program were intended to expand the interactive and representational capabilities of hypermedia learning environments beyond what are commonly found to make salient facets of complex knowledge (in this case the domain of evolutionary biology) that students have difficulty learning [Jacobson, Maouri, Mishra, & Kolar, 1995; Jacobson & Spiro, 1994].

The Evolution TI has seven main components that were used in this study: (a) a *conceptual change lesson* on evolution, (b) *multiple cases* of evolutionary biology, (c) presentation of a *neo-Darwinian model of evolution with five core themes*, (d) *case-theme commentaries* to make themes of the neo-Darwinian model explicit in the context of different case examples, (e) *mental model visualizations* of both naive Lamarckian and expert neo-Darwinian evolutionary models, (f) *scaffolded problem-solving* with the interactive Story Maker modules, and (g) *guided thematic criss-crossing* with knowledge synthesis study questions. Given the constraints of space, we can only briefly discuss these seven major features of the Evolution TI in the next section.

Conceptual Change Evolution Lesson

As noted above, prior research has established that many students enter biology classes with a strongly entrenched naive Lamarckian mental model. A computer-based evolution conceptual change lesson was developed by the first author that implemented the basic recommendations of a conceptual change approach to science education: (a) create dissatisfaction with existing conceptions, (b) make a new conception intelligible, (c) make a new conception appear initially plausible, and (d) demonstrate how a new conception can open up new areas of inquiry [Posner et al., 1982; Strike & Posner, 1990]. The evolution conceptual change lesson presented naive Lamarckian and neo-Darwinian mental model visualizations (see below), discussed the inadequacies of the naive model of evolution, and demonstrated how the neo-Darwinian model could successfully be used in place of the naive Lamarckian model.

Multiple Cases of Evolutionary Biology

Four different hypermedia-based cases of evolutionary biology were developed: *The Peppered Moth*, *Antibiotics and Drug Resistance*, *Anglerfish*, and *Rabbits in Australia*. These cases illustrated central themes of neo-Darwinian evolutionary theory. In addition, these cases depicted evolutionary phenomena that we hoped high school students would find interesting, distinctive, and relevant. For example, the *Antibiotics and Drug Resistance* case discussed the relevance of neo-Darwinian evolution by natural selection to what is becoming an important health issue. Another case, *Anglerfish*, dealt with a variety of fish that have a particularly distinctive anatomical feature: they have appendages in place of the top dorsal fin that are used as lures to "fish for other fish." The various cases of evolutionary biology were intended to illustrate the situated variability of knowledge while making salient the deep conceptual structure of this domain, that is, the neo-Darwinian model of evolution by natural selection.

Central Themes for Neo-Darwinian Model

The contemporary neo-Darwinian theory of evolutionary biology is quite elaborate and complex. The purpose of this study, however, was not to have students learn evolutionary biology at the level and depth of a professional biologist. Instead, this research focused on having students acquire a mental model based on core components or themes of neo-Darwinism. Five neo-Darwinian themes were selected for this study: (a) Environmental Conditions, (b) Population Variety, (c) Natural Selection, (d) Origin of New Traits, and (e) Generations and Time.

Case-Theme Commentaries

Case-theme commentaries made explicit how structural dimensions of knowledge (e.g., in this study, the neo-Darwinian themes) applied in various case-specific or situated contexts [Jacobson et al., 1995; Jacobson & Spiro, 1995]. The Evolution TI provided case-theme commentaries in which the neo-Darwinian themes were discussed in terms of specific details in the evolution cases. For example, the theme of Population Variety had a case-theme commentary in the Peppered Moth case that pointed out the variations in the wing colorations of these moths, while in the case of Antibiotics and Drug Resistance, the Population Variety commentary discussed the variation in bacterial resistance to antibiotics.

Mental Model Visualizations

Newly available visualization technologies are allowing dramatic animated scientific images to represent complex scientific data [Gordin & Pea, 1995]. Scientific visualizations have been primarily used to provide representations of quantitative data for complex phenomena (e.g., weather data) and are typically based on expert scientific models about the phenomena under investigation. We have been developing another approach to using visualizations for learning that we call *mental model visualizations.* Our intent is to create computer-based visualizations that *reify mental models* held by learners and experts. In contrast to scientific visualizations, the mental model visualizations we have developed are qualitative in nature and are based on cognitive analysis of novice and expert mental representations about a particular domain. In terms of this specific study, the evolution mental model visualizations were intended to *make neo-Darwinian thinking visible* to students by providing computer animated representations about evolutionary biology to supplement the case, theme, and case-theme commentaries that were primarily textual. Four neo-Darwinian visualizations and one naive Lamarckian evolution mental model visualization were created (based partly on the research of Bishop & Anderson, 1990). Each of these followed the same basic template in which the learner stepped through the visualization with short informational text augmenting the graphics in four to eight different environmental situations selected by the user.

Other Program Features

There were two additional features of the Evolution TI: *scaffolded problem-solving* with the Story Maker and *guided thematic criss-crossing.* The Story Maker modules provided interactive, scaffolded problem-solving activities. Students were given evolutionary biology problems to solve, such as "How did giraffes get their long necks?" They would then select from a pool of randomly arranged statements consistent with naive Lamarckian and neo-Darwinian models on the left side of the screen. The statements they selected would each be changed to an italics style and then copied to the right side of the screen. Statements on the right side could be rearranged in order or removed. When the students were satisfied with the statements they had selected, the program would evaluate the response and provide brief feedback about whether their answer was similar to the old scientific view of evolution by acquired traits associated with the nineteenth century biologist Lamarck or to the now accepted view of evolution by natural selection formulated by Darwin.

The Evolution TI program also provided *guided thematic criss-crossing* (Guided TCC) in conjunction with *knowledge synthesis study questions* [Jacobson et al., 1995; Jacobson & Spiro, 1995]. Knowledge synthesis questions asked the students to consider issues and problems that required the integration of information distributed across the hypermedia case materials they had been studying. Previous research suggests that students who are novices in a domain have difficulty with learning and integrating conceptual knowledge in hypermedia materials [Jacobson et al., 1995; Neuman, Marchionini, & Morrell, 1995]. Guided TCC provided cognitive scaffolding to demonstrate the conceptual interconnectedness of knowledge in the hypermedia cases through the use of different sets of hyperlinks based mainly on neo-Darwinian thematic indices. These different sets of hyperlinks were tailored to specific knowledge synthesis questions in a manner that has been found to contribute to learning for transfer in previous research [Jacobson et al., 1995; Jacobson & Spiro, 1995].

Method

The subjects in this study were in high school, ages 14 to 16, four boys and four girls. The sessions for six of the students were audio taped and those of the other two students were video taped. Each student worked alone with an experiment monitor. The study employed a combination of cognitive think aloud protocols and verbal interviews of the students using the system and engaging in several learning and problem-solving activities.

The study was conducted over three sessions lasting approximately two hours each. The pretest was administered at the beginning of session one to ascertain each student's science and evolutionary biology background (e.g., science courses taken; exposure to evolution ideas in previous courses or outside television shows, videos, or movie). The students were asked to rate, on a seven point Likert scale, their *personal understanding of the concept of evolution* and their *personal belief about whether the modern scientific view of evolution is true.* These two items were asked again at the posttest administered at the end of the third session. The students also were given an evolutionary biology problem to solve concerning the development of the cheetah's ability to run at speeds up to 60 miles per hour (they were also given the cheetah problem to solve on the session three posttest). After the pretest, the students began using the Evolution TI and completed the conceptual change lesson. During sessions two and three, the students read four evolutionary biology cases and case-theme commentaries, ran neo-Darwinian mental model visualizations for different evolution cases, completed Story Maker scaffolded problem-solving activities, and studied

knowledge synthesis questions using guided thematic criss-crossing. The students completed a series of factual acquisition and evolution problem-solving tasks at the end of sessions two and three. (Only a portion of the data collected in this study is discussed in this paper due to space limitations; a full report is in preparation.)
The audio and video tapes of the verbal protocols and the students' hand written answers and comments were transcribed. For the evolution problem-solving tasks (the main focus of this paper), two trained raters scored each response as exemplifying one of four mental models: (a) neo-Darwinian (i.e., view of evolution as the change in the proportion of genetically determined traits in a population over time occurring through the process of natural selection), (b) Darwinian (i.e., the same as the neo-Darwinian model but with no understanding of genetics as the mechanism for determining traits) (c) Naive Lamarckian (i.e., view of evolution as the overall change in a species population that occurs through traits acquired by the parents being passed on to the offspring), (d) Synthetic (i.e., view of evolution with both neo-Darwinian and Lamarckian components). Responses that contained no relevant facts or ideas to the problem or which were incoherent were scored as "No Model." Also, the raters assigned an overall composite session model based on all of the tasks for each of the three sessions. The two raters independently analyzed the data and the few discrepancies were resolved by discussion.

Results

On the seven point Likert scale items of the students' evaluation of their personal understanding of evolution, the pretest mean score was 4.0 (SD = 1.20) and the posttest mean score was 5.6 (SD = 0.52). This difference was significant ($t_7 = 3.87$, $p < .05$). This result suggests that the subjects had a metacognitive awareness that their understanding of evolution improved after working with the Evolution TI (which our data suggests in fact was the case, see below). In contrast, the mean score of the students' self report on whether they believed the current scientific view of evolution for the pretest was 4.9 (SD = 1.46) and for the posttest was 6.0 (SD = 0.76); this was not a statistically significant difference ($t_7 = 1.84$, $p > .05$). This finding suggests that while the subjects assessed their personal beliefs about the validity of the current scientific view of evolution as being higher by the end of the study, this was not a statistically significant difference. A significant difference was found between the pretest and posttest on the models used by the subjects in answering the Cheetah problem ($t_7 = 3.87$, $p < .05$). In the pretest, the mean score of the subjects' model was 2.29 (SD = 0.76), however, by the posttest, the overall mean score increased to 3.71 (SD = 0.76). Thus there was a significant change in the mean score for the mental models used to solve the Cheetah problem, moving from a mainly naive Lamarckian model at session one to a predominately neo-Darwinian model by the end of the last session, *even though the Evolution TI learning materials did not deal with the evolution of cheetahs.*

In terms of the composite models of evolution (based the students' answers to multiple evolution problem-solving tasks completed at each of the three sessions), five out of eight students initially held a Naive Lamarckian model [see Table 1]. The mean session one score for the composite models was 2.38 (SD = 0.52). By the session three posttest, six of the subjects demonstrated a neo-Darwinian model and two exhibited a Synthetic model, with no subjects using the Naive Lamarckian model. The mean composite model score by session three was 3.63 (SD = 0.52), which was a significant difference from the pretest ($t_7 = 7.64$, $p < .05$). These results indicate that the student models of evolution significantly changed from pretest to posttest, with the majority of the students acquiring a neo-Darwinian model by the end of the study.

Discussion

The literature on evolutionary biology education is replete with reports of learning failures and limited learning efficacy of various instructional treatments [Bishop & Anderson, 1990; Bizzo, 1994; Brumby, 1984; Greene, 1990; Settlage, 1994]. We are therefore encouraged by the significant findings of conceptual change from naive Lamarckian to neo-Darwinian mental models by the majority of the students in this study, particularly in the limited amount of time available for actually using the Evolution TI (approximately 4 hours). We were also encouraged the students demonstrated a metacognitive awareness that their understanding of neo-Darwinian evolutionary biology had improved by the end of the study. The students in this study accepted the scientific view of evolution. However, they did not significantly change their personal beliefs about evolution from pretest to posttest, a finding that is consistent with other research [Bishop & Anderson, 1990; Demastes, Settlage, & Good, 1995]. Overall, these students were able to significantly improve their conceptual understanding of neo-Darwinian evolutionary theory, and they evinced a metacognitive awareness of their improved understanding over the relatively short duration of the study. Evidently, it was not so easy for them to change their underlying personal beliefs about the validity of the current scientific view of evolution.

Subject IDs	Session 1 Pretest	Session 2	Session 3 Posttest
357	Synthetic	Neo-Darwinian	Neo-Darwinian
425	Naive	Synthetic	Synthetic
454	Naive	Neo-Darwinian	Synthetic
824	Darwinian	Darwinian	Neo-Darwinian
847	Naive	Synthetic	Neo-Darwinian
870	Naive	Neo-Darwinian	Neo-Darwinian
985	Synthetic	Neo-Darwinian	Neo-Darwinian
986	Naive	Neo-Darwinian	Neo-Darwinian

Table 1: Composite mental models of evolution.

Why did the students in this study change their initial mental models of evolution, with the majority of the students successfully acquiring a neo-Darwinian model? We feel there are two main reasons. First, the materials in the Evolution TI's conceptual change lesson were specially developed to show the limitations of the student's current understanding of evolution, and to make the new neo-Darwinian view of evolution understandable, plausible, and useable. However, there have been other attempts to implement a conceptual change framework for evolution that have met with only limited success (e.g., Bishop & Anderson, 1990). Distinctive features of our approach that we feel contributed to the efficacy of the learning activities used in this study include the use of a sophisticated case-based hypermedia learning environment augmented with the case-theme commentaries and the mental model visualizations. These program features functioned to help make important aspects of the neo-Darwinian model explicit. Further, the hyperlinking capability afforded by this technology system allowed the conceptual interconnectedness underlying the surface variability of multiple cases of evolutionary biology to be demonstrated to (and also explored by) the students. The case-theme commentaries were textual representations of this case-specific/structural knowledge while the mental model visualizations provided dynamic representations by "running" the neo-Darwinian mental model for different cases. The Evolution TI materials also provided active, scaffolded learning opportunities for the students through the problem-solving Story Maker module and the knowledge synthesis questions with guided thematic criss-crossing. As the design of this study precluded making a determination of the relative contributions of the different features of the Evolution TI for promoting conceptual change, future research controlling for different design features may be warranted given the significant findings of conceptual change in this study.

Finally, we feel the data documenting synthetic models of evolution is important as research to date has tended to focus on either the naive Lamarckian model (sometimes called an "evolution misconception") or the expert neo-Darwinian model. Our findings of synthetic mental models of evolution (for which we are completing a detailed paper) are consistent with other research in different domains that have found synthetic models [Vosniadou & Brewer, 1992; Vosniadou & Brewer, 1994; Wiser & Carey, 1983]. It may well be that many students will form synthetic models as part of the process of conceptual change in this difficult to learn domain of evolutionary biology--again, an area for future research.

Conclusion

The centrality of the neo-Darwinian theory of evolution by natural selection to the biological sciences–and increasingly to other areas as diverse as immunology, philosophy, neuropsychology, and artificial intelligence--is incontestable [Cziko, 1995; Dawkins, 1986; Dennett, 1995; Dobzhansky, 1973; Kauffman, 1995]. That the complex knowledge associated with evolutionary biology has proven very difficult for students of a variety of ages and levels of academic ability to learn thus presents an important challenge to the learning sciences. We feel the significant findings in this study have relevance both for general issues associated with the design of technological learning environments and for informing our understanding of the types of mental models students have about evolutionary biology and how these change in response to learning activities. Further research is necessary to understand how students can learn other facets of neo-Darwinian theory, such as the non-teleological nature of evolution and the importance of stochastic processes, which were not explicitly addressed in the current study. However, we feel this study is suggestive of how a case-based hypermedia system such as the Evolution Thematic Investigator can be designed to help promote conceptual change from the commonly held naive Lamarckian model to a more expert-like neo-Darwinian model. This in turn should provide students with a solid conceptual foundation upon which to build richer and more elaborated understandings of what is certainly one of the most important, elegant, and powerful system of ideas to be articulated in the modern scientific age.

References

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, *27*(5), 415-427.

Bizzo, N. M. V. (1994). From down house landlord to Brazilian high school students: What has happened to evolutionary knowledge on the way? *Journal of Research in Science Teaching*, *31*(5), 537-556.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, *18*(1), 32-42.

Brumby, M. N. (1984). Misconceptions about the concept of natural selection by medical biology students. *Science Education*, *68*(4), 493-503.

Cognition and Technology Group at Vanderbilt. (1992). Technology and the design of generative learning environments. In T. M. Duffy, & D. H. Jonassen (Eds.), *Constructivism and the technology of instruction: A conversation* (pp. 77-89). Hillsdale, NJ: Erlbaum.

Collins, A., Brown, J., & Newman, S. (1987). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. Resnick (Eds.), *Knowing, learning, and instruction*. Hillsdale, NJ: Erlbaum.

Cummins, C. L., Demastes, S. S., & Hafner, M. S. (1994). Evolution: Biological education's under-researched unifying theme. *Journal of Research in Science Teaching*, *31*(5), 445-448.

Cziko, G. (1995). *Without miracles: Universal selection theory and the second Darwinian revolution*. Cambridge, MA: The MIT Press.

Dawkins, R. (1986). *Blind watchmaker*. New York: Norton.

Demastes, S. S., Settlage, J., & Good, R. (1995). Students' conception of natural selection and its role in evolution: Cases of replication and comparison. *Journal of Research in Science Teaching*, *32*(5), 535-550.

Dennett, D. C. (1995). *Darwin's dangerous idea: Evolution and the meanings of life*. New York: Simon & Schuster.

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *Journal of Biological Education*, *35*, 125-129.

Glaser, R. (1991). The maturing of the relationship between the science of learning and cognition and educational practice. *Learning and Instruction*, *1*, 129-144.

Gordin, D. N., & Pea, R. D. (1995). Prospects for scientific visualization as an educational technology. *The Journal of the Learning Sciences*, *4*(3), 249-279.

Greene, E. D. (1990). The logic of university students' misunderstanding of natural selection. *Journal of Research in Science Teaching*, *27*(9), 875-885.

Jacobson, M. J., Maouri, C. , Mishra, P., & Kolar, C. (1995). Learning with hypertext learning environments: Theory, design, and research. *Journal of Educational Multimedia and Hypermedia*, *4*(4), 321-364.

Jacobson, M. J., & Spiro, R. J. (1995). Hypertext learning environments, cognitive flexibility, and the transfer of complex knowledge: An empirical investigation. *Journal of Educational Computing Research*, *12*(5), 301-333.

Jacobson, M. J., & Spiro, R. S. (1994). *Learning and applying difficult science knowledge: Research into the application of hypermedia learning environments (Second year report to the National Science Foundation Applications of Advanced Technologies program).* University of Illinois, Department of Educational Psychology.

Kauffman, S. (1995). *At home in the universe: The search for laws of self-organization and complexity*. New York: Oxford University Press.

Mayr, E. (1991). *One long argument: Charles Darwin and the genesis of modern evolutionary thought*. Cambridge, MA: Harvard University Press.

Neuman, D., Marchionini, G., & Morrell, K. (1995). Evaluating Perseus 1.0: Methods and final results. *Journal of Educational Multimedia and Hypermedia*, *4*(4), 365-382.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*(2), 211-227.

Settlage, J. (1994). Conceptions of natural selection: A snapshot of the sense-making process. *Journal of Research in Science Teaching*, *31*(5), 448-457.

Spiro, R. J., Feltovich, P. J., Jacobson, M. J., & Coulson, R. L. (1992). Cognitive flexibility, constructivism, and hypertext: Random access instruction for advanced knowledge acquisition in ill-structured domains. In T. M. Duffy, & D. H. Jonassen (Eds.), *Constructivism and the technology of instruction: A conversation* (pp. 57-75). Hillsdale, NJ: Erlbaum.

Strike, K., & Posner, G. (1990). A revisionist theory of conceptual change. In R. Duschl, & R. Hamilton (Eds.), *Philosophy of science, cognitive science, and educational theory and practice.* Albany, NY: Sunny Press.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*, 535-585.

Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science*, *18*(1), 123-183.

White, B. Y. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction*, *10*(1), 1-100.

Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner, & A. L. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Erlbaum.

Acknowledgments

This research was supported by a grant to the first author from the National Science Foundation under Grant No. RED-9253157. The United States government has certain rights in this material. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies. The authors gratefully acknowledge the contributions of the Rand J. Spiro, Punyashloke Mishra, Susan Ravlin, Chrystalla Maouri, and Brian Levine to this research project.