Effecting conceptual change in evolution education by visual scaffolding

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September 1st, 2017

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ABSTRACT

Misconceptions in natural selection are significantly prevalent and prevent undergraduate students from building a foundational understanding of evolution and advancing in many other topics in life sciences. Supplemental interactive visualizations teaching natural selection are limited, poorly designed, and do not confront and may even reinforce misunderstandings. The main goal of this project is to develop and evaluate an interactive learning tool that will foster understanding and remediate misconceptions that undergraduate students may have in natural selection. The learning framework will be based on a combination of model-based and guided-discovery learning, with a focus on visual scaffolding. It will feature simulations, visual and textual representation and prompts for prediction, note-taking, data interpretation, evaluation, and reflection; ultimately, aiming to aid students' revision of their mental models into a more correct and robust mental model. The resource will be field-tested with undergraduate life science students at University of Toronto Mississauga to evaluated its efficacy in effecting conceptual change.

INTRODUCTION

Natural selection is a fundamental concept in evolution education; the understanding of this concept impacts the understanding of evolution and biodiversity, has significant pertinence to multiple topics within life science education such as ecology and cell biology, and has daily life relevancy in medicine and agriculture. However, learning natural selection is challenging for students and frequently leads to the formation of misconceptions. It is hard for students to grasp because it requires them to be able to understand abstract and complex sub-concepts (e.g., variation, randomness, population versus individual, process versus event) that often cross multiple spatial and temporal dimensions (White et al., 2013). For example, students have difficulty comprehending that natural selection is mostly driven by or is a result of random processes that occur at both the molecular and populational scale throughout many generations (Klymkowsky & Garvin-Doxas, 2008). Furthermore, student preconceptions and cognitive biases, such as teleological and intentionality thinking, prevent them from thoroughly understanding the nuances of natural selection. (Gregory, 2009; Sinatra et al., 2008). Expanding on the aforementioned example, students tend to think that trait shifts in a population are due to a "need" from individual organisms in response to external pressure, and that all processes have a desired purpose or outcome (i.e. evolution is goal-oriented). Even more confusing is that the terms used in teaching evolution are also used in daily life and the quotidian meanings of these words have less exact definitions and encourage bias. For example, "adaptation" and "competition" in evolution education can be confused with everyday meanings of which imply agency and purpose (Moore et al., 2002; Smith, 2010; Pobiner, 2016). These challenges in learning natural selection and the associated misconceptions are exceedingly prevalent and prevent students from building a foundational understanding of evolution and advancing in many other topics within life sciences. Thus unsurprisingly, there are decades of research that have been devoted to thoroughly dissecting and documenting these learning obstacles and misunderstandings (Gregory, 2009).

Biology is an inherently visual domain and with the increasing use of diverse visualizations to explain complex concepts such as natural selection, the pedagogical value of these visual representations need to be closely examined. Research on the efficacy of scientific visualizations are mixed (Lowe, 2003; Wylie & Chi, 2014); some evaluations indicate positive outcomes while some show that visual representations can reinforce or even create misconceptions (Gilbert et al., 2008). Recent research efforts have been concentrating on examining science education frameworks and design principles in greater detail. However, visual representations and pedagogic resources that teach natural selection are scarce and often inadequate. Furthermore, these resources rarely confront or remediate misconceptions. Hence, there stands much potential to investigate how integrating learning frameworks and visual scaffolding can effectively engage students to confront their misconceptions and biases, and ultimately help them overcome the challenges in their learning of natural selection.

BACKGROUND

Natural selection and its learning challenges

Darwin provided the first detailed explanation of natural selection and its implications in *On the Origin of Species by Means of Natural Selection* (1859). Mayr (1982) condensed Darwin's extensive exposition down to five observations and three associated inferences as illustrated in Fig. 1.

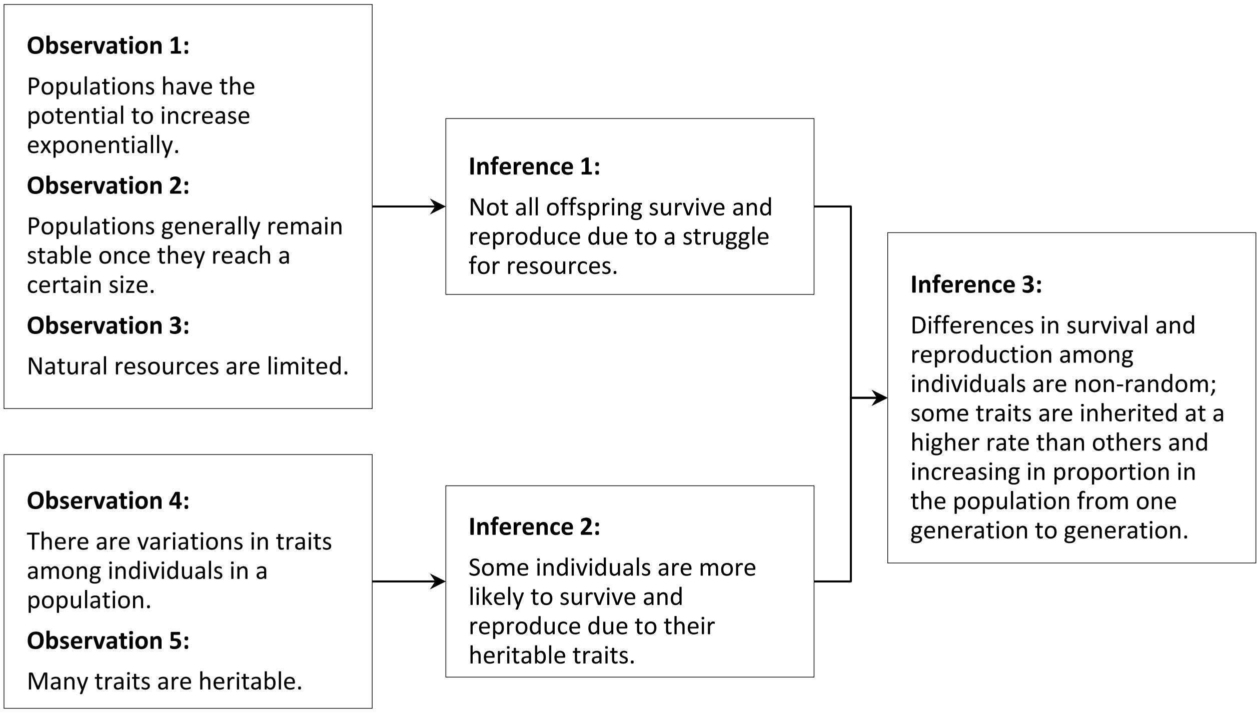

Fig. 1 Summary of natural selection by Mayr (1982), first presented by Darwin (1859)

Many decades of research have revealed unambiguous data indicating a significant prevalence of misunderstandings about natural selection among the general public and in students of all levels (Alters & Nelson, 2002). Scientific explanations of phenomena can often be counterintuitive and dissonant from notions of the world as observed in everyday experience. Several studies have elucidated the cognitive biases and obstacles that students and instructors face when attempting to understand natural selection. Most notable are teleological, anthropomorphic, and transformationist biases. Teleological bias refers to the tendency to think that objects and behaviours have a "purpose" or "function". A common misconception is that students often think of adaptation as a change that occurs in response to a particular need or external pressure (Kelemen & Rosset, 2009; Ware & Gelman, 2014). Teleological thinking also lends to the naïve conception that only beneficial or "useful" mutations are passed on the next generation and that vestigial or lost traits are due to disuse

(Gregory, 2009). Anthropomorphism (also known as intentionality) is when human-like conscious intent is attributed to objects of natural selection or the process itself. Anthropomorphic misconceptions are further characterized into either internal or external. Internal anthropomorphism is the thinking that individuals evolve in response to obstacles established by the environment rather than recognizing evolution as a population-level process (Gregory, 2009). External anthropomorphism is the thinking, often aligned with creationist beliefs, that natural selection or "Nature" is a conscious agent (Sinatra et al., 2008). Transformationist bias refers to the tendency to think that adaptation occurs to an entire population rather than a portion of the population. Thus, students often have trouble understanding the threshold concept of variation in natural selection in which a proportion of traits within populations changes and not the population as a whole (Batzli et al., 2016). Another concept that is difficult for students to grasp is that natural selection is a continuing and probabilistic process; it occurs over many generations within a population and some traits make it more likely for an organism possessing them to successfully reproduce but does not necessarily guarantee they will (Gregory, 2009; Sinatra et al., 2009). Lastly, emotional investment and motivation is a barrier that impacts the motivation for students to learn and correct their misunderstandings. There is often a disconnect between the course material and experiences in the daily life of the student; if the students do not view the topic of natural selection as personally relevant, they are less likely to experience conceptual change (Sinatra et al., 2008). Evidently, there are numerous, multifaceted challenges to teaching natural selection without imparting and reinforcing misconceptions.

Current teaching methods and available supplemental resources

The standard teaching method includes lecture instructions and textbook readings that explain the phenomenon and uses fictional and real-life examples (e.g., Galapagos finches) to illustrate natural selection. Being such a visual domain, teaching biology frequently calls for the usage of other visual resources to supplement the standard class material. Supplemental learning is available through clips from documentaries, whiteboard explanatory videos and other non-interactive visual media such as educational websites that include static figures, text, and videos.

Interactive visualization offers a unique opportunity in that it can more efficiently represent the complexity of natural selection (e.g., the crossing of spatial and temporal dimensions) and provide user control therefore promoting engagement and a more wholistic interpretation. While some interactive visual media for natural selection education exist, they are usually not widely promoted nor easily accessible in that they are often only restricted to students and instructors of a specific program or institution. In addition, they are generally unengaging, poorly designed or executed (e.g., difficult mechanics, unintuitive UI/UX, etc.), have limited functionality and disregard the integration between different visual representations. Most importantly, many of these interactive visualizations do not address misconceptions and biases directly (see media audit in Appendix A). Abundant research support that the teaching and learning of natural selection must include efforts to identify, confront, and supplant misconceptions (Gregory, 2009; Nelson, 2008; Sinatra et al., 2008; Tidon & Lewontin, 2004). Indubitably, there is room to explore methods of misconception remediation in the design of interactive visualization for natural selection education.

Effecting conceptual change

Two complementary learning frameworks offer a promising approach in effecting conceptual change: model-based and guided-discovery learning. Model-based learning is a "dynamic, recursive process of learning by building mental models" (Buckley, 2000). It involves the formation, testing,

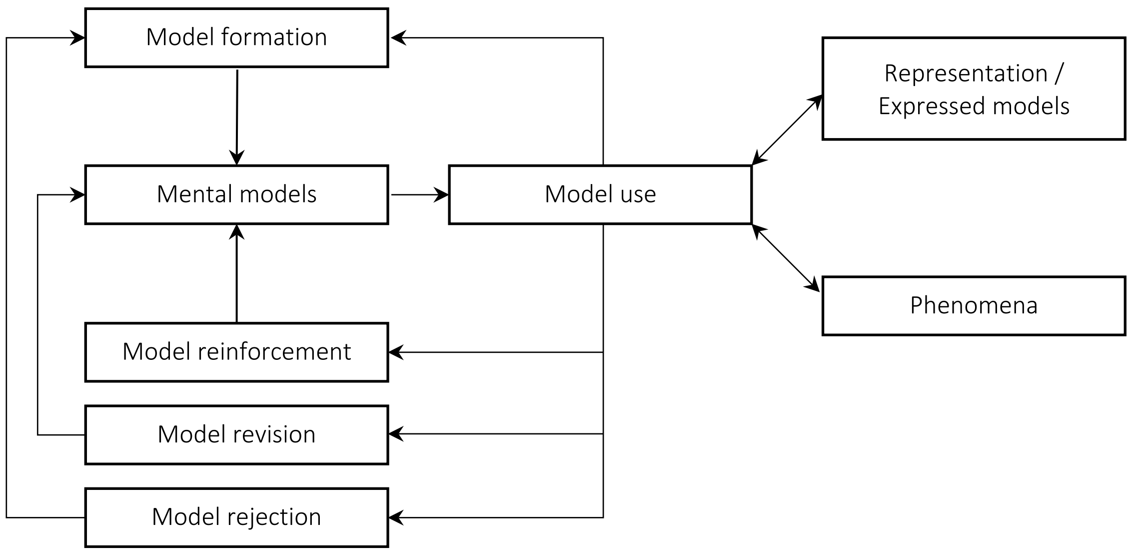

Fig 2. Model-based learning as described by Buckley (2000).

reinforcement, and revision of mental models of a phenomenon (see Fig. 2). Mental models are internal, cognitive representations that are used to express an external representation for communicating, reasoning and problem-solving. Mental models influence a learner's perceptions of phenomena and their understanding of representations. In turn, interactions with phenomena and representations influence our mental models (Gilbert, 2000). This process provides a basis for effecting conceptual change; in order to remediate misconceptions, educational approaches must first help students recognize the constraints and errors in their mental models of natural selection and its sub-concepts and then guide them in constructing more scientifically valid mental models (Duit & Treagust, 2003). Discovery (inquiry-based) learning, particularly in a multimedia and simulation-based context, assumes that learners take on an active role in constructing their own knowledge base via hypothesis generation, experimentation, and data interpretation. The systematic scientific method of discovery learning supplements the iterative process of model building in model-based learning. However, providing a discovery learning environment is insufficient. Studies show that students learn better when there is guidance (scaffolding) in an inquiry-based learning environment (de Jong, 2005). Guided-discovery learning is more effective because scaffolding supports the learner's abilities to integrate new information thereby decreasing extraneous cognitive load (Moreno, 2004; Quintana et al., 2004). Scaffolding in inquiry-based visualizations may include instructional advice that direct students towards appropriate actions (Davis & Linn, 2000), self-monitoring tools, or embedded domain-specific explanations (Rieber et al., 2004). Most importantly, scaffolding can also involve providing explanatory and corrective feedback (Moreno & Mayer, 2005), and prompts for hypothesizing, generating explanations, conducting experiments, constructing arguments, critique, and reflection (Linn, 2000; Linn & Eylon, 2011; Reiser, 2004; Ryoo & Linn, 2014; Quintana et al., 2004; Zhang & Linn, 2011). These guidance methods not only support students in their mental model formation but also help them in recognizing misconceptions and concept revision (Moreno, 2004; Moreno & Mayer, 2005).

However, guidance is not limited to instructional or cognitive scaffolding. Visual scaffolding has a significant impact on learning and plays an important role in interactive multimedia. Inevitably, it is a critical aspect in effecting conceptual change. In dynamic visualization, scaffolding involves both visual and interaction design principles that assist users in the learning environment. Scaffolding in visual design minimizes cognitive load and includes cueing to direct learners' attention to critical information, using narration or text to support pictorial information (i.e., dual coding), placing related objects near one another and avoiding the presentation of two dynamic sources of information at the same time (i.e., split-attention, spatial and temporal contiguity), and dynamic linking and integrating multiple representations (Mayer, 2005; Plass et al., 2009). Scaffolding in interaction design may include interactive features such as segmentation (e.g., dividing material into discrete sections corresponding to meaningful concepts), allowing learners to control the rate and timing of information, ability to view the phenomenon from multiple different perspectives, and allowing learners to experiment using manipulatable input variables (Mayer & Chandler, 2001; McElhaney et al., 2014; Plass et al., 2009; van der Meij & de Jong, 2011). Ultimately, the combination of model-based learning and scaffolding in an inquiry-based learning environment presents a specific learning framework that holds much potential to remediate misconceptions and support scientific learning in a dynamic visualization context.

RESEARCH AIMS

Natural selection is a fundamental concept in evolution; misconceptions in natural selection not only affect the understanding of evolution, but also many other topics in science. Secondary educative resources are limited, poorly designed and do not confront or may even encourage misunderstandings. Thus, the main goal of this project is to remediate misconceptions in natural selection that undergraduate life science students have. Three main objectives are as follows:

1. Develop a learning framework that would effectively teach accurate concepts of natural selection, confront misconceptions and guide students in revising their mental models.

2. Develop an interactive tool by integrating the previously formulated framework with visual scaffolding.
3. Implement iterative design involving ongoing formative assessment and evaluate the effectiveness of the educational interactive tool (summative assessment).

METHODS

Audience

The primary target audience are undergraduate students enrolled in evolution courses, with a secondary focus for science instructors and the scientific communication community. The developed tools and study results will also be made available online for the lay public and will potentially be disseminated in other academic platforms.

Establishing design scope

The design strategy is mainly two-fold, involving the development of 1) a robust educational framework and 2) an extensive visual design approach. In order for the learning tool to be relevant and beneficial, it should supplement an existing curriculum and not function as a standalone. Therefore, the first step is to clarify the learning objectives based on the curriculum with the help of the course instructor, Professor Fiona Rawle, and discuss learning solutions to misconceptions recognized in external research and in Professor Rawle's own research. The following step is to collaborate with the supervisory committee to develop and refine an appropriate learning framework and media design that fulfills the learning objectives.

The proposed learning environment

The main features of the interactive visualization will include a) simulations of populations undergoing natural selection (e.g., manipulation of variables affecting a population on a microscale leads to a change in visual representation of the population on a macroscale), b) visual and textual representation and c) prompts for prediction, note-taking, generating explanations, evaluation, and reflection

The educative framework will be based on two complementary concepts: model-based learning and guided-discovery learning. To address model-based learning, the interactive tool will promote students to confront their misconceptions indirectly and directly in order to identify their own erroneous beliefs and revise their mental models. Indirect confrontation will be effected via activities that create cognitive conflict (question the students understanding) while direct confrontation will be facilitated via corrective and explanatory feedback. In addition, the learning tool will feature multiple, varying simulations that will allow the students to form and test hypotheses (their mental models) by experimentation (content manipulation) and observation, ultimately aiding in the students' revision of their mental models into a more correct and robust mental model. In order to achieve this, model progression design will be implemented; students will be required to apply their concepts of natural selection in increasingly complex scenarios in which they formulate hypotheses, evaluate evidence (i.e., the simulation) and explain the underlying causes of the observed evolutionary events (Swaak et al., 1998; Swaak et al., 2004). To address guided-discovery learning, this learning tool will implement scaffolding via both instructional and visual means. While scaffolds have been shown to be beneficial, there are trade-offs in which students may become overwhelmed with extraneous information and struggle to focus and integrate the educational content (e.g. Lee et al., 2004). Thus, a formative assessment will be conducted to inform subsequent design revisions and ensure the minimization of cognitive load.

Other considerations in the visual and interaction design to support the learning process will include anchoring, task appropriateness, referential processing, and language. Research has shown that anchoring learning experience in an information-rich, realistic, problem scenario fosters interest and meaning (Leu & Kinzer, 2000; Sinatra et al., 2008). Thus, this learning tool will implement some real-life examples to establish relevancy to student's daily life (meaningfulness) and encourage emotional investment. In addition, by working with the course instructor, the material and educative framework in the visualization will align with course objectives and the needs of the students. Learning is also enhanced when information is encoded in both systems (Rieber, 2004), thus, the interactive tool will encourage students to translate between (internal and external) verbal and non-verbal explanations and observations; this may be achieved by include space for note-taking (verbalizing thought), visual interactive space (visualizing thought), and both visual and textual representations (visual and verbal observation). Lastly, there will be careful attention to the defining of terms to avoid language that may create confusion or reinforce bias.

Assessments

In order to evaluate the interactive visualization, an assessment protocol will be developed and followed. A formative assessment will be utilized to evaluate the efficacy of visual solutions, user journey and usability. The results from the formative assessment will subsequently inform iterations of the design. A summative assessment will be used to evaluate the efficacy of the educational program and whether it meets the research goals.

Usage

The final tool will be web-based and available cross-platform. It will be hosted online in which relevant courses in the University of Toronto learning portal will link to the learning tool. The visualization will complement core lecture material. It will be used for in-class demonstrations by the instructor and supplemental learning by students.

SIGNIFICANCE

The primary goal of this project is to remediate misconceptions that undergraduate students have about natural selection by visually scaffolding learning, confronting learners' biases and misunderstandings, and helping them reconstruct a robust, correct mental model of natural selection. The exploration of visual scaffolding in the role of mental model confrontation and revision has rarely been examined in other literature before. Therefore, the project outcomes will provide significant insight into design principles and offer applicable guidelines for educators and multimedia designers in the usage and creation of visual learning tools. The interactive visualization developed from this project aims to improve student's understanding of natural selection and thus provide a solid foundation for comprehending more advanced concepts in evolution and in a variety of other fields such as ecology, medicine, and environment. Ultimately, the results of this project will provide impactful means to improve science literacy.

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APPENDIX A: MEDIA AUDIT

Media	Purpose	Audience	Criteria[1]				
			1	2	3	4	5
Grotzer et al. (2009). *EcoMUVE*. Retrieved from http://ecolearn.gse.harvard.edu/ecoMUVE/overview.php	A computer simulation that engages students in exploring an ecosystem, collecting data from the simulated ecosystem and allowing observation of a population of a species over time	Secondary students	x	x			x
Danish et al. (2011). *BeeSign*. Retrieved from http://crlt.indiana.edu/projects/beesign.html	A computer simulation that promotes inquiry-based learning, allowing students to manipulate variables (environment or behavior) and observe a population of bees	Elementary students	x		x		x
PBS (2001). *Pollenpeepers.* Retrieved from http://www.pbs.org/wgbh/evolution/darwin/origin/	Educational web simulation allowing user to explore adaptive radiation of a fictitious group of birds over a period of 5 million years; in broader terms, it aims to facilitate understanding of adaption by natural selection over generations	Elementary and Secondary students	x				x
Lemmon, Alan R. (2000, Sept 6). *Evotutor.* Retrieved from http://www.evotutor.org	Educational interactive simulation and learning modules that cover a wide variety of topics within evolution (such as genetic drift, natural selection, mutation and more)	Post-secondary students	x				x
Genetic Science Learning Center. (2013, July 1) *Variation, Selection, and Time.* Retrieved April 28, 2017, from http://learn.genetics.utah.edu/content/selection/	Educational website that includes animation, interactive media and text that explain and provide real-life examples of natural selection	Secondary and post-secondary students	x	x	x	x[2]	
Meir E, Herron J C, Maruca S, Stal D, Kingsolver J. (2005) *EvoBeaker* [Computer software]. Retrieved from http://www.simbio.com	Educational lab simulation software that teach principles of natural selection	Post-secondary students	x		x		x
Jeanne et al. (2003). *Connecting Concepts: Interactive Lessons in Biology.* Retrieved from http://ats.doit.wisc.edu/biology/lessons.htm	Interactive modules that teach natural selection and speciation	Post-secondary students	x				x

[1] Criteria outlined on the second page

[2] This section only includes topics in natural selection which may reinforce the misconception that natural selection is the predominant mechanism in evolution

APPENDIX A: MEDIA AUDIT *(…continued)*

Criteria:

1. Scientifically accurate: accurate and non-misleading representation of concepts
2. Aesthetically pleasing: harmonious and thoughtful choices in design and visual representation
3. Low cognitive load: clear informational hierarchy, easy navigation, minimized visual search, intelligible visual representation
4. Confronts misconceptions: identify, explain, and provide refutations to common misconceptions
5. Interactivity: includes component which allows active participation in learning via self-testing, simulation and/or experimentation