Utilizing Cognitive Model Construction Strategies to Support Students' Participation in Kinesthetic Simulations

Grant Williams, Ryan Oulton, & Laura Taylor
St. Thomas University, Fredericton, New Brunswick Canada

Introduction

Students are frequently exposed to computer-based simulations of science concepts by interacting with them individually, relatively passively, and without direct instruction from the teacher with the hopes that simply experiencing the simulations will result in learning of the target concept. This study adds a socio-physical aspect to the use of simulations as a teaching medium by having K-12 students step away from computer-based simulations and take on active roles of key elements of natural systems in order to cooperatively act out or kinesthetically simulate particular scientific phenomena. We refer to these kinesthetic simulations as Kinulations. While having students participate in these kinds of human-based simulations is not a new instructional strategy, our interest lies in exploring the ways teachers can support students' engagement in the modeling of and reasoning about abstract scientific concepts during these simulations, as opposed to simply following teachers' directions.

Theoretical Framework

One of the eight core scientific and engineering practices identified by the Next Generation Science Standards (2013) to help learners construct understandings of abstract concepts is the development and use of *models*. The term model has many uses; however, in the context of this study, a model is considered to be a simplified representation of a system, which concentrates attention on specific aspects of the system (Ingham & Gilbert, 1991; Johnson-Laird, 1983).

Models are a useful instructional support in cases where the phenomena being studied occur at rates that are either too fast or slow to observe, take place on scales that are too large or small to see, or take place in hidden or concealed locations. This includes concepts such as planetary motion, human respiration & circulation, erosion and continental drift, cellular reproduction, chemical reactivity, magnetic fields, electric circuits, etc. Instructional models are often developed and used by teachers and curriculum developers to promote learner understanding of a particular target concept and include molecular model kits, solar system mobiles, ripple tanks, and computer simulations.

Research on the use of *simulations* as a type of scientific model (Ajredini et al., 2014; Barab & Dede, 2007; Podolefsky et al., 2010; Colella, 2000; Campbell et al., 2010; Hegarty, 2004) indicates that students can develop deep conceptual understanding as a result of interacting with dynamic visual representations of phenomena that may be difficult to experience first-hand. The vast majority of these simulations currently exist in animated video or computer generated formats for student viewing and digital interaction.

Research on *movement education* (Griss, 2013; Clancy, 2006; Carrier & Rex, 2013; McGregor & Precious, 2010, Begel et al., 2004) also tells us that students can develop deep and lasting conceptual understanding as a result of participating in kinesthetic activity while learning new concepts. Supporting research in cognitive psychology indicates that meaningful conceptual structures arise: (1) from the structured nature of bodily and social experience and (2) from our innate capacity to imaginatively project from certain well-structured aspects of bodily and interactional experience to abstract conceptual structures (Varela et al., 1991).

The pedagogical approaches (simulation-based education and movement-based education) being addressed in this study remain essentially unrelated in the current science education research literature. Since they are inherently mutually exclusive in current practice (as most simulations exist in computer animated form requiring relatively passive student viewing), we believe this research will establish a bridging of the literature and will offer important contributions in the emerging field of research in model-based science teaching and learning. Research in the areas of embodied cognition (Shapiro, 2010; Holton, 2010) and enactive metaphors (Gallagher & Lindgren, 2015) is beginning to surface in the area of educational psychology, however research on the specific application of such ideas to K-12 science teaching and learning remains an area in need of exploration. Our hypothesis is that participation in such physically-engaging student-centered simulations can offer students a learning experience in which bodily and cognitive stimuli work together to foster reasoning about abstract scientific notions.

Supporting Research

In a recent study (Williams & Clement, 2015) we identified and described a set of *Cognitive Model Construction Strategies* that are aimed at promoting model construction and development through whole-class discussions. These strategies consist of teacher questions and comments that respond to specific strengths and weaknesses in the ideas being expressed by students. The strategies are intended to foster students' reasoning about the domain and support specific steps in the construction and refinement of explanatory models, including kinesthetic simulations.

We observed that in attempting to foster reasoning, the teachers in the study engaged students in four distinct phases of a model construction process. Starting from students' 1) *Observations* of phenomena and their prior knowledge about the concepts being explored, the teachers supported students' 2) *Generation* of explanatory models for the phenomena. It was further observed that teachers acted to scaffold students' repeated cycles of 3) *Evaluation* and 4) *Modification* of those models through the evolution of what Clement (2000) refers to as *intermediate models*. These intermediate models are viewed as stepping stones on a learning pathway to a *target model* or desired knowledge state that one wishes students to attain after instruction. We collectively refer to these four model construction process as the OGEM Cycle (*Observation, Generation, Evaluation, and Modification*). Existence of these phases had been supported by earlier studies of the model-based teaching of a wide variety and levels of conceptually challenging secondary science topics, from middle school units on human circulation and respiration (Nunez-Oviedo et al., 2008) and atomic theory and particle behavior (Price & Clement, 2014), to high school units on universal gravitation (Stephens & Clement, 2012).

We then analyzed video recordings of student/ teacher dialogue from whole class discussions in these teachers' classrooms in order to look for finer-grained model-based teaching strategies (Williams & Clement, 2015). We converged on a set of fifteen cognitively-focused discussion-based teaching strategies that we refer to as *Cognitive Model Construction Strategies* since they are believed to support students' construction of explanatory models for the science concepts they are studying. The Next Generation Science Standards (2013) have highlighted the importance of models and modeling cycles. However, those Standards are necessarily painted with a broad brush and teachers are seeking details about how to implement modeling cycles with student participation. The fifteen Cognitive Model Construction Strategies are intended to provide such detail.

Table 1 below sub-divides the fifteen cognitive model construction strategies into the 4 general model construction processes that we refer to above as the OGEM Cycle. We describe the fifteen strategies as *Micro Level* strategies because we view each of them as being a sub-strategy for one of the *Macro Level* OGEM processes.

Macro Level – OBSERVATION	
Micro Level Strategies	***Classroom Transcript Examples***
Requests or provides observations	T: What color did the cabbage juice turn when you added the vinegar (acetic acid) to it?
Requests or provides diagram to help students recall results of an experiment	T: Look on the whiteboard at the drawing of the circuit from yesterday's exploration. Which bulbs should be shown glowing the brightest?

Macro Level - MODEL GENERATION	
Micro Level Strategies	***Classroom Transcript Examples***
Requests or provides the initiation of model construction	T: So how do different people end up with different eye colors? Does anyone have any ideas to explain how that happens?
Requests or provides new detail or elaboration of the model	T: Well, we have a good start on a model that explains why the seasons are different in Canada and Chile, but who can add a bit more to the model to explain why the seasons happen when they do?
Requests or provides a model element to explain specific observation	T: Does anyone have any ideas about why the cabbage juice changes from purple to that greenish blue color when we add a base to it?
Requests or provides an analogy	T: One way to think about the cell is to compare it to a city. Can anyone think of how the specific parts of a cell might be comparable to parts or aspects of a city?
Requests or provides spatial direction of effect	T: So what evidence do we have that the Earth spins counter-clockwise as viewed looking at the North Pole?

Macro Level - MODEL EVALUATION	
Micro Level Strategies	***Classroom Transcript Examples***
Requests or provides evidence to support or refute a model	T: Tracy thinks the rockets travel furthest at a 45 degree launch angle because they will be in the air for the longest possible time. What does the data your group collected say about that?
Requests or provides running a model for prediction or evaluation	T: Imagine if we enclosed the spring scale and the weight in a glass jar and then we sucked all of the air out of it. What do you think the scale would read compared to what it reads in normal conditions?
Requests or provides the design of an experiment or thought experiment	T: What if we were to test that model by placing a compass under the wire on either side of the bulb? Would that tell us whether the bulb consumes charge?
Requests or provides a discrepant question or discrepant event	T: So everyone here agrees that moss grows on the north side of trees. But, Miguel, who came here from Argentina says that there, moss grows on the south side. How can that be true?

Macro Level - MODEL MODIFICATION PHASE	
Micro Level Strategies	***Classroom Transcript Examples***
Requests or provides additions or changes to the model	T: Can anybody think of a way to make the model better –to account for the finding that not all bulbs light with the same brightness?
Requests or provides integration of two models or concepts	T: When we added a resistor to the circuit with one bulb, what did you notice? S: The bulb got dimmer. T: Like when you added a second bulb to the circuit? S: Yes –the same thing happened. T: So, that pretty much tells us that *a light bulb is a type of resistor*; at least in term s of their effects on other elements in the circuit.
Requests or provides differentiation between elements of models.	T: So when we talk about the idea of "neutrality" in this model of acids and bases, are we talking about neutrality of positive and negative charges or neutrality of H+ and OH- ions?
Requests or provides repair to or refinement of the language describing the model	T: So Geoff, when you say that the air molecules inside the tire are packed closer together than the air molecules outside the tire, do you mean that they are under greater pressure?

Table 1 – Discussion-Based Model Construction Teaching Strategies: Macro and Micro Levels

Objectives

The objectives of this study were to:

A) Develop a set of approximately 30 kinesthetic simulations (Kinulations) lessons designed to cognitively and physically engage students in learning about a variety of science concepts and phenomena,

B) Investigate the discourse interactions between the teachers and students participating in pilot trials of the Kinulations lessons to determine whether previously identified Cognitive Model Construction strategies (Williams & Clement, 2015) can be utilized to support student participation in these activities, and

C) Create a web-based collection of Kinulations lesson plans and classroom video exemplars for the reference of practicing K-12 science teachers, university level science teacher educators, and pre-service science education students.

Methodology

Corresponding to Objective A, thirty Kinulations lessons addressing various science concepts were developed and piloted with classes of students ranging from Kindergarten to twelfth grade. The pilot tests of these activities were video recorded for later analysis and professional sharing. The grade levels and concepts are listed in Table 2 below.

Grade	Concept	Grade	Concept
K	Needs of Living Things	Grade 9	The Solar System – Size & Scale
Grade 1	Plant Growth & Change	Grade 9	Electric Circuits
Grade 2	Butterfly Metamorphosis	Grade 10	Weather Dynamics
Grade 2	Liquids, Solids & Gases	Grade 10	Bioaccumulation
Grade 2	Atomic Structure	Grade 11	Human Muscle Types
Grade 3	Magnetic Forces – Fields	Grade 11	Human Digestion
Grade 4	Light – Shadows & Reflection	Grade 11	Human Circulation
Grade 4	Sound – Causes & Travel	Grade 11	Inertia
Grade 5	Simple Machines	Grade 11	Epidemiology/ Disease Spread
Grade 5	Measuring Weather	Grade 12	Reproduction – Menstrual Cycle
Grade 6	Electricity – Static & Current	Grade 12	Radioactive Decay
Grade 6	The Solar System – Size & Scale	Grade 12	Reaction Mechanisms & Catalysts
Grade 6	Flight – Forces Involved	Grade 12	Natural Selection
Grade 7	Ecosystems & Food Webs	Grade 12	DNA Replication
Grade 7	Heat Transfer	Grade 12	Fluid Dynamics

Table 2 – Kinulations by Grade Level and Concept

The process utilized in the development of these kinesthetic simulations as explanatory teaching models involved the following steps:

1) Selecting concepts in the science curriculum that were abstract in that they were difficult for students to readily understand. This may be because they are centered on phenomena that occur at rates that are either too fast or slow to observe, take place on scales that are too large or small to see, or take place in hidden or concealed locations.

2) Investigating common text-based and digitally-based models and simulations that have been traditionally used to explain the concepts. The focus is on determining what the primary teaching goals were and what aspects of the resources may or may not transfer well into a kinesthetic approach.

3) Identifying causal agents in those models and simulations that can be simulated kinesthetically; allowing the student to build on the natural causality of his or her muscular system. It is believed that this process can tap into intuitive kinesthetic or tactile knowledge that most students have developed through their everyday bodily interactions with the physical world (Stephens & Clement, 2008).

4) Selecting materials, props, and music that will provide strong visual and auditory cues to help students organize and manage important details of the model. This may include colored pinnies (worn over shirts) to distinguish components of the model (ie: protons, electrons and neutrons), colored floor tape to section off parts of the classroom (ie: chambers of the heart), signs that students can hold or wear to identify their roles in the simulation (ie: positive and negative ends of a battery), and music of varying styles and tempos to signify important changes (ie: seasons, temperatures, pressures, velocities).

5) Creating lesson plans for the Kinulation activities that include all or as many students as possible. This may require accommodating students with physical, cognitive, and/or behavioral challenges. In all cases, the focus is on engaging students kinesthetically, verbally, visually, auditorialy, and socially in investigating the scientific concepts and figuring out how to model them with their bodies in a collaborative way.

To provide some insight to the nature of these Kinulations, we offer here brief descriptions of four of the activities:

A) Grade 9- Electric Circuits: The class constructs a classroom sized functioning electric circuit model in which the students play the roles of batteries, wires, switches, and light bulbs and use objects such as volleyballs and post-it notes to represent the movement of electric charge and transfer of energy throughout the circuit,

B) Grade 6 – Solar System: The class constructs a soccer field-sized scale model of the solar system in which students assemble in small groups at varying distances from a center point (sun) to represent the planets. The larger the planet being represented, the greater the number of students in the group. The human planets revolve around the sun at various rates to represent the different lengths of a year on each planet,

C) Grade 2 – Solids, Liquids & Gases: The class constructs a gymnasium-sized model in which students behave as particles of solids, liquids, and gases responding to changes in temperature and pressure to explore changes in state. Music of varying tempos is used to represent various energy levels and to cue the students as to when temperatures of the environment are changing,

D) Grade 5 – Simple Machines: Students assemble in six small groups (4-5 students) to determining how they will act out one of the basic simple machines (pulley, wheel and axle, wheel, inclined plane, screw, and lever). Each group develops a human model of their assigned simple machine with a focus on how they can collectively use their bodies to demonstrate its key features and utilization of mechanical advantage. Once the six groups are satisfied with their human mechanical models, the entire class is challenged to assemble each of their simple machines end to end in a Rube Goldberg style machine with the task of cooperatively moving a soccer ball from start to finish.

It is important to note that having students participate in these kinds of human simulations is not a new teaching strategy but rather one we are exploring the utility of within the context of model-based teaching and learning. In all of the Kinulations utilized in this study, students play active roles in the modeling of and reasoning about abstract scientific concepts, as opposed to simply following teachers' directions. Fostered by intermittent rounds of whole-group discussion, the students demonstrate, evaluate and critique each other's kinesthetic simulations for the purpose of making improvements to them. It is these aspects of student engagement in explanatory model construction that is of greatest interest.

Regarding Objective B, as an exploratory study of the discourse interactions between the teachers and students participating in these Kinulations lessons, the research methodology consisted of a grounded theory qualitative approach (Strauss & Corbin, 1998) of analyzing video recordings and the resulting transcriptions of the Kinulations-based classroom sessions. Specifically, the constant comparison method (Strauss & Corbin, 1990) was utilized in an effort to develop descriptions of the interactions between teachers and students during the kinesthetic simulations for the purpose of identifying pedagogical strategies that appeared to support student learning. This facilitated the isolation of particular statements, questions, responses, gestures, actions, and movements that were hypothesized to support the student conceptual change process.

Results

At the current stage of analysis of the Kinulations episodes, we are finding evidence that the Cognitive Model Construction teaching strategies that we identified and described in our previous research (Williams & Clement, 2015) can be useful in supporting students' learning during Kinulations-based activities. By accessing students' prior knowledge and *Observations* of phenomena and concepts, teachers can foster the *Generation* of explanatory models in the forms of students' verbal explanations and corresponding bodily simulations. By encouraging students to critically assess the clarity and accuracy of their kinesthetic simulations for the concepts in question, teachers support the *Evaluation* of the models. In some cases, students are prompted to suggest *Modifications* to their Kinulations to bring them closer in line with the desired target model. We believe the following transcript excerpts from classes of various grade levels and topics illustrate that teachers can engage students in the previously described OGEM model construction cycle while teaching through kinesthetic simulations.

Grade 5 – Simple Machines

Speaker	Statement	Teacher Strategy Type
Teacher	So what did you see in the Lever group's demonstration	Requests Observations
Student 4	I like how Jasper was the fulcrum.	
Teacher	How did their model show how levers work?	Requests Model Construction
Student 2	You could see the work input when one end went down and the work output when the other end went up.	
Teacher	Does anyone have any thoughts regarding Mechanical Advantage?	Requests Support or Refutation of a Model
Student 7	Yeah – I was thinking about that. In their model, Jasper (the fulcrum) was pretty much right in the middle so I don't think their lever really had any Mechanical Advantage.	
Teacher	Anyone have any suggestions about that?	Requests Additions or Changes to the Model
Student 3	Maybe move the fulcrum closer to one end.	
Student 1	Yeah, Jasper could move closer to the output end of the machine. Then they would get more work out of the system.	

Table 3 – Cognitive Model Construction Strategies Used During Simple Machines Kinulation

Grade 7 – Ecosystems & Food Webs

Speaker	Statement	Teacher Strategy Type
Teacher	T: Right now, I'm in the middle of this crazy thing that resembles a big spider web. Can anybody tell me what this represents or what this thing is?	Provides diagram to help students recall results of an experiment
Student 5	S1: A food web	
Teacher	T: This is what we call a food web. Now, what would happen if all the things that are plants, so that would be the clover, the maple, birch, and the grass, what would happen if they let go of the string?	Requests running a model for prediction or evaluation

Student 2	S2: They'd be sad.	
	T: Well let's see, drop your strings! Ok, clover you drop the string, maple did you drop? OK, so something weird happened to our food web. Can anyone explain what this represents? What's going on here?	Requests a model element to explain specific observation
Student 3	S3: When everybody let go like everything…	
Teacher	T: Did everybody let go?	
Student 3	S3: No, not everybody. Just birch, clover, maple and grass. When they all let go, like all the plants, they just like everybody would have died because they don't have oxygen	
Teacher	T: When the plants are out of the ecosystem what happens to the animals?	Requests running a model for prediction or evaluation
Student 5	S1: They die!	
Student 2	S2: They get sad!	
Teacher	T: They start to d…do they just get sad?	
Student 4	S: No…	
Teacher	T: They start to die; why do they start to die?	
Student 5	S1: They're starving.	
Teacher	T: They're starving; they don't have enough to eat. Hold on a second though, if I'm a hawk, I don't eat plants. So why do I care if I'm a hawk?	Requests differentiation between elements of models.
Student 3	S3: Because it eats things that eats things that eat plants.	
Teacher	T: Because it eats things that eats things that eat plants. Eventually everything comes back to the plants. You may not eat plants directly but you eat things that eat plants.	Provides new detail or elaboration of the model

Table 4 – Cognitive Model Construction Strategies Used During Ecosystems/ Foodweb Kinulation

<u>Grade 4 – Sound: Causes & Travel</u>

Speaker	**Statement**	**Teacher Strategy Type**
Teacher	T: You guys are all air particles inside this big box. So, if I was the source of the sound, I want you to show me how you think you would respond as particles of air in the box. So is everybody ready for the sound to pass through the box of air?	Requests the initiation of model construction
Students	Yes!!	
Teacher	Makes a dramatic motion extending arms outward while thumping foot loudly	Provides observations

Teacher	Okay, I saw some people move around a little bit. I saw some people look like "I don't know what I'm supposed to do". Let's make a decision, how are we going to show that the sound travels from up here to the back of this box? What do you think?	Requests the design of an experiment or thought experiment
Student 1	Well I think when you made that sound it actually made the particles jump and move around …	
Teacher	Interesting, so you think the particles should jump and move around when they get hit with the sound wave?	Requests new detail or elaboration of the model
Student 1	Yes.	
Teacher	Which ones should jump and move around first?	Requests spatial direction of effect
Student 4	These ones.	
Teacher	The ones here close to me? Why not them back there?	Provides a discrepant question or discrepant event
Student 2	Because they're farther.	
Student 3	It's coming this way.	
Teacher	T: Oh, okay, the energy is coming this way, so it hits you guys first?	Provides spatial direction of effect
Student 5	Yes – we're the closest	
Teacher	Who should be the last ones to jump and move around?	Requests spatial direction of effect
Student 6	We will	
Teacher	You guys in the back row? How are you going to know when to jump and move around?	Requests new detail or elaboration of the model
Student 6	Right after the people in front of us do	
Teacher	Why is that?	Requests new detail or elaboration of the model
Student 7	Because the sound has to go through them before it gets to us.	

Table 5 – Cognitive Model Construction Strategies Used During Sound- Causes & Travel

In these three brief segments, 12 of the 15 Cognitive Model Construction strategies were implemented by the teachers to support students' reasoning about the kinesthetic simulations they were participating in. The whole class conversations in these classroom segments seem to indicate that students were constructing understandings of their participation as components in the Kinulations and that the teachers' questions were fostering the learners' generation, evaluation and modification of the models as they evolved. It is important to note that in the 20 teacher statements featured in the three transcripts above, only 5 of them had the teacher "providing" information to the students. In the remaining 15 statements, the teachers were "requesting" the students' input to the creation and explanation of the model. This is representative of the highly student-centered approach that these Kinulations activities embody.

Conclusion

This study set out to add a socio-physical aspect to simulations as a teaching medium by providing an alternative to computer-based simulations. By having students take on active roles of key elements of natural systems, they were encouraged to cooperatively act out or kinesthetically simulate particular scientific phenomena. We refer to these kinesthetic simulations as Kinulations. While having students participate in these kinds of human-based simulations is not a new instructional strategy, our interest lies in exploring the ways teachers can support students' engagement in the modeling of and reasoning about abstract scientific concepts during these simulations, as opposed to simply following teachers' directions. Building on our previous research (Williams & Clement, 2015), we were curious to see whether the Cognitive Model Construction teaching strategies we identified successful model-based teachers using during whole class discussions could also be used during the implementation of Kinulations: a different type of scientific modelling activity.

Although our data analysis is still underway, based on a sampling of transcripts from the Kinulations pilot tests in classrooms of various grade levels and science concepts, we have observed that the discussion-based Cognitive Model Construction strategies can play an important role in guiding students' participation in the kinesthetic simulations as well as the development of their explanatory models for the concepts under study. It was encouraging to see that 12 of the 15 identified strategies were effectively utilized by the teachers in the three classroom episodes and more so that of the 20 teacher statements featured in these transcript segments, 15 of them were requesting students' input to the models as opposed to providing information from the teacher. Our belief is that this kind of student-centered pedagogy is crucial to having students develop personally relevant explanations for abstract scientific concepts.

Since the pedagogical approaches (simulation-based education and movement-based education) being addressed in this study remain essentially unrelated in the current science education research literature, and because they are inherently mutually exclusive in current practice (as most simulations exist primarily in computer animated form requiring passive student viewing with limited physical interaction), we believe this research on kinesthetic simulations makes a useful contribution to the field of research in model-based teaching and learning.

Additionally, this research is furnishing useful resources for practicing elementary, middle-level, and high school science teachers, university level science teacher educators, and pre-service science education students. In particular, in response to Objective C of the study, a web-based collection of Kinulations lesson plans and classroom video exemplars has been developed to provide the guidance that these educators will require to adopt an instructional model designed to actively engage K-12 science learners in developing increased understandings of a variety of abstract and challenging scientific concepts through kinesthetic simulations. These resources can be found at www.kinulations.com. Interested users must register and request login permission from the website administrator since the project's research ethics requirements prohibit open viewing of the K-12 classroom based video content.

References

Achieve Inc. (2013). Next generation science standards. *www.nextgenscience.org/next-generation-science-standards*.

Ajredini, Fadil, Neset Izairi, and Oliver Zajkov. "Real Experiments versus Phet Simulations for Better High-School Students' Understanding of Electrostatic Charging." *European J of Physics Education* 5.1 (2014): 59-70.

Barab, S. & Dede, C. (2007). Games and immersive participatory simulations for science education: An emerging type of curricula. *Journal of Science Education and Technology*. Vol. 16, No. 1, pp. 1-3.

Begel, A., Garcia, D., & Wolfman, S. (2004). Kinesthetic Learning in the Classroom. *Proceedings of the 35th technical symposium on computer science education*. 183-184.

Carrier, S. & Rex, T. (2013). Learning the ropes with electricity: A classroom model illustrating a closed circuit for advanced students. *Science and Children.* Vol. 50, No. 7, pp. 36-39.

Campbell, T., Wang, S. K., Hsu, H. Y., Duffy, A. M., & Wolf, P. G. (2010). Learning with web tools, simulations, and other technologies in science classrooms. *Journal of Science Education and Technology*, *19*(5), 505-511.

Clancy, M.E. (2006). *Active Bodies, Active Brains: Building Thinking Skills through Physical Activity.* Champaign, IL: Human Kinetics.

Clement, J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education*, 22(9), 1041-1053.

Colella, V. (2000) Participatory simulations: Building collaborative understanding through immersive dynamic modeling. *The Journal of the Learning Sciences*. Vol. 9, No. 4, pp. 471-500.

Gallagher, S., & Lindgren, R. (2015). Enactive metaphors: learning through full-body engagement. *Educational Psychology Review*, *27*(3), 391-404.

Griss, S. (2013). The power of movement in teaching and learning. *Education Week.* Published Online: March 20, 2013

Hegarty, M. (2004). Dynamic visualizations and learning: getting to the difficult questions. *Learning and Instruction*, 14, 343-351.

Holton, D. L. (2010). Constructivism + embodied cognition= enactivism: theoretical and practical implications for conceptual change. *Paper presented at the AERA Conference, Denver, CO.*

Ingham, A.M., & Gilbert, J.K. (1991). The use of analogue models by students of chemistry at higher education level. *International Journal of Science Education,* 13, pp. 193-202.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

McGregor & Precious (2010). Dramatic Science. *Science and Children.* Vol. 47, 10, 56-59.

Nunez-Oviedo, M.C., Clement, J. & Rea-Ramirez, M.A. (2008). Developing complex mental models in biology through model evolution. In J. Clement & M.A. Rea-Ramirez (Eds.), *Model based learning and instruction in science* (pp. 173-194). Dordrecht: Springer.

Podolefsky, N.S., Perkins, K.K. and Adams W.K., (2010). Factors promoting engaged exploration with computer simulations. *Physical Review Special Topics Physics Education Research, 6(020117).*

Price, Norman & Clement, John J. (2014), "Generating, evaluating, and modifying scientific models using projected computer simulations", *Science Scope, 38*(2), 39-46

Shapiro, L. (2010). *Embodied cognition*. Routledge.

Stephens, L., & Clement, J. (2008). Anchoring student reasoning in prior knowledge: Characteristics of anchoring cases in a curriculum, *Proceedings of the 2008 Annual Meeting of the National Association for Research in Science Teaching* (NARST), Baltimore, MD.

Stephens, L., & Clement, J. (2012). The role of thought experiments in science and science learning, In B. Fraser, K. Tobin, & C. McRobbie (Eds.), *Second International Handbook of Science Education: Springer International Handbooks of Education*, Vol. 24, Part 2 (pp. 157-175). Dordrecht: Springer.

Strauss, A., & Corbin, J. (1990). *Basics of qualitative research: Grounded theory procedures and techniques.* Sage Publications. University of Michigan.

Strauss, A., & Corbin, J. (1998). *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory.* Sage Publications. Thousand Oaks, CA. pp. 12 & 101.

Varela, F., Thompson, E., & Rosch, E. (1991). *The Embodied Mind: Cognitive Science and Human Experience.* MIT Press, Cambridge, MA.

Williams, G., & Clement, J. (2015). Identifying multiple levels of discussion-based teaching strategies for constructing scientific models. *International Journal of Science Education*, 37(1), 82–107.