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Cycles of Exploration, Reflection, and Consolidation in Model-Based Learning of Genetics

Beaumie Kim[1] · Suneeta A. Pathak[2] · Michael J. Jacobson[3] · Baohui Zhang[4] · Janice D. Gobert[5]

Abstract Model-based reasoning has been introduced as an authentic way of learning science, and many researchers have developed technological tools for learning with models. This paper describes how a model-based tool, *BioLogica*™, was used to facilitate genetics learning in secondary 3-level biology in Singapore. The research team co-designed two different pedagogical approaches with teachers, both of which involved learner-centered "exploration and reflection" with *BioLogica* and teacher-led "telling" or "consolidation." One group went through the stand-alone *BioLogica* units for all topics prior to a series of teacher-led instructions, whereas the other group was engaged in teacher-led activities after using *BioLogica* for each topic. Based on the results of a series of tests on genetics, the groups performed differently from what the teacher had expected. We explore how the design of the two approaches and interactions among students might have contributed to the results.

Keywords Model-based reasoning · Science learning · Genetics · Educational technology

✉ Beaumie Kim
beaumie.kim@ucalgary.ca

1 University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada

2 University Preparation Centre, T1, SK Mall, College Road, Nashik 422005, India

3 The University of Sydney, Rm 243, Education Building, Sydney, NSW 2006, Australia

4 Shaanxi Normal University, 199 South Chang'an Road, Xi'an 710062, China

5 Worcester Polytechnic Institute, 100 Institute Rd, Worcester, MA 01609, USA

If science is only understood through its practices (Latour 1987), then learning about science in school should be aligned with the practices of real science. Science education in most schools, however, is frequently taught in a didactic manner, which generally helps learners gain an understanding of a subject of use on standardized tests but often without deeper understanding (Bransford et al. 2000). This is especially apparent in upper secondary levels (grades 9 and 10) of Express Stream in Singapore where the focus is on students' performances on a high-stakes examination (GCE "O" Level), which determines their entry into Junior College (pre-University) (Singapore Ministry of Education 2013). One of the biggest challenges of introducing alternative pedagogical approaches to secondary school education is supporting deep learning without compromising good examination results. To this end, we have explored model-based reasoning in science in the Singapore context.

Increasingly, the conduct of scientific inquiry in the twenty-first century involves the use of computational *models* (Barab et al. 2001; Brown et al. 1989; Clement 2000; Krajcik et al. 1998; Penner 2001; Zhang et al. 2006). A model, a simplified representation of a system, concentrates attention on specific aspects of the phenomena of interest, such as conceptual dimensions, objects, events, or processes (Ingham and Gilbert 1991). Models are thus used to represent, explain, and predict natural phenomena. Creating and testing models, as well as collecting, analyzing, and representing data, are central to the daily practices of scientists (Latour 1987). Adapting scientific models and visualization tools in education has been the focus of important research not only for physical models (Lehrer and Schauble 2000) and student-generated models (Gobert 2000) but also for computer models (Loh et al. 2001) for the last 15 years. Edelson et al. (1999), in a

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pioneering research project incorporating scientists' tools in the classrooms, suggested that technology support (e.g., computer models and visualizations) is an important aspect of implementing inquiry-based learning in science classrooms. Model-based practices often engage students in processes similar to those of scientists by creating and testing their hypotheses, and using scientific methods (Clement 1989; Gobert and Buckley 2000).

Research on the use of computer-based models and visualizations for K-12 science—which involve learner-centered inquiry activities—has found significant learning outcomes related to scientific knowledge and skills in physics (Jacobson et al. 2013; Sengupta and Wilensky 2011; White and Frederiksen 2000), chemistry (Kozma 2000), biology (Horwitz and Christie 2000; Wilensky and Reisman 2006), earth science (Edelson et al. 1999; Gobert and Pallant 2004), and astronomy (Kim and Hay 2005). Researchers and practitioners should always consider appropriate pedagogical approaches when adopting these scientific learning tools. If they are used solely in a didactic manner to enhance a lecture (e.g., showing the simulated models or visualizations), students may still not experience deeper engagement and understanding.

The research reported in this paper was focused on how two different lesson frameworks could impact learning genetics with *BioLogica*™, which is a model-based genetics learning tool (Buckley et al. 2010; Horwitz and Gobert 2000; Horwitz et al. 2009). Although significant learning of genetics ideas has been found in research conducted by the developers, there is a concern about how regular classroom science teachers might use an innovative learning technology such as this. For example, in research with *BioLogica* carried out in Perth, Australia, it was found that teachers idiosyncratically incorporated *BioLogica* activities in their classroom teaching based on how they perceived the role *BioLogica* could play in their classroom teaching (i.e., as a supplement, as a multimedia to suit different learning styles, or as a tool to think with) (Tsui and Treagust 2007).

The authors have been exploring the role of guidance structure when using dynamic models for science learning and found that students who received minimal structure and guidance at the beginning (low-to-high structures) performed better than those received guidance for multiple problem solving lessons with computational models in physics (Jacobson et al. 2013; Pathak et al. 2011). Our findings are consistent with the Kapur and Bielacyzc's (2012) framework of designing for productive failure (i.e., a generation and exploration phase followed by a consolidation phase). In this study, we developed and explored two approaches of providing teacher's guidance effectively when adopting *BioLogica* to Singapore curriculum, not only to promote deep learning of the subject but also to address the teachers' concerns about adopting innovations in their classrooms when preparing students for high-stakes examinations. Our study therefore explore two questions: (1) how two different ways of supporting learners in both model-based reasoning and test-specific tasks influence their understanding and (2) how two different approaches afford different types of interactions. We approach these questions with the assumption that receiving minimal structure and guidance at the beginning better activates learners' cognitive efforts based on our previous findings (Jacobson et al. 2013; Pathak et al. 2011). In the following, we begin by describing what it means to learn genetics with *BioLogica* and how we designed two approaches and our study.

Learning Genetics with *BioLogica*

In learning genetics, students often have difficulty connecting the visible traits of organisms (phenotypes) to the underlying mechanism of inheritance (genotypes) (Stewart and Hunt 1982; Tsui and Treagust 2007). In order to address this issue, *BioLogica* uses imaginary dragons as a species for students to manipulate "digital" DNA, chromosomes, and gametes and to explore the genotypic and phenotypic expressions of the dragons' traits (e.g., wings, number of legs, and whether or not having fire breathing; see Fig. 1) (Buckley et al. 2010; Horwitz and Burke 2002; Horwitz et al. 2009). The purpose of *BioLogica* is to provide an environment that incorporates core genetics *content* that students learn through *interaction* and *exploration*, in what Tinker and Horwitz (2000) called CIE (Content, Interaction, and Exploration) model. *BioLogica* contains twelve stand-alone online learning activities that teach genetics through increasingly elaborate models of structures, functions, and mechanisms of genetics within this framework. The activities include making predictions from representations, interpreting data from representations, and making explanations about calculations and models. As part of these online learning activities, *BioLogica* uses five types of scaffolding: representational assistance; model pieces acquisition; model pieces integration; model-based reasoning; and reconstruct, reify, and reflect (Gobert et al. 2004). Research on *BioLogica* has mainly focused on content learning (Buckley et al. 2010; Horwitz et al. 2009), epistemological understanding (Gobert et al. 2011), relationships among modeling, content learning, and inquiry strategies (Buckely et al. 2006).

The Context

A study was carried out in an all-boy school that was among the highly academically ranked Singapore secondary schools (i.e., express stream), and this paper reports

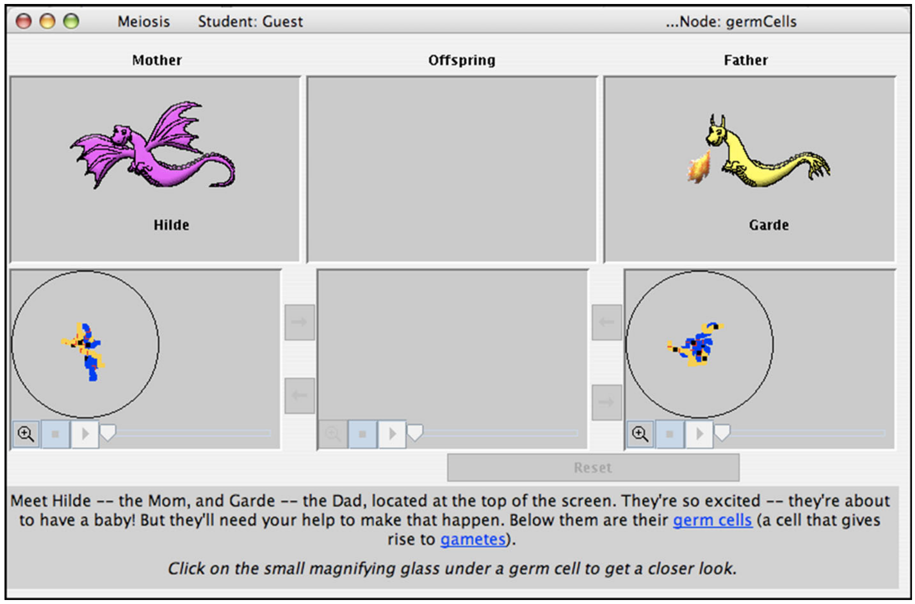


Fig. 1 *BioLogica* screen from Meiosis unit

on the results from two secondary 3 (equivalent to US grade 9) classes. This study was conducted during the last term of the year[1] when students have finished most of the regular lessons and examinations for the year. This allowed this implementation to take place everyday for 3 weeks. The students were moving to secondary 4 in a few months, which is a critical year preparing for O-level examination, which determines their entrance to the A-level course (Junior College) before entering a university. This implementation was important for teachers in order to prepare students for O-level examination. Introducing this research, teachers reminded students that these topics would not be covered in the following year to encourage them to take this implementation seriously.

A female teacher (Ms. Chia)[2] led the two classes reported in this paper. She had four years of teaching experience at the time of the study. The two classes were academically lower-ranked compared to the other classes in the school. In many schools, students are placed in ranked classes every year. According to Ms. Chia, her two classes were quite comparable in terms of their academic rankings, but she still considered one of them to be better than the other.

The adoption of *BioLogica* genetics study to Singapore schools involved adaptive design for local circumstances (Dede 2000; Krajcik and McNeill 2006), specifically its education system. Given such a high-stakes national examination, schools provide test preparation as the center of the teaching and learning practices. Clearly, there is a tension between didactic instructional approaches to prepare students for examinations and recent calls for twenty-first century skills (e.g., Partnership for twenty-first Century Skills; http://www.p21.org/) and even Singapore governmental and institutional initiatives such as *Teach Less Learn More (TLLM)*[3] *and Teacher Education Model for the* twenty-first *Century (TE21)*[4] that emphasize approaches to foster students' deep learning, critical thinking, and creativity.

Two Designs

Our designs of adopting *BioLogica* thus involved mitigating these tensions and helping teachers embrace the conflicting demands of innovative teaching approaches and successes in high-stakes examinations. The two explored approaches were our attempts to create a "time for telling" (Schwartz and Bransford 1998) for addressing the O-level examination questions and to bridge between the local curricular requirements (e.g., acquisition of terms and knowledge) and *BioLogica*'s way of reasoning and exploring with models. The research team and teachers worked together to select modules from *BioLogica* that aligned with Singapore O-level syllabus, in order to integrate it into the biology classes. We selected a total of six units from *BioLogica*: (1) Introduction, (2) Rules, (3) Meiosis, (4) Mono Hybrid, (5) Horns Dilemma, and (6) Invisible Dragons (for descriptions of units, see Buckley et al. 2004). The two approaches involved mixing learner-centered ("exploration and reflection") and teacher-led

[1] Singapore schools have four terms in a school year, which follow the calendar year.

[2] All names mentioned in this paper are pseudonyms.

[3] Details at http://www3.moe.edu.sg/bluesky/tllm.htm.

[4] Details at http://www.nie.edu.sg/about-nie/teacher-education-21.

("consolidation") activities, where such consolidation time would be meaningful to the students after they would have gone through the CIE process using *BioLogica*.

In the first approach, the learner-centered and teacher-led activities were divided into separate sessions: Students initially use *BioLogica* for multiple units in a "stand-alone" manner by working in pairs with no direct teacher-led presentations, and then the teacher gives regular lectures on genetics for the lessons with the intent to reinforce the content the students explored in *BioLogica*. This approach was devised as an easy-to-adopt model, which any teacher who would like to use stand-alone tools as *BioLogica* can do using their existing teaching methods. We call this approach "Sequestered" design.

The second approach integrated the student-centered and teacher-led activities within a topic, involving cycles of individual and collaborative learning with the *BioLogica* model activities followed by solving structured questions (similar to questions in worksheets) and a teacher-led whole class discussion (i.e., telling). To support the second pedagogical approach, a *BioLogica* laboratory book was developed that supported cyclical process of student-centered and teacher-led activities that were intended to help learners elaborate on their explorations and solutions in a timely manner. We unpacked the existing teaching materials, analyzed the syllabus, teaching plan, and O-level learning outcomes, in order to align the content the students work on in the laboratory book treatment with the typical preparations for O-level examinations. The laboratory book approach mainly had three kinds of activities: working with *BioLogica* (exploration), questions within "dragon" genetics (exploration and reflection), and questions beyond "dragon" genetics relating to real-life examples (exploration, reflection, and consolidation).

1. Working with *BioLogica*: Students are encouraged to work in pairs to explore, explain, justify, and respond to the questions posed in the software during this activity. Students start out with orienting task descriptions, such as *Design and test creation of a baby dragon by manipulating genes according to the rule chart*.
2. Questions within "dragon" genetics: After a sizable number of nodes are explored in establishing a genetics inquiry task, students respond to additional questions based on the models they used, such as providing a representation of tasks in hand, predicating and inferring, and integrating knowledge. Questions include sample O-level examination items, building upon the understanding through *BioLogica*, such as *There are four stages in Meiosis. Please explain the purpose of each stage.*
3. Questions beyond "dragon" genetics: Each laboratory book unit ends with a small group activity to initiate reflective learning from everyday experiences. Students share their work with other students either as a presentation or as a whole group discussion with a teacher acting as a facilitator. The following example is about genetically caused disease:

> Did you realize that the dragon dies when you changed a particular allele for color? This allele is lethal. Others alleles might not be lethal, but they may cause certain disease. Can you think of any examples?

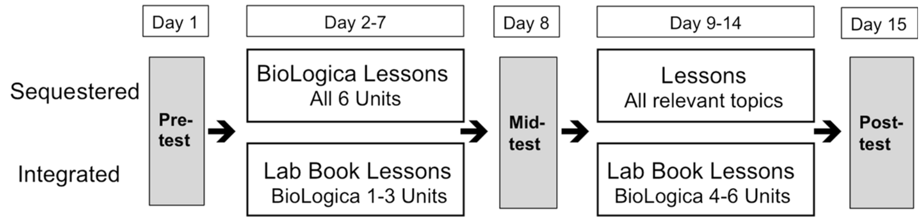
In the first two units, "Introduction" and "Rules," the group activity caters to creating a broader context for target topic learning, which may develop the resources they might need later (Gallas 1995). In the next three units, "Meiosis," "Horns dilemma," and "Monohybrid," the laboratory book focuses on specific topics that are required as part of their O-level examinations such as elaborating concepts and presenting structured questions. The group activity in the last *BioLogica* software activity, "Invisible Dragons," allows for making connections between the topics learnt and major concepts of O-level genetics topics.

Study Design

Two designs and tests were implemented over 15 days for Ms. Chia's classes. Each day, students came to biology class for double periods (40 min per single period). Figure 2 summarizes the design of this study. Even though these two classes were prepared with the same assumption that receiving minimal structure and guidance at the beginning better activates learners' cognitive efforts, there was a clear distinction between the two, which made Ms. Chia's differentiate two classes very clearly.

As seen in Fig. 2, she used more traditional and familiar lecture materials in Sequestered group during the second set of lessons. The students in this class (34 total) were asked to do all six *BioLogica* activities over the first six lessons (a shorter version of the sequence used in earlier research at the Concord Consortium) with very minimal guidance from the teacher. Six teacher-led lecture-based classes that deal with same topics followed the *BioLogica* lessons. On the other hand, she used laboratory book materials throughout the lessons for Integrated group. Students (29 total) went through the *BioLogica* plus laboratory book cycle across the 12 lessons. Students in both classes were encouraged to work in pairs for the *BioLogica* lessons.

Fig. 2 Study design



Again, both designs intended to engage learners in both model-based reasoning as well as test-specific tasks. The main difference is how such processes were sequestered or integrated within the topic. In order to answer the first research question of how two different ways of supporting learners in both model-based reasoning and test-specific tasks influence their understanding, we conducted a performance test for three times. We used the assessment items that had been tested and validated in the larger-scale research with *BioLogica* (Buckley et al. 2006, 2010; Gobert et al. 2011). The participating teachers reviewed and agreed that the items within the topic areas are consistent with the kinds of multiple-choice items that the students would encounter in the high-stakes examinations. They were developed for curricular materials of 12 genetics topics in the *BioLogica* package. Even though we chose six of 12 units in our research, we used all the assessment items (33 multiple-choice questions) for our pre-, mid-, and posttests to gain general sense of their development of genetics concepts. The 33 items were identical for all three tests, but ordered differently. We conducted a mid-test in order to investigate differences at the mid-point where one group has gone through the six target topics, whereas the other group did not.

In order to answer the second research question of how two different approaches afford different types of interactions, we collected various qualitative data. Teachers selected three student pairs in each class that would represent the varying levels of their previous biology performances (i.e., low, mid, and high levels). Process data for those students (student computer screen recordings, and video and audio recordings) were collected to understand students' learning trajectories and how different designs affect student-learning outcomes. We conducted focus group post-interviews for the target students, which asked their general impression about their experience, their perception of the change in pedagogies and working in pairs, and their understanding of models. With the participating teacher, we conducted pre- and post-implementation interviews to understand her perceptions about two groups of classes, expectation for their performances, and ideas and perceptions about teaching with technology, model-based learning, the two approaches of using *BioLogica*, and to understand any changes in her perceptions after the implementation.

Findings

Previous research studies using *BioLogica* centered on relationships among content learning, inquiry strategies, and epistemological understanding for individual learners (Buckley et al. 2006; Gobert et al. 2011). Its potential for a deeper engagement in scientific processes has motivated our project, but the main question to be addressed in our context was what can be done in Singapore secondary level classrooms where preparations for high-stakes examinations are important objectives. Ms. Chia chose to have the integrated approach with the weaker class because she saw the laboratory book as an extra resource for these students. She expressed her concerns multiple times about this particular class regarding their motivation to perform during our pre-implementation interview. In discussing them, Ms. Chia mentioned:

> Ya… look through every student, and see that… actually this student do have a conceptual problem. So that means erm… Biologica will have a lot of (challenge) for the students… Ya, (I am concerned) even with (the help of) lab book.[5]

The findings in the following concern the learning outcomes and processes associated with these two different approaches for using *BioLogica* in Singapore classrooms. The number of student participants was varied during the three tests as well as throughout the implementation since their participation was informed with consents, but voluntary.

The 32 of 34 students in the Sequestered group took all three tests, whereas the 22 out of 30 students took all three tests in the Integrated group. This participation difference also reflects with Ms. Chia's concern and expectation that students in Integrated would be less motivated to participate in the implementation. In order to be more conservative in our findings, we intended to use pretest scores as a covariate in computing repeated measures analysis of covariance (ANCOVA). To make sure that treating pretest scores as covariate affects both groups similarly, we conducted the Pearson's correlation test among the three tests

[5] We retained original transcripts with Singapore Colloquial Expressions (SCEs). SCEs often use plural verbs for singular nouns and present tense for past occurrences.

Table 1 Comparison of means and SD for pre-, mid-, and posttests

Class design	N	Pretest		Mid-test		Posttest	
		Mean	SD	Mean	SD	Mean	SD
Sequestered	32	41.95	11.52	55.59	12.66	63.48	13.53
Integrated	22	36.09	9.01	63.64	12.08	67.66	14.99

for each group. There were significant correlations among the tests for the Sequestered group, whereas the Integrated group's tests scores did not have significant correlations. We concluded that computing repeated measures analysis of variance (ANOVA) is a better treatment with our data. In Table 1, we report the means and standard deviations for pre-, mid-, and posttests for the comparison.

In conducting repeated measures ANOVA, Mauchly's test was not significant [$X^2(2) = .977$, $p = .55$], so sphericity is assumed for the main effect of two learning designs. Overall, there was a significant main effect [$F(2, 104) = 92.87$, $p = .000$, $\eta^2 = .641$[6]], which indicates a significant improvement in genetics understanding for both groups over time. There was also significant interaction between time and class [$F(2, 104) = 6.174$, $p = .003$, $\eta^2 = .106$]. This interaction implies that the patterns of the improvements are different between the two groups during the implementation, which can be seen from the pattern shown in the plot in Fig. 3.

On the other hand, no significance was found for the test of between-subject effects [$F(1, 52) = .706$, $p = .404$, $\eta^2 = .013$]. With this result, we conclude that both groups' improvements were significant, but there was no significant difference between the two groups' achievements.

The results from the 33 multiple-choice questions for two pedagogical approaches indicate that the both designs of using *BioLogica* activities (i.e., Sequestered and Integrated approaches) helped learners to gain conceptual understanding. What is notable, however, is that the teacher-identified lower-achieving class (i.e., the group with Integrated approach) performed at a statistically similar level on both mid- and posttest to the higher-achieving class (i.e., the group with Sequestered approach). During the post-implementation interview, we told Ms. Chia about the mid-test performance of the two groups before we had computed the posttest performance. She answered:

> Oh, quite surprised actually. Because, umm, for myself, I would have thought that, umm, (Integrated) class would not do so well… …Umm, in terms of for my, uh…primary analysis, I would think that (Sequestered) class should have done better. In terms of ability and the fact that there was traditional teaching… But mid assessment didn't have traditional teaching. So I want to see how that extra bit would help la.[7]

Unlike Ms. Chia's expectation, Integrated group did similarly well and even slightly better. Her account on valuing teacher's lecture (i.e., telling), however, might be an apt observation since the Integrated group had more telling and consolidation activities from early on. In the following sections, we further explore how other aspects of the two approaches looked during the implementation and what might have contributed to the lower-achieving group to perform at this level. The second author of this paper initially engaged in open coding to look for themes and patterns of interactions from each class. The first author then examined the data, and both discussed and reached the agreement on the following themes presented below.

Exploring the qualitative differences between two designs

Based on the above findings that both groups of students had significant improvements, we hypothesize that what are often deemed important in predicting the effectiveness of classroom lessons, such as students' academic ranks indicated by previous test results and coverage of content, are not sufficient. On the other hand, it is necessary to create appropriate moments for "talking" and "telling" (Schwartz and Bransford 1998). Based on how we designed two classes and how the teacher conducted the lessons, each approach had certain affordances in addition to what *BioLogica* offers as a tool for learning. Table 2 summarizes them.

In the below, we examine students' "talking" and the teacher's "telling", which may indicate how they were engaged in the process of exploration and reflection with *BioLogica* and how the Integrated approach was mediated the teacher and the designed laboratory book. We explored their interaction (audio and video) data to investigate what might have contributed to their learning and prepared them to use their knowledge and reasoning skills. Specifically, we looked for the ways in which the interaction and structure of the Integrated approach might have encouraged students' conceptual agency. According to Greeno and van de Sande (2007),

> acting with conceptual agency involves selection, adaptation, and critical judgment about the appropriateness, utility, relevance, and meaning of alternative understandings, strategies, concepts and

[6] For effect sizes, a partial $\eta^2 = .01$ is considered small, .06 medium, and .14 large.

[7] The words "la," "ah," "lah," "leh," "ohr" and "meh" are all commonly used in SCE with subtle contextual differences. They usually come at the end of a clause or statement. They do not have any significant meaning, but emphasize and conclude the speaker's statement.

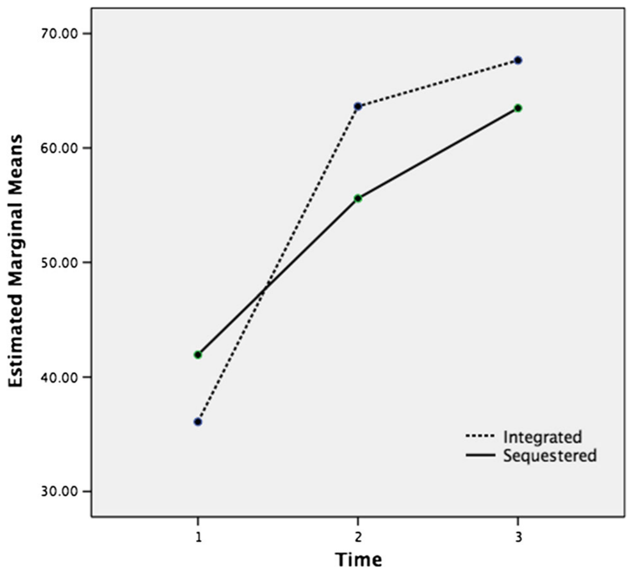


Fig. 3 Plot for the means of three tests by the class design

> methods in a domain of activity so that a positive contribution can result in choosing or adapting a method for use in solving a problem or better understanding of a problem or concept (p. 12).

When talking happens

Varying levels of discussions (i.e., talking) encouraged through the activities seem to be the important parts of their learning experience in the Integrated approach. In the following excerpt, Jian and Kent, in the class with Integrated design, were learning some rules for allele combination using *BioLogica*. They manipulated various combinations and observe the traits developed, which can sometimes cause the dragon to die. In Fig. 4, some allele combination made a male dragon die as they explored various allele combinations.

During their interaction, Jian's question on how his dragons died (turns 1–9) prompted them to explore lethal conditions of both male and female dragons (turns 10–14):

1. Jian : He die right.
2. Kent: Ya.
3. Jian : Huh, eh, really ah, he die ah?
4. Kent: Yes.
5. Jian : Just now you saw right, he die right?
6. Kent: Ya lah, walau,[8] don't ask stupid questions leh. Cannot even figure out which one died. ((Making the "wings" both small case)) It can be the same.
7. Jian : ((taps Kent's shoulder))
8. Kent: Yes?…What?
9. Jian : I don't understand. My one ((referring to his *BioLogica* model)), I think this one die already.
10. Kent: I think you change the male one…You, try to change… I can't…The female one just can't die.
11. Jian: The female died↑. Color 2.
12. Kent: My female can't…really meh. ((changes Color 2 of Chromosome X on the left to lowercase B, and his female dragon dies))
13. Jian: ((Laughs)) Told you.
14. Kent: Okay. You good one… ((flips lab book, then looks back on screen)) Color 2 small B ah? ((changes Color 2 to lowercase B of Male)) Eh. ((reads & points to screen)) Don't leave the poor dragon lying there… Bring it back to life… click here okay already. ((changes Color 2 to uppercase B, male dragon came back to life))

In turn 10, Kent did not seem to have a clear idea of the lethal conditions, but he saw that only his male dragon died. Jian, however, saw his female dragon dying when changing Color 2 of two X chromosomes (turn 11), and Kent changed the condition as well (turn 12). Kent then consolidates the lethal condition associated with Color 2 allele and easily brings the male dragon back to life (turn 14).

The associated laboratory book activity asks learners to think beyond this particular case, "*Did you realize that the dragon dies, when you changed a particular allele for color? This allele is lethal. Others alleles might not be lethal, but they may cause certain disease. Can you think of any examples?*" When Ms. Chia directs them to engage in this activity, she says, "Look, I know you did not learn this, but genetics is about application," which could indicate that students usually do not have a chance to make connections with their everyday knowledge outside of what they learn.

As Ms. Chia tried to facilitate learning of these concepts, students came up with various examples, such as sexually transmitted diseases, premature aging, albino, myopia, visionary deficiency, jaundice, Parkinson's, photographic memory, diabetes, and so forth. She gave examples of sickle-cell anemia, which is genetic abnormality resulting from gene mutation, and Down Syndrome, which is caused by the presence of an extra chromosome. For her examples, students asked questions, such as "Teacher, what happens if a guy has a lot of sickle cell genes?" and "When parents are normal, how do children get (Down Syndrome)?" Students also wrote down their ideas about mutation in the laboratory book in connection with this teacher-facilitated discussion, which, we assume, became meaningful and generative only because of their earlier explorations with *BioLogica* (Schwartz and Bransford 1998).

[8] A SCE that is typically used to convey speaker's dismay or sarcasm to the other.

Table 2 Differences between two classes

Sequestered: *BioLogica* + lecture	Integrated: *BioLogica* w/Laboratory book
Going through the content twice	Group activities and discussions
Teacher providing important content	Teacher helping tying ideas together

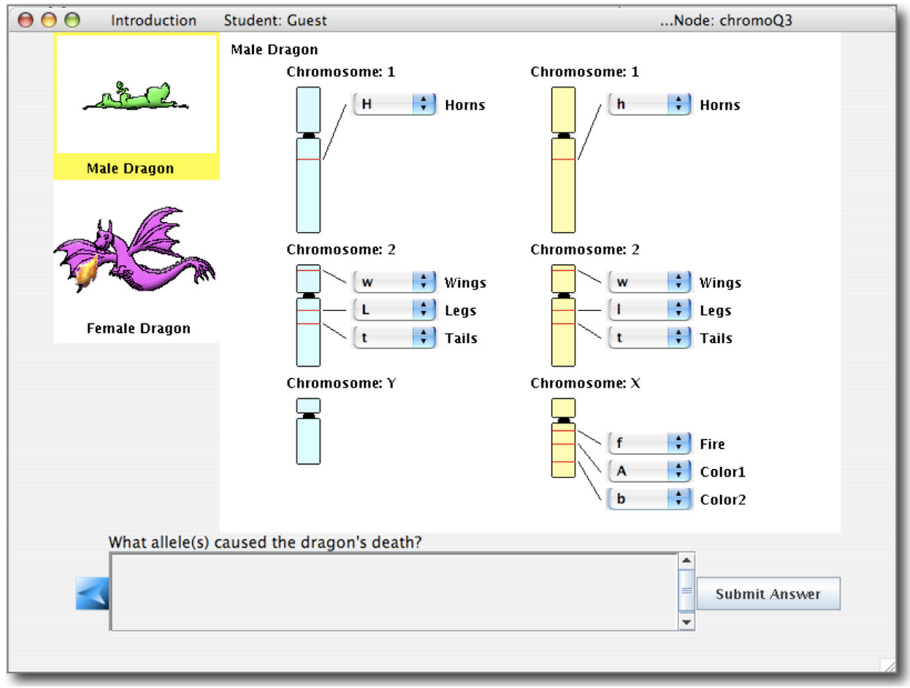


Fig. 4 Node from *BioLogica* introduction unit: male and female dragon alleles

Similar to the account of Kent and Jian above, students in the class with Integrated design spoke with each other in exploring the model, correcting each other, trying to understand representations, and clarifying concepts together (see Appendix for excerpts of Kent and Jian for examples of these interactions). On the other hand, students in the Sequestered design class mostly worked alone even though they also had partners. When we asked those students during the focus group interview on what were they talking about when they talk to each other, one of them answered:

> Uh, sometimes about the key words in the question like uh, s-some word…that are more… more scientific and we don't really understand and we ask our partner question before we ask the teacher.

It seems that the overall structure of the Integrated approach encouraged varying levels of discussions through the questions in the laboratory book and more interactions between partners and other students even during *BioLogica* activities. The conceptual agency of students beyond the understanding of definitions can be observed with students in the class with Integrated design: We could actually hear what they were talking about in our video data as they explored and tied ideas in the *BioLogica* and the laboratory book in their pair level, small group level, and the whole class level. On the other hand, we could not hear much discussion for students in the Sequestered design class, and their limited "talking" might have exhibited their disciplinary agency[9] on what is normative for classroom conversations (i.e., clarifying terms).

When telling happens

When Ms. Chia's telling was happening in the Integrated design class, it was not a lecture that helped them improve their understanding. First of all, her "telling" was focused on consolidating students' ideas based on the discussion of what they explored with their partners and other students. The time for "telling" was created in advance, so that what she was talking about was meaningful to them. In the next excerpt, students had done their very first small group activity for the question, *What are the links between the plants and animal to their DNA? DNA, Chromosomes and*

[9] "Acting with disciplinary agency involves following accepted procedures and terminology with authority vested in the discipline so that a positive contribution depends only on its correspondence with established procedures (Greeno & van de Sande, 2007, p. 12)."

Genes? Are these just different terms for the same thing? Kenneth shared his group's ideas (rather than what he found from Internet) with the rest of the class, and Ms. Chia facilitated the discussion:

15. Ms. Chia: So where does gene come in?
16. Kenneth: Genes are formed in DNA.
17. Yang: Genes are found inside DNA and genes make up DNA.
18. Ms. Chia: Anybody wants to argue against the point?
19. Yang: It's the other way.
20. Ms. Chia: Think through this, it's not look up at internet and get something. Think through… So, summarize, Kenneth. After DNA, what is the next level?
21. Kenneth: Genes make up DNA and DNA make up chromosomes.
22. Ms. Chia: So after chromosome, what come in?
23. Kenneth: Chromosomes are found in nucleus of a cell…Cell is in organism.
24. Ms. Chia: After cell is, it's true that next level is organism?
25. Kenneth: No, (it's) tissues, organs, whole body.
26. Ms. Chia: You know that from cell onward you have learned something in cell theory. That is one half of life, other portion is where DNA comes in… this is what I meant, class. From DNA to organism, because without clear understanding of terms, we all feel that DNA is chromosome.

In this excerpt, students were certainly encouraged and respected for their ideas. In turn 18, Ms. Chia invites other students to provide different points instead of directly providing the connection with cell theory. In turn 20, she stresses on students' own ideas as opposed to what they can reproduce from information on the Internet. She also encourages elaboration from the students themselves (turn 23–25). In the class with Sequestered design, however, teacher's consolidation activity was not present in combination with *BioLogica*. Students, therefore, individually focused on each unit in each period and depended on definitional information in *BioLogica* (e.g., many wrote down notes from the screen as they would normally do from their teacher's lectures in regular lessons).

Transforming the culture of talking and telling

What we see by examining learners' processes and their interviews is that the culture and quality of classroom interaction might indeed strongly impact their learning (Barron 2003). The idea of talking and telling for the students in the Integrated approach seemed to be changing as well as how the teacher perceives it.

Culture of "talking"

Having a safe environment to talk about their own ideas and share their work without fear of losing face or ideas being stolen can be difficult in competitive settings. Classrooms can be one of those among high-achieving students preparing for high-stakes tests. When conversing about the high achievers in the school during the post-interview, Ms. Chia commented on their talking culture:

> They are very, they are so competitive, they don't trust their friends. Very very different. High end achievers, high end achievers are…[Interviewer: They can only trust their teachers?] Because they are so competitive, if I get something more from the teacher, I win. I must win my friend. That's how they work… Very different.

In our study, culture of talking about their ideas was starting to build in the class with Integrated design. In their mind, talking in class was not allowed, so when we used the word "talk" some were thinking of chatting off the learning topic (turn 28):

27. Interviewer: so did you feel that you talked more, or less when you were using the software, compared to a traditional class? Were you talking to neighbor? Asking questions? …
28. Charles: Hmm, talked more in class, "cause actually teaching is like so boring to me. Uh," cause just keep staring at the teacher.

On the other hand, exploring and interacting with *BioLogica* as a pair encouraged them to talk about what was happening with the dragons, and questions in the laboratory book challenged them to think deeper with their partners. Kenneth in the Integrated approach class admitted that he would not have talked to his partner if the tasks were easy enough to solve by himself:

> I think it's ah… very much in our culture that we do not discuss much, so um… it's probably nothing to do with the lab book, it's just that you know… it… we're not used to discussing stuff… So… if the question allows us… to… answer, if it… if it allows us to answer the questions ourselves, we would… we would have… done it ourselves rather than to discuss it with our partners than… than to do the thing.

Kenneth's comments might indicate that the questions in the laboratory book that go beyond the immediate concepts they went through in *BioLogica* made them "talk" about their ideas. The laboratory book instruction also tells them to discuss with their partners, which in return might have built their habit of discussing with their partners about their ideas in other parts of activities.

Culture of "telling"

The students in the Integrated approach class valued the teacher as the main person who clarifies their misunderstanding (turn 40–41), but some of them, especially Kenneth, started to think that such "telling" should also come from themselves (turn 31 and 33). Wayne and Andy, however, expressed that such activities are obviously not part of their classroom culture (turn 34 and 36).

29. Interviewer 1: You said, the answer should be clarified, what you're thinking is correct or not. So, did it happen in the class?
30. Daniel: Yeah, the teacher did um… correct us if anything… if… we… presented if anything…
31. Kenneth: But other students didn't correct them. There was no counter point from other students, you see.
32. Andy: So yeah, they had the same idea.
33. Kenneth: So the teacher was able to clarify other students. So… um… it is… it is… I think it will be beneficial to the students if they're actually willing to share their answers. I think many students for our…not willing to share the answers, but if they were willing to share their answers, it would have been… very beneficial.
34. Wayne: It's not that they are unwilling to share the answers, they are too shy to share their answers.
35. Interviewer 2: Now, is this something that you… commonly do… in a regular class?
36. Andy: No. Sit and listen to teacher ((laughs)).

How students and teachers perceive their roles in the classroom learning thus began to change in the class with the Integrated approach. After the initial lesson and conversations with us, Ms. Chia stressed on students' conceptual agency, helping them placing each other as part of the questions, and assuming herself as more in the guidance role:

> Let's move to activity part 2 page 13 answer first column, do these organisms contain gene, next column, do they contain chromosomes? Find relevant information on internet, at the same time start looking at part three activity: discuss with your partner why living things look this way… **why Daniel look like Daniel?** Is there any reason for this? How to answer this question? Use whatever information you know from part 1 and part 2 to answer this question, part 3 is **more about your own thoughts, coming out with your own construction.** Any question, check with us. **We will guide you along your way.**

What we are seeing here is a potential of changing the culture of the classroom where students' ideas and voices are appreciated while their conceptual understanding is developed. There were collaborative interactions and exchange of ideas among students in the classroom, and the teacher and the students themselves were experiencing working with students' ideas for learning.

Discussion

The findings in this paper reaffirm that adopting innovations using low-to-high structures approaches (i.e., from exploration and reflection to consolidation) are effective in their understanding, consistent with the recent findings (Jacobson et al. 2013; Pathak et al. 2011; Kapur 2010; Kapur and Bielacyzc 2012). There still remains a big challenge of conflicting ideals of "educating" versus "training" students for the high-stakes examinations. Indeed, one of the students in our focus group interview (Sequestered approach) articulated this dilemma. They told the interviewer that they like using *BioLogica* because of being able to think independently, but prefer traditional teaching because a teacher would better prepare them for the O-level examination. The teachers certainly have high confidence in the existing lesson materials, which had been very effective in preparing students for examinations. Our findings suggest that an opportunity for thinking independently would not compromise their performance in high-stakes examinations.

Our findings also illustrate that the different ways of providing low-to-high guidance structures, though both of them are effective, afforded interactions that the lower-achieving group (Integrated approach) could perform at a similar level as the higher-achieving group (Sequestered approach). Students in the Integrated approach class were engaged in the cycles of activities, including small discussions with their partners, sharing their ideas, and participating in the teacher's consolidation of ideas, which were tightly connected with the six *BioLogica* units. Their interactions described above provide some important discussion that the authors raised earlier. First, the students' "talking" practices might be relevant to what we termed as "zone of proximal failure" (ZPF) (Jacobson et al. 2013, p.13) when Kenneth discussed how their lack of talking culture and easier questions might prevent them from exploring and reflecting together with their partners. Second, we had also pointed out that the durations of the low structure and the high structure might matter in creating appropriate moments for teachers' telling (Jacobson et al. 2013). Our findings indicate that multiple cycles of short durations might be more effective than one cycle of longer duration low–to-high structure activities. At the same time, the "telling" that is temporally detached from the "talking" of conceptual exploration and reflection, may not be as productive as those that happen closely together. In our case, however, we did not design two approaches to test the granularity of same activities and their durations, which calls further investigations in relation to the nature of content and types of activities.

In our findings, we used the lay terms of "talking" and "telling" that do not necessarily explain their learning and cognitive activities. We used these terms not only to adopt the ideas put forward by Schwartz and Bransford (1998) but also to represent what is being valued in the Singapore Secondary classroom (i.e., teacher's telling). The ways we think about and do talking and telling seemed to be very important in student learning in addition to other design decisions. Highlighting their "talking" activities has two folds: Talking among students is not academically valued in school, whereas students were able to push their thinking when it happened during these implementations. We do not intend to undermine the value of personal exploration and reflection, but to highlight the value of "talking". Talking in the classroom is important when it comes to students' ideas. These "talking" interactions are where reflective thinking happens among students, through which their verbally expressed thoughts are treated as "ideas" to be further discussed and tied together rather than something that should be corrected by the teacher. Secondly, the exploration with computer-based models becomes more meaningful when "talking" can be expanded to their ideas outside of the textbook contents. When providing or allowing students to situate the concepts in contexts of their everyday lives, they can explore and reflect with more conceptual agency, which makes particular concepts in discussion their own rather than those of textbook.

Highlighting "telling" activities also provide multiple implications. Teacher's telling is highly valued in schools, and their telling activities can become much more productive when succeeding students' own exploration and reflection. The teacher's role as a facilitator becomes very critical for informal "telling" activities where she or he consolidates ideas from students to advance their thinking, not to mention the performance improvement for high-stakes examinations. Teachers' roles in elaboration and integration are identified as features for deep level approaches (Chin and Osbrone 2008), but not well practiced in science classrooms. Students' own exploration is very critical in model-based learning approach in the science classroom, but it should not be adopted at the expense of teacher's time for telling and consolidation activities. The findings from our study reaffirm the importance of a teacher's role in the classroom, but differently from the initial perceptions of students and the teacher (i.e., explaining contents well and correcting their misconceptions).

Conclusion

Adopting and experimenting with new approaches in any classroom can be a difficult task for both researchers and practitioners. The effort to adopt a new approach, such as model-based learning in science, often accompanies calculating its risks. For example, teachers and schools may try new methods and technologies with grades without impending high-stakes examinations and outside of curriculum time. Having more dedicated time for a particular science topic is not a common practice in any school accountable for students' high-stakes examination results, and the existing culture of talking and telling in the classroom cannot easily be transformed in a short time when there exists a prevalent practice for examination preparation. Our findings underscore that a learning technology may be implemented in ways that still have overall effective learning of difficult content. At the same time, the students perceived as academically less competent were able to develop their understanding at a similar level in comparison with the students perceived as "stronger" when we used two different approaches. Based on our research, both approaches (Sequestered and Integrated) were effective in supporting students' test performances by creating appropriate time for the teacher's "telling." On the other hand, students' time for "talking" and collaborative learning enabled by the Integrated approach seemed to contribute to the students' understanding at a higher level than expected. It is often the case that we focus on the value of computer-based models and model-based reasoning in working with teachers for classroom-based research, which should be expanded to the value of above-mentioned important aspects of "talking" and "telling." Learning scientists might be guilty of presenting the "ideal" of how people can learn science better rather than working out practical solutions with teachers. We hope that our research presented here would encourage schools' use of models and modeling in various levels of schooling in Singapore and other places where high-stakes examinations are important life events.

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Appendix

See Table 3.

Table 3 Excerpts from students' class interactions with the integrated approach

Excerpts	
Correcting each other	Jian: Chromosome
	Kent: ((Reading from screen)) Opps you clicked a gene. Orh…
	Jian: The chromosome ↑.
	Kent: Orh, click the chromosome…Orh…
	Jian: ((Reading from screen)) Wing genes…
	Kent: So easy eh.
	Jian: ((Yawns)) Yaa…
	Kent: Do you understand this? ((in mixture of Chinese and English))
	Jian: () actually, got connection () black () connection la.
	Kent: For male dragon it's small H then no horn right.
	Jian: …ya.
	Kent: Then female it's big H and small H. Small H and big H ah.
Trying to understand representations	Kent: You try to do the (male dragon) and male dragon.
	Jian: This one don't know if it's male or not.
	Jian: Anyway this thing right, you no need to know, just need () same thing la. You need to take out horn, then it's the connection right, this place. Then it's just one line () Yellow patch la…blue patch la…() Then the black line in between is the…the black dot la.
	Kent: Don't understand.
	Jian: Why? Very simple what, this one. ((Mouse cursor circles around first pair of Chromosome 1))
	Kent: Oh…right. That means, compare this one with this one la.
	Jian: Only that the…the line of the chromosome and then the patch right, is this one
	Kent: I thought the line is the gene.
	Jian: What line?
	Kent: I thought this line is the gene.
	Jian: No, no () this line…is the black ()
	Kent: Orh..Okk.
	Jian: Matching ()
	Kent: Let me take a look first. This is very difficult…
	Jian: This is about the chromosome.
	Kent: ((clicking back and forth between "Another View of Chromosomes" and "Sex Determination")) This is so easy, this patch doesn't have, because doesn't have this () This is so easy, yet I do not know it.
Excerpts	
Clarifying concepts together	Kent: ((reads question from screen)) Incomplete…incompletely. That means what? The recessive allele and dominant allele does not control the trait.
	Jian: No. [Kent: Then?] It means that all the combinations…ah…can produce…ah… Three traits.
	Kent: That means the recessive and, and dominant alleles can, can produce three traits.
	Jian: Ya…() can produce three traits. Because there is three right, No one of them is ()
	Kent: Orh…that means all of them are heterozygous la
	Jian: No la.
	Kent: It is la, look. ((Refers to workbook book and jabs hard at it)) Heterozygous is two different leh… Then this is…
	Jian: (Actually) dominant means you can produce three traits. It means all the different combinations right,… Take for example this. ((points to explains an example in workbook)) there is()
	Kent: hmmm
	Jian: Then that means right…Dominant means right, got one is main… But when there's three right, none of them is main.
	Kent: Oh…

References

Barab SA, Hay KE, Yamagata-Lynch LC (2001) Constructing networks of action-relevant episodes: an in situ research methodology. J Learn Sci 10(1):63–112

Barron B (2003) When smart groups fail. J Learn Sci 12(3):307–359

Bransford JD, Brown AL, Cocking RR, Donovan S (eds) (2000) How people learn: brain, mind, experience, and school, expanded edn. National Academy Press, Washington, DC

Brown JS, Collins A, Duguid P (1989) Situated cognition and the culture of learning. Educ Res 18(1):32–42

Buckley BC, Gobert JD, Kindfield ACH, Horwitz P, Tinker RF, Gerlits B, Willett J (2004) Model-based teaching and learning with BioLogica™: what do they learn? How do they learn? How do we know? J Sci Educ Technol 13(1):23–41. doi:10.1023/B:JOST.0000019636.06814.e3

Buckley BC, Gobert JD, Horwitz P (2006) Using log files to track students' model-based inquiry. Proceedings of the seventh international conference of the learning sciences (ICLS). Erlbaum, Mawah, pp 57–63

Buckley BC, Gobert JD, Horwitz P, O'Dwyer LM (2010) Looking inside the black box: assessing model-based learning and inquiry in *BioLogica*™. Int J Learn Technol 5(2):166–190

Chin C, Osborne J (2008) Students' questions: a potential resource for teaching and learning science. Stud Sci Educ 44(1):1–39. doi:10.1080/03057260701828101

Clement J (1989) Learning via model construction and criticism: protocal evidence on sources of creativity in science. In: Glover G, Ronntng R, Reynolds C (eds) Handbook of creativity: assessment, theory and research. Plenum, New York, pp 341–381

Clement J (2000) Model based learning as a key research area for science education. Int J Sci Educ 22(9):1041–1053

Dede C (2000) Emerging influences of information technology on school curriculum. J Curric Stud 32(2):281–303

Edelson DC, Gordin DN, Pea RD (1999) Addressing the challenges of inquiry-based learning through technology and curriculum design. J Learn Sci 8(3–4):391–450

Gallas K (1995) Talking their way into science: hearing children's questions and theories responding with curricula. Teachers College Press, New York

Gobert JD (2000) A typology of causal models for plate tectonics: inferential power and barriers to understanding. Int J Sci Educ 22(9):937–977

Gobert JD, Buckley BC (2000) Special issue: introduction to model based teaching and learning in science education. Int J Sci Educ 22(9):891–894

Gobert JD, Pallant A (2004) Fostering students' epistemologies of models via authentic model-based tasks. J Sci Educ Technol 13(1):7–22

Gobert JD, Buckley B, Clarke CE (2004) Scaffolding model based reasoning: representations, cognitive affordances and learning outcomes. Paper presented at the 2004 annual meeting of American Educational Research Association, San Diego, CA

Gobert JD, O'Dwyer L, Horwitz P, Buckley BC, Levy ST, Wilensky U (2011) Examining the relationship between students' understanding of the nature of models and conceptual learning in biology, physics, and chemistry. Int J Sci Educ 33(5):653–684

Greeno JG, van de Sande C (2007) Perspectival understanding of conceptions and conceptual growth in interaction. Educ Psychol 42(1):9–23. doi:10.1080/00461520709336915

Horwitz P, Burke E (2002) Technological advances in the development of the hypermodel. Paper presented at the Annual meeting of the American Educational Research Association, New Orleans, Louisiana

Horwitz P, Christie MA (2000) Computer-based manipulatives for teaching scientific reasoning: an example. In: Jacobson MJ, Kozma RB (eds) Innovations in science and mathematics education: advanced designs for technologies of learning. Lawrence Erlbaum Associates, Mahwah, pp 163–191

Horwitz P, Gobert JD (2000) Fostering transfer from open-ended exploration to scientific reasoning (NSF-REC# 0087579). Grant awarded by National Science Foundation

Horwitz P, Gobert JD, Buckley BC (2009) Learning genetics from dragons: computer-based manipulatives to hypermodels. In: Jacobson MJ, Reimann P (eds) Designs for learning environments of the future: international perspectives from the learning sciences. Springer, New York, pp 61–88

Ingham AM, Gilbert JK (1991) The use of analogue models by students of chemistry at higher education level. Int J Sci Educ 13(2):193–202

Jacobson MJ, Kim B, Pathak SA, Zhang B (2013) To guide or not to guide: issues in the sequencing of pedagogical structure in computational model-based learning. Interact Learn Environ. doi:10.1080/10494820.2013.792845

Kapur M (2010) A further study of productive failure in mathematical problem solving: unpacking the design components. Instr Sci 39(4):561–579. doi:10.1007/s11251-010-9144-3

Kapur M, Bielaczyc K (2012) Designing for productive failure. J Learn Sci 21(1):45–83. doi:10.1080/10508406.2011.591717

Kim B, Hay KE (2005) The evolution of the intellectual partnership with a cognitive tool in inquiry-based astronomy laboratory. In: Koschmann T, Suthers DD, Chan T (eds) Computer supported collaborative learning 2005: the next 10 years!. Lawrence Erlbaum, Mahwah, pp 281–290

Kozma RB (2000) The use of multiple representations and the social construction of understanding in chemistry. In: Jacobson MJ, Kozma RB (eds) Innovations in science and mathematics education: advanced designs for technologies of learning. Lawrence Erlbaum Associates, Mahwah, pp 1–46

Krajcik JS, McNeill KL (2006, 16 March 2008). A learning goals driven design model for developing science curriculum. http://www.hice.org/iqwst/Papers/Krajcik_McNeil_Reise_AERA06.pdf

Krajcik J, Blumenfeld PC, Marx RW, Bass KM, Fredericks J, Soloway E (1998) Inquiry in project-based science classrooms: initial attempts by middle school students. J Learn Sci 7(3–4):313–350

Latour B (1987) Science in action: how to follow scientists and engineers through society. Harvard University Press, Cambridge

Lehrer R, Schauble L (2000) The development of model-based reasoning. J Appl Dev Psychol 21(1):39–48

Loh B, Reiser BJ, Radinsky J, Edelson DC, Gomez LM, Marshall S (2001) Developing reflective inquiry practices: a case study of software, the teacher, and students. In: Crowley K, Schunn CD, Okada T (eds) Designing for science: implications from everyday, classroom, and professional settings. Lawrence Erlbaum, Mahwah, pp 279–323

Pathak SA, Kim B, Jacobson MJ, Zhang B (2011) Learning the physics of electricity: a qualitative analysis of collaborative processes involved in productive failure. Int J Comput Support Collab Learn 6(1):57–73. doi:10.1007/s11412-010-9099-z

Penner DE (2001) Cognition, computers, and synthetic science: building knowledge and meaning through modeling. Rev Res Educ 25:1–36

Schwartz DL, Bransford JD (1998) A time for telling. Cogn Instr 16(4):475–522. http://www.jstor.org/stable/3233709

Sengupta P, Wilensky U (2011) Lowering the learning threshold: multi-agent-based models and learning electricity. In MS Khine, IM Saleh (eds.), Models and modeling: cognitive tools for scientific enquiry (pp. 141–171). Dordrecht: Springer

Netherlands. http://www.springerlink.com/index/10.1007/978-94-007-0449-7_7

Stewart AD, Hunt DM (1982) The gentic basis of development. Blackie Academic and Professional, London

Tinker R, Horwitz P (2000) Modeling across the curriculum (IERI Planning Grant No. REC-0089198). National Science Foundation

Tsui CY, Treagust DF (2007) Understanding genetics: analysis of secondary students' conceptual status. J Res Sci Teach 44(2):205

White BY, Frederiksen JR (2000) Technological tools and instructional approaches for making scientific inquiry accessible to all. In: Jacobson MJ, Kozma RB (eds) Innovations in science and mathematics education: advanced designs for technologies of learning. Lawrence Erlbaum Associates, Mahwah, pp 321–360

Wilensky U, Reisman K (2006) Thinking like a wolf, a sheep or a firefly: learning biology through constructing and testing computational theories—an embodied modeling approach. Cogn Instr 24(2):171–209

Zhang BH, Liu X, Krajcik JS (2006) Expert models and modeling processes associated with a computer modeling tool. Sci Educ 90(4):579–604