Impacts on Student Understanding of Scientific Practices and Crosscutting Themes through an NGSS–Designed Computer-Supported Curriculum and Instruction Project

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Abstract: This paper presents a curriculum intervention intentionally designed to align with *Next Generation Science Standards* in the high-school biology classroom. The project emphasizes learning about complex systems through an agent-based modeling tool called StarLogo Nova. Five curricular units have been developed on the topics of enzymes, ecology, protein synthesis, gene regulation, and sugar transport. In this exploratory study we were interested in understanding the extent to which students demonstrated understanding and skills in NGSS areas as they were designed. Evidence is gleaned from classroom observations and interviews with 50 students selected from the larger population of 352 students who worked with project resources during the 2013-2014 school year. Findings revealed that students demonstrated understanding and skills in all NGSS scientific practices and crosscutting themes particularly in the areas of developing and using models, analyzing and interpreting data, cause and effect, and systems and system models.

Keywords: education, learning outcomes, science education, simulations

Introduction

The release of the *Next Generation Science Standards* (NGSS) in the US has required a shift in understanding and doing science in the classroom. There is a greater focus than ever before on problem-solving, applying knowledge, argumentation, systems thinking, and constructing models, to name a few differences from previous science education standards. This new vision of science education is instantiated in scientific practices and crosscutting themes that permeate domain-specific content and requires new pedagogical approaches, curricula, and resources. As we begin to translate the NGSS into classroom practice, we need to articulate and explore activities that adequately address the standards with fidelity to their original intent (Bybee, 2013; NRC, 2014a; NRC, 2014b). In this paper, we highlight a curriculum and instruction project that was constructed to tightly align with the NGSS. Through the central learning goal of developing complex systems understanding in high school biology, the project team has developed five units in the content areas of enzymes, ecology, protein synthesis, gene regulation, and sugar transport. The project is anchored in activities delivered through computer simulations constructed in *StarLogo Nova*–an agent-based modeling program with a 3D game-like interface. The curriculum includes student packets and teacher guides that support teaching and learning about biological systems through, among other things, modeling, argumentation, mathematical and computational thinking, and collaboration.

We have worked extensively with teachers in professional development (PD) activities and have piloted project resources in classrooms over the last two years. Thus, we are aware that myriad variables can impact the success of a new intervention. For example, Wilson (2013) states that helping teachers acquire this new set of pedagogical tools to teach using the NGSS is a challenging task. Through research on fidelity of implementation of science education interventions, we also know that criteria such as adherence to the intervention's design, and quality of delivery can significantly impact student-learning outcomes (Lee et al., 2009). We have written about our experiences with teachers (Yoon et al., accepted) and implementation variables (Yoon et al., 2013) elsewhere. Here our major goal was to conduct an exploratory study to determine the extent to which students in our project demonstrated knowledge of and skills in the NGSS scientific practices and crosscutting themes. A secondary goal was to identify those practices and themes that were most frequently shown by students thereby locating particular strengths of the project activities and resources. Below we describe the curriculum and instruction framework that underpins all project activities and provide a sample of the curriculum that highlights its alignment with NGSS standards.

Research on the next generation science standards

Developing curricular materials and pedagogical tools for NGSS is an important next step in implementing these reforms. Currently, two of the primary challenges facing implementation of NGSS are developing curriculum materials and instructional strategies that successfully instantiate them (Bybee, 2013). Despite significant standards reform, "much science and mathematics teaching still emphasizes rote skills and memorization" (NRC, 2014b, p. 136). While there are curricular developments intended to support NGSS learning, they are developed at the state level and different standards are favored or deemphasized depending on local preferences (NRC, 2014a). None adequately address the entire range of new skills outlined in the NGSS (Penuel et al., 2014), though most promising among these are project-based curricula, such as the Project Based Inquiry Science (PBIS) units funded by NSF, that combine scientific knowledge with constructing arguments and using models (Harris et al., 2014; Penuel et al., 2014). Our project activities were designed around a curriculum and instruction (C&I) Framework based on the NGSS that includes the same promising characteristics of PBIS.

Curriculum and instruction framework (C&I)

The C&I framework is divided into four categories that are aligned with NGSS in addition to the literature on needs and best practices for STEM teaching and learning (Figure 1). The first category is *Curricular Relevance,* which focuses on developing 21st century competencies (NRC, 2012), ensuring standards alignment (Desimone, 2009), and collaboration with teachers to promote teacher ownership (Ertmer et al., 2012, Mueller, 2008; Thompson et al., 2013). The second category, *Cognitively-Rich Pedagogies*, involves pedagogies that address situated needs in individual classrooms (Penuel et al., 2011), social construction of knowledge through collaboration and argumentation (Osborne, 2010), and constructionist learning by constructing models (Kafai, 2006). The third category, *Tools for Teaching and Learning*, builds knowledge through computational modeling tools (Epstein, 2008), teacher guides and student packets that provide scaffolds for learning with technology (Quintana et al., 2004), and off-computer participatory simulations to support students' understanding of modeling and complex systems (Colella et al., 2000). The fourth category, *Content Expertise*, builds deeper content understanding in complex systems (Author, 2008), biology (Lewis & Wood-Robinson, 2000), and computational thinking (NRC, 2010).

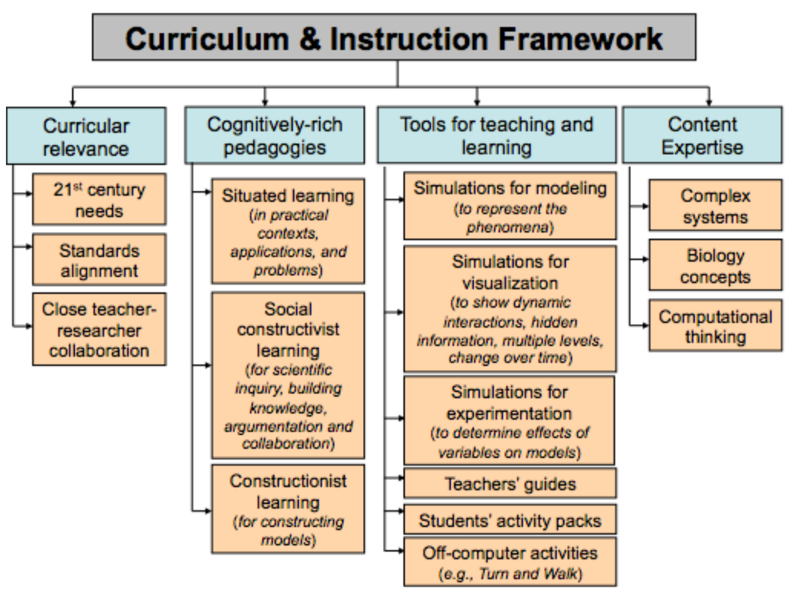
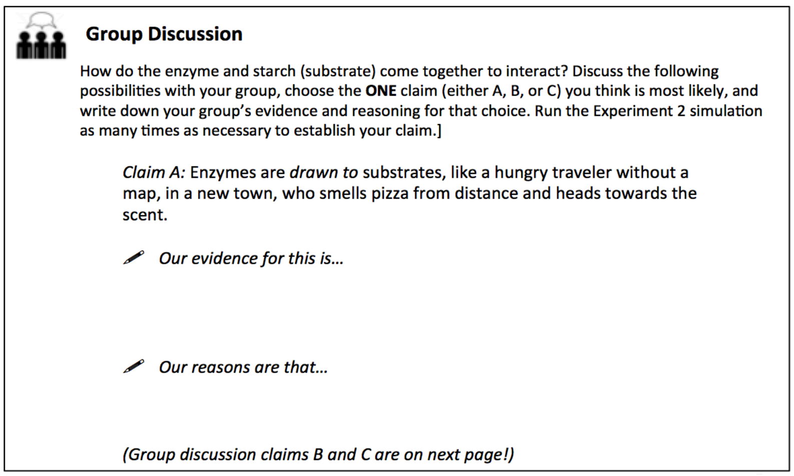


Figure 1. Teaching and learning about complex systems C&I framework

To better understand how the C&I framework informed the construction of the curricular units, we briefly describe an activity in the enzyme unit *Chew on This!* In this activity students are asked to explore the break down of starch into sugar that begins in your mouth and is completed in the small intestine. The simulation enables students to compare and contrast the conversion of starch to sugar both with and without enzymes. The aim is to help students understand the role of enzymes in digestion. Students conduct various experiments and are asked to plot the results and share their data with others in the class. Students can take as much or as little time as they would like to observe the behavior of starch. Along the way students are asked to pick among several claims and in groups come to consensus on the evidence and reasoning used to support the claim to help them understand various aspects of the science. Figure 2 shows an excerpt from the student activity packet. Here students are asked to observe and consider the random movement of enzymes in the system. Figure 3 shows a snapshot of the simulation with a sample student's graph constructed with data collected while interacting with the simulation, which is a representative task students complete in these units.



Group Discussion

How do the enzyme and starch (substrate) come together to interact? Discuss the following possibilities with your group, choose the **ONE** claim (either A, B, or C) you think is most likely, and write down your group's evidence and reasoning for that choice. Run the Experiment 2 simulation as many times as necessary to establish your claim.]

Claim A: Enzymes are *drawn to* substrates, like a hungry traveler without a map, in a new town, who smells pizza from distance and heads towards the scent.

Our evidence for this is…

Our reasons are that…

(Group discussion claims B and C are on next page!)

Figure 2 Excerpt from student packet showing directions to use an argumentation process

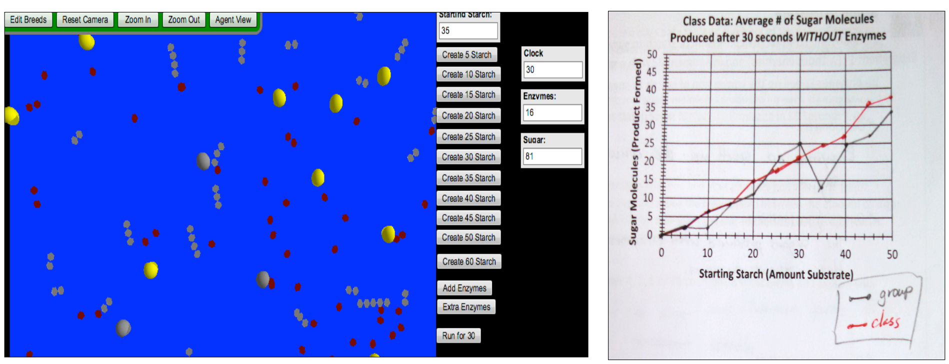


Figure 3. Simulation of *Chew on this!* and student graph of system variable change over time

Methods

Context and participants

To address our research goals, we conducted observations and interviews with students in 2 participating schools comprised of 5 classrooms in the greater Boston area, during the 2013-2014 school year. In school A, in terms of selected demographic and academic variables, 59% of students were on free or reduced priced lunch, 68% identified as non-white, and 61% scored at or above proficient on the state standardized science exam. In school B, 34% of students were on free or reduced price lunch, 38% identified as non-white, and 70% scored at or above proficient on the state standardized science exam. In the subsample of the larger study population, 56 students in groups of two were randomly selected to be video taped interacting with the simulation and activity packet for the unit *Chew on This!*. We also conducted 3 focus group interviews with 13 randomly selected students to understand in more detail the learning benefits accrued through interaction with project activities.

Data sources and analysis

A total of 14 hours of video footage was captured of students participating in this unit. Video cameras were specifically focused on groups of students while they engaged with the simulation. The second data source came from student focus group interviews, which were conducted at the end of each classroom observation with 3 or 5 students.

Table 1: *NGSS* coding framework and examples

NGSS Primary Categories	Subdomain Descriptions	Examples Within BioGraph Context
Science and Engineering Practices	**Developing and using models**: using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds	Yeah, I didn't know if they sought out all the time or if they were just moving randomly most of the time. So I tried I think it was like 20 starches and then I added like 10 enzymes. I thought because it was 10 and 20 that it would come out like that, but it didn't. It came out to totally different numbers and that just made me understand how no matter the number, you can always have different outcomes. (ID 5, Focus Group, 11/21/2013)
	Planning and carrying out investigations: investigations that provide evidence for and test conceptual, mathematical, physical, and empirical models.	I think since we had the control over how many starches and how many enzymes we wanted to add helped a lot because I think by five intervals and everything like that, but you could change it manually to whatever number you wanted. So I think having the control over it helped a lot because then if we were unclear on something we could… Like if a greater number of starches versus a smaller number of enzymes and vice versa, we could see how it interacted and how it changed. (ID 5, Focus Group, 11/21/2013)
Crosscutting Concepts	**Cause and effect**: empirical evidence is required to differentiate between cause and correlation and to make claims about specific causes and effects. They suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about smaller scale mechanisms within the system. They recognize changes in systems may have various causes that may not have equal effects.	And then even though this was with starch specifically, it also taught me how enzymes are really important in the human body and everything like that because without them you wouldn't be able to break down food. And if you couldn't break down food you would have a serious problem and you'd get sick and you would gain weight. So it helped me understand how enzymes really have a big impact on the digestive system and everything like that. (ID 5, Focus Group, 11/21/2013)
	Systems and system models: investigate or analyze a system by defining its boundaries and initial conditions, as well as its inputs and outputs. They can use models (e.g., physical, mathematical, computer models) to simulate the flow of energy, matter, and interactions within and between systems at different scales. They can also use models and simulations to predict the behavior of a system, and recognize that these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models. They can also design systems to do specific tasks.	Couldn't it partially be complex systems because it shows how the enzymes decide what, if they're going in any sort of pattern to find the starch. Whether they're following them or just bumping into them randomly. They're just traveling around. Kind of being like a random complex system. (ID 3, Focus Group, 10/17/2013)

The interview protocol was comprised of 5 semi-structured questions that explored students' perceptions of the pedagogy, what they learned in terms of biology and complex systems, and what they thought about the use of computational tools to support their learning. The interviews lasted for 25 minutes on average.

Both data sources were coded according to a framework directly adapted from the NGSS to assess student learning. A categorization manual was constructed using descriptions of the 8 scientific practices and the 7 cross cutting themes (NRC Framework, 2012, p. 30). The videos were coded using the method of Interactional Analysis (IA) which involves collaborative analysis of video and/or audio clips by a group of researchers to examine the details of social interaction (Jordan & Henderson, 1995). The basic goal of IA methodology is to use video and/or audio data to understand what people are doing during their social and discourse interactions and if, how, and what people are learning. The collaborative investigation avoids the preconceived notions of a single researcher. The IA constituted of over 30 hours of collective coding between three project researchers. Transcripts of focus group interviews were coded for the frequency of utterances indicating learning of each specified NGSS category. The first 20% of data was coded independently by four project researches until internal reliability was satisfactory ($\alpha = 0.78$). An individual researcher then coded the remainder of the focus group interviews. A full version of the categorization manual cannot be accommodated in this paper format however Table 1 shows a selection of several scientific practices and crosscutting themes with codes and examples from the student data.

Results

Results from the video data and focus group analysis indicate that students demonstrated understanding and skills in nearly every NGSS category. As expected, some topics were more prominent than others. We discuss salient findings below.

Video data observations

Figure 4 shows the distribution of video observation data. Out of 390 coded utterances, 76 referred to analyzing and interpreting data. The second most frequent Science and Engineering Practice observed in the video data was developing and using models with 70 utterances. From the Cross Cutting Concepts, cause and effect had the greatest number of utterances with 43.

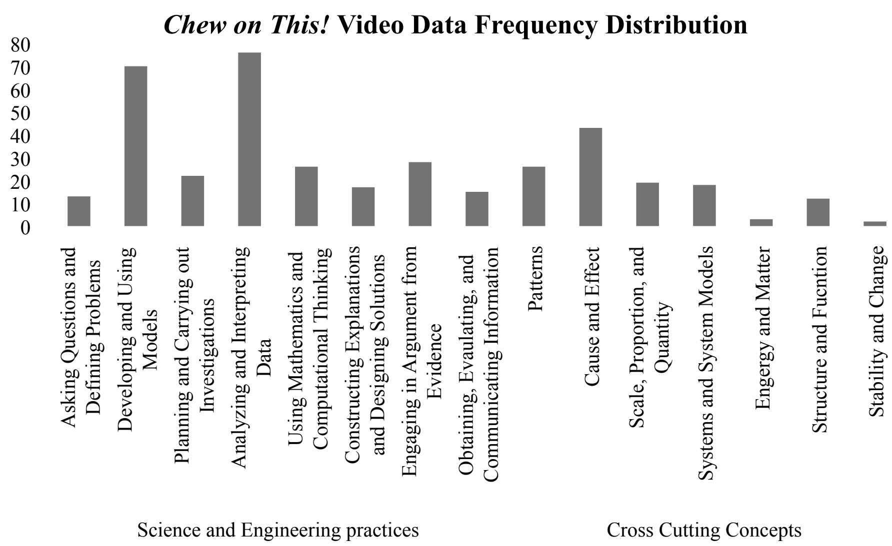


Figure 4. Video observations of *Chew on This!* frequency distribution of NGSS codes

As evidence of student learning, the following example includes the discourse between a group of students answering a multiple-choice question in the student packet after running several experiments and collecting data on how much sugar formed over time. The question states: "Based on the experiments just run *without* enzymes, the graph of the amount of sugar produced vs. starting amount of starch looks most like?"

Figure 5 below provides an illustration of the four answer choices followed by the corresponding student discourse.

In this example, there is evidence that students were learning a number of NGSS skills. Here the students were analyzing and interpreting their data (numbers of sugar and starch molecules over time) obtained from using the model to determine which graph best represented the rate of change from starch to sugar. Since their data was numerical and the question involved understanding graphical representations, this is also evidence they were using mathematics and computational thinking. Initially S1 described her data (line 1) and others corroborated the results (lines 2-3). They then began analyzing the data to link their numbers to the appropriate graph (line 4). The answer was not immediately apparent and they continued this discussion and analysis of their numbers (lines 5-8). The entire discussion is also evidence that the students were communicating their findings and engaging in argument using their data to support their answer choice.

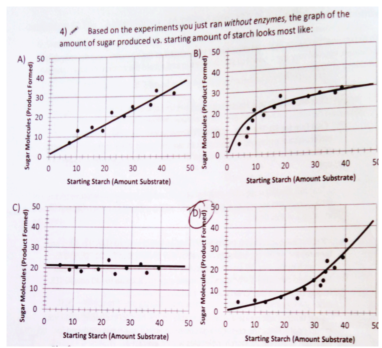


Figure 5. Graphs from student packets

Excerpt from ID 2, Video Data, 11/21/2013, 20:10-20:50

1. S1: Mine there was a point where it was increasing and then decreasing and then increasing again.
2. S2: Yeah, me too.
3. S3: Me too.
4. S4: So that's not C, that's D.
5. S2: Yeah between 25 and 40 mine went up down up down
6. S1: So it's B. Mine was weird because it was like 0, 5, 7, 2, 13, 14
7. S2: So I think it would be B because it goes up and then…
8. S4: Yeah there's like a point where it kind of slows down.

Focus group interviews

Figure 6 shows the distribution of focus group interview data. Of the 122 coded utterances, in reference to Science and Engineering Practices, 66 were coded as developing and using models. For Cross Cutting Concepts, the greatest frequency of utterances, 56, were coded as having to do with systems and system models. For example, in response to the question *What is the main biology idea represented in the unit?,* one student responded:

> We learned how over time starch turns into sugar because we had to click that 5 starch, 10 starch, 15 starch thing and then like each had 30 seconds. And then as many starch comes, and just for the same amount of time, it's different. Different answers come out." (ID 1, Focus Group, 11/22/2013)

In this excerpt, the student recognizes the relationship that sugar and starch develop over time through scaffolded interactions with the model. In understanding cause and effect another student remarked:

> We were discussing [the argumentation question] once and I ran [the simulation] like five different times just to see the different answers. (ID 3, Focus Group,10/17/2013).

Here, he and his partner debated how to answer the argumentation question, which required students to provide evidence for their reasoning. In order to be able to provide evidence, the student went back to the simulation and ran it multiple times to find the empirical evidence that they needed to understand the relationships being shown in the simulation. The students interpreted evidence to respond to the question prompt in order to understand cause and effect.

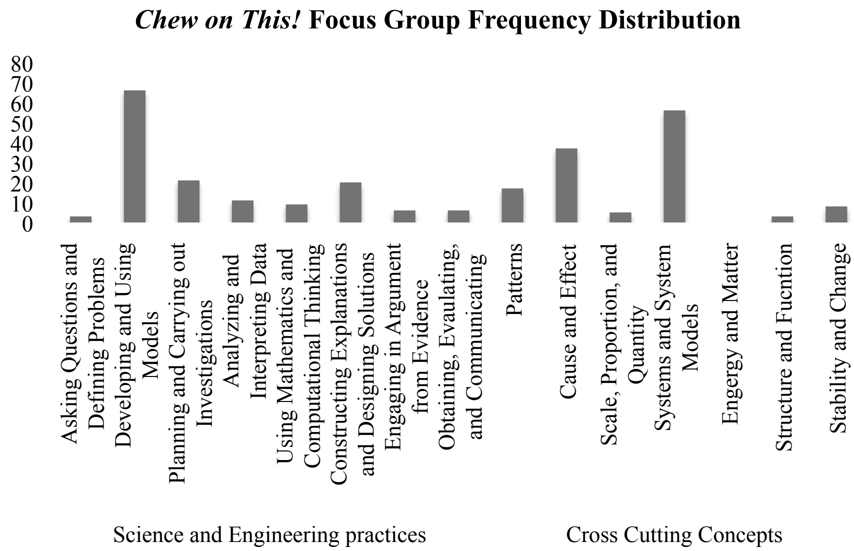


Figure 6. Focus group interview frequency of utterances of NGSS codes

Discussion

The recently developed *Next Generation Science Standards* have expanded the goals of K12 science education to emphasize problem-solving, applying knowledge, argumentation, using computers, systems thinking, constructing models, and making connections across scientific domains. Implementing these standards requires new and appropriate curricula and pedagogical tools–two components critical to success but remain a challenge for researchers and educators. In order to address the need for curricular materials and pedagogical approaches that instantiate the recent NGSS, our project has developed a five-unit biology curriculum using simulations, argumentation, computational thinking, and systems understanding in conjunction with traditional Biology content. In this study, we present findings from one unit of our project on enzymes, to investigate whether students interacting with project materials demonstrate the science and engineering practices, and crosscutting concepts outlined in the NGSS. Based on the results, we have concluded that students can demonstrate knowledge and skills in all but one of the science and engineering practices and cross cutting concepts as is evident in classroom observations of students engaging with the simulation and in their self-reported learning during focus group interviews. To answer the second research goal of identifying those practices and concepts that were most frequently shown by students thereby locating particular strengths of the project activities and resources our findings show that using models, analyzing and interpreting data, understanding cause and effect, and systems understanding were the most prominent. Overall, we have shown evidence of students learning the science and engineering practice and the cross cutting concepts. Students are grappling with data, and using and manipulating models to understand systems.

In the future, an experimental study would validate these findings, since a limitation of the current study is the lack of a control group. As such, we do not know how much of the NGSS is incorporated into student learning outside of our project intervention, so this warrants further exploration. Our findings do provide insight into curriculum development for the NGSS, in that we have shown how science and engineering practices, and crosscutting concepts can be incorporated into curriculum content.

References

Bybee, R. W. (2013). Translating the NGSS for classroom instruction. Arlington, VA: NSTA Press.

Colella, V. (2000). Participatory simulations: Building collaborative understanding through immersive dynamic modeling. *The journal of the Learning Sciences*, *9*(4), 471-500.

Desimone, L. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational Researcher*, *38*(3), 181-199.

Epstein, J. (2008). 'Why Model?'. *Journal of Artificial Societies and Social Simulation* 11(4)12 <http://jasss.soc.surrey.ac.uk/11/4/12.html>

Ertmer, P.A., Ottenbreit-Leftwich, A.T., Sendurur, E., & Sendurur, P. (2012). Teacher beliefs and technology integration practices: A critical relationship. *Computers & Education*, *59*, 423-435.

Harris, C. J., Penuel, W. R., DeBarger, A., D'Angelo, C., & Gallagher, L. P. (2014). Curriculum Materials Make a Difference for Next Generation Science Learning: Results from Year 1 of a Randomized Control Trial. Menlo Park, CA: SRI International.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences*, *4*(1), 39 – 103.

Kafai, Y. B. (2006). Playing and making games for learning instructionist and constructionist perspectives for game studies. *Games and culture*, *1*(1), 36-40.

Lee, O., Penfield, R., Maerten–Rivera, J. (2009). Effects of fidelity of implementation on science achievement gains among English Language Learners. *Journal of Research in Science Teaching*, *46*(7), 836-859.

Lewis, J., & Wood-Robinson, C. (2000). Genes, chromosomes, cell division and inheritance-do students see any relationship?. *International Journal of Science Education*, *22*(2), 177-195.

Mueller, J., Wood, E., Willoughby, T., Ross, C., & Specht, J. (2008). Identifying discriminating variables between teachers who fully integrate computers and teachers with limited integration. *Computers & Education, 51*, 1523-1537.

National Research Council. (2010). Report of a Workshop on the Scope and Nature of Computational Thinking. Committee for the Workshops on Computational Thinking; Computer Science and Telecommunications Board; Division on Engineering and Physical Sciences. Washington, DC: National Academies Press.

National Research Council. (2012). Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century. Committee on Defining Deeper Learning and 21st Century Skills, James W. Pellegrino and Margaret L. Hilton, Editors. Washington, DC: The National Academies Press.

National Research Council. (2014a). Developing Assessments for Next Generation Science Standards. Committee on Developing Assessments of Science Proficiency in K-12; Board on Testing and Assessment; Board on Science Education; Division on Behavioral and Social Sciences and Education; James W. Pellegrino, Mark R. Wilson, Judith A. Koenig, and Alexandra S. Beatty, Editors. Washington, DC: National Academies Press.

National Research Council. (2014b). STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research. Committee on Integrated STEM Education; National Academy of Engineering. Margaret Honey, Greg Pearson, and Heidi Schweingruber, Editors. Washington, DC: National Academies Press.

Osborne, J. (2010). Arguing to learn in science: The role of collaborative, critical discourse. *Science*, *328*(5977), 463-466.

Penuel, W. R., Fishman, B. J. Haugan Cheng, B., & Sabelli, N. (2011). Organizing research and development at the intersection of learning, implementation, and design. *Educational Researcher*, *40*(7), 331-337.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., ... & Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *The Journal of the Learning Sciences*, *13*(3), 337-386.

Thompson, J, Windschitl, M., & Braaten, M. (2013). Developing a theory of ambitious early-career teacher practice. American Educational Research Journal, 50(3), 574-615.

Wilson, S. M. (2013). Professional development for science teachers. *Science, 340*, 310-313.

Yoon, S., Koehler-Yom, J., Anderson, E., Lin, J., & Klopfer, E. (accepted). Using an adaptive expertise lens to understand the quality of teachers' classroom implementation of computer-supported complex systems curricula in high school science. *Research in Science and Technology Education*.

Yoon, S., Klopfer, E., Wang, J., Sheldon, J., Wendel, D., Schoenfeld, I., Scheintaub, H., & Reider, D. (2013). Designing to improve biology understanding through complex systems in high school classrooms: No simple matter! In the proceedings of the *Computer Supported Collaborative Learning*, Madison, Wisconsin.