Enhancing Classroom Learning by Coupling Interactive Computer Simulations with Real-Time Formative Assessment through Technology-Mediated Open-Format Questioning

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Structured Abstract

BACKGROUND

Interactive computer simulations are widely used to engage engineering students and help them better visualize abstract and difficult concepts. However, the most effective way to use these tools to enhance learning has not been established. This research investigates learning gains achieved when students' explorations of these simulations are coupled with real-time formative assessment of their understanding. Classroom technology is used to facilitate an instantaneous exchange, guide and reinforce student learning, and actively engage students. Earlier pilot studies indicate that this promising model warrants more rigorous investigation.

PURPOSE

This research compares learning achievements when using computer simulations in two environments: with and without the intervention of combining the simulations with open-format, in-class scaffolding mediated by technology.

DESIGN/METHOD

Intermediate electromagnetics students (junior-year engineering physics undergraduates, n= 44) independently explored assigned computer simulations. In class, each used digital ink on a Tablet PC to submit responses (drawings, words, equations, graphs, etc.) to open-format questions posed by the instructor. For this, *InkSurvey*—free, web-based software—was used but other collection methods are also possible. The instructor used this real-time formative assessment to guide further student explorations and refine student understanding. For each concept taught using a computer simulation, three data points of student understanding are compared: before exposure to the simulation (pre-test), after exploring the simulation independently, and summative assessment after guidance in further exploration of the simulation by open-format questions posed by the instructor.

RESULTS

This study confirms that exploring simulations without guidance often results in misconceptions and/or little improvement in learning. In contrast, real-time formative assessment collected using open-format questioning can guide student explorations, require students to reveal their thinking, and provide the instructor with insight for designing subsequent pedagogical strategy. Descriptive and inferential statistical analyses show that this instructional model results in significant learning gains.

CONCLUSIONS

For engineering physics students, the use of interactive computer simulations results in greater learning gains when coupled with real-time formative assessment. This can be readily facilitated by students responding to open-format questions, in this case electronically and instantaneously on tablet computers or other mobile devices. These questions focus and reinforce student explorations and the responses provide a glimpse into student thinking that effectively guides refinement of understanding.

KEYWORDS: interactive simulations, formative assessment, mobile technology, engineering education, InkSurvey

1. Introduction

1A. Interactive Computer Simulations

Educators in diverse STEM areas have ready access to myriad highly interactive computer simulations, commonly known as "simulations." Free, web-based, platform-independent simulations can be easily found using any search engine, and many others accompany textbooks. These pedagogical tools are designed to let students explore, experiment through trial and error, and actively construct a more robust conceptual understanding of fundamental engineering and science principles and their connections to real-life phenomena.

Although there is still a great need for further research leading to better understanding of the nature of the cognitive interaction between students and screen-based information (NRC, 2011), there is emerging evidence of the pedagogical effectiveness of simulations. Recent extensive literature reviews, such as those by Rutten *et al*. (2012) and Scalise *et al*. (2011) reflect largely positive impacts across diverse K-16 STEM disciplines. Working with simulations can develop more expert-like thinking in STEM students (McKagan *et al*., 2007), provide a common framework for students and instructors to attend to relevant details leading to better understanding of underlying concepts (Perkins *et al*., 2006), and yield better long-term retention of the concepts (Zhou *et al*., 2005; Fraser *et al*., 2007).

Nevertheless, simulations alone may not be enough for students to master the concepts involved (deJong & van Joolingen, 1998; Kirschner *et al*., 2006). Students working with simulations but without instructor intervention may not cognitively engage at a level deep enough to interpret abstract aspects (Yeo *et al*., 1998), may not use the information available to them nor isolate the features that they need (Healy *et al*., 2002), may not understand the significance or application of what they learn (McKagan *et al*., 2008), or may interpret something in the simulation differently than intended and thus construct the concept incorrectly (Wieman *et al*., 2008). As a result, there has recently been a shift in the research focus to how to best use computer simulations in conjunction with other instructional methods in STEM (Smetana & Bell, 2011).

To realize their full pedagogical potential, simulations should be used in the classroom in tandem with other well-established principles aligned with current learning theory, such as collecting real-time formative assessment (Bransford *et. al*., 1999; ERIC, 2002). In this light, some, such as Ong & Mannan (2004), have embedded questions within the simulations, but not all useful simulations incorporate this. Others, including Yeo *et al.* (2004) and Martin *et al.* (2009), suggest appropriately timed reflection and assessment of understanding during students' explorations, but do not offer a viable classroom mechanism. McKagan *et al.* (2007) and others effectively combine the use of simulations with clicker questions, but this technology is clearly limited by its restriction to multiple-choice and short-answer formats, and the reliability of using multiple-choice questions to accurately probe student understanding of various concepts has been questioned by Steinberg & Sabella (1997) and Allen & Tanner (2005), among others.

To accurately reflect the process of scientific investigation, there is a fine balance in the optimal type and amount of instructor intervention to guide learning without excessively constraining or directing the students' explorations (Adams *et al.,* 2008; Rutten *et al*., 2012*)*. Ideally, instructors would work one-on-one with students to guide explorations (just enough), increase student metacognition, and reinforce correct conclusions. This paper presents results of scaling up this ideal to a class of 44 students and one instructor, by guiding student exploration of simulations with open-format real-time formative assessment questions.

1B. Using tablet computers to gather real-time formative assessment

Pen-enabled mobile computing devices (tablet PCs, slates, some smart phones, etc.) are becoming increasingly common in STEM classrooms and there is a growing body of research-based evidence (Cromack, 2008) that they can effectively support all seven of

Chickering and Gamson’s (1987) highly influential principles for good practice in undergraduate education. Although there are various tools commercially available for using tablet computers to easily gather real-time formative assessment from students, this research uses *InkSurvey* (Kowalski *et al.,* 2007) since this free, robust, web-based software is designed specifically for this purpose and has been successfully implemented in a variety of university engineering classrooms with enrolments up to 60 (Kowalski *et al.,* 2013). Using *InkSurvey*, the instructor poses open-format (*i.e.,* not multiple-choice) questions and students use pen-enabled mobile computer technology to facilitate constructing (with digital ink) and submitting their responses. This enhances learning by actively engaging each student, probing his/her understanding, and revealing any misconceptions. The real-time formative assessment aids student metacognition; the instantaneous window into student thinking guides the instructor as he/she clarifies, modifies, reinforces, and refines student understanding. It enables data-driven instruction on the shortest of time scales.

(A.) ***(B.)***

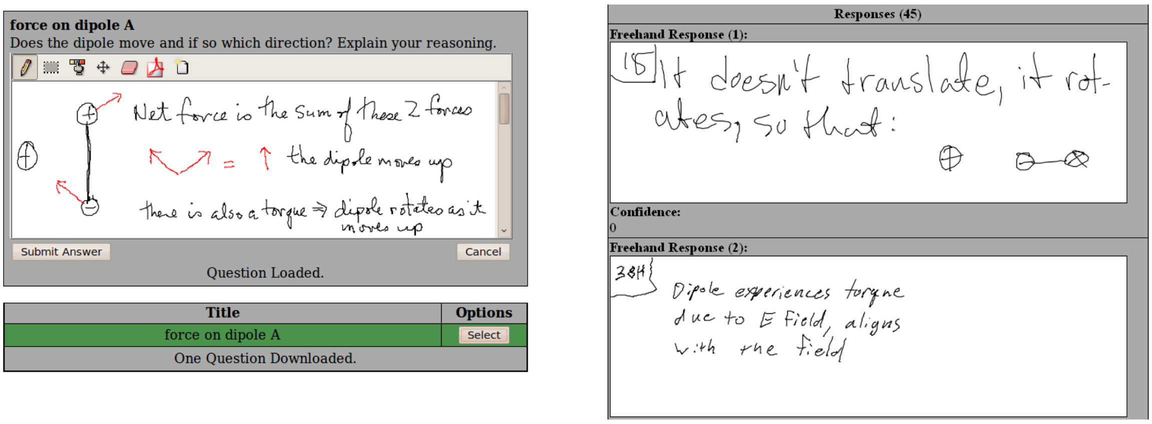

Figure 1: (A.) Student’s web browser, as response is being prepared to submit

(B.) Instructor’s view as other student responses are received

Figure 1 shows sample teacher and student web pages in *InkSurvey*. Thus by using technology to facilitate real-time formative assessment, the instructor can better capture the essence of the Socratic method in a larger class setting, and better probe higher-level thinking skills. With well-crafted questions, responses can disclose essential details of student thought processes at every step of the journey toward solution of a problem or understanding of a concept. This reveals and documents how a student gets to his/her answer, exposes the varied ways in which student learning occurs, and opens the door for further research into how students learn STEM concepts. Additionally, analysis of the archived *InkSurvey* responses is much less time- and labour-intensive than traditional student interviews and “think alouds” that have previously contributed to our understanding of pedagogical advantages of using computer simulations.

1C. Coupling interactive computer simulations with real-time formative assessment facilitated by open format questions on tablet computers

In this novel coupling, students are presented (via *InkSurvey)* with a series of open-format, concept-based questions to guide their explorations with interactive simulations as they construct new understandings. The students then submit their responses electronically. A pilot study in chemical engineering (Gardner *et al*., 2012) indicates this promising model should be investigated further. The guided exploration and exchange of information, facilitated by pen-enabled mobile computing devices (tablet computers) in the hands of both instructor and students, affords a close mirroring of McDermott’s (2001) elicit/confront/ resolve strategy of teaching STEM concepts as well as the visualization/interaction/ assessment ternary structure of an effective use of simulations proposed by Martin *et al*.

(2009). To scaffold instruction most effectively, an instructor needs to be able to actively diagnose student understandings, provide tailored assistance, and give feedback to the learners (Hogan and Pressley, 1997). Without technology, it is difficult to collect and respond to meaningful formative assessments quickly. The real-time assessment gathered with *InkSurvey* is particularly authentic since it is seamlessly integrated with the activity (Young, 1995)—in this case not only temporally, but physically as well, with a single device being used for both exploring simulations and using *InkSurvey*. An additional advantage of this coupling is that students can engage in further manipulation of the simulations as they construct their responses, allowing them to explore facets they may have initially ignored and to test and verify their conclusions.

2. Experimental Procedure

This work compares learning achievements gained when using computer simulations with and without the intervention of combining the simulations with scaffolding in-class, open-format questioning using *InkSurvey*. Students in this study were 44 second semester juniors (third year) taking an intermediate electromagnetics class at an engineering university.

For this study, the operational definition of learning a given concept is for the students to express or apply that concept correctly in writing. For each concept included in this study, individual student learning achievements were assessed three separate times:

a.) Pre-Test: prior to any exposure to the simulation, submitted by paper and pencil;

b.) Post-Exploration: after students were allowed to explore the simulation without any intervention, submitted by open-format responses on *InkSurvey;* and

c.) Summative Assessment: after the guided questioning intervention, submitted by a paper and pencil exam at the conclusion of the unit.

This experimental design, based on one by Shadish *et al.* (2002), uses the same students for the control group (before intervention) and the experimental group (receiving intervention), eliminating the necessity of random assignment or matching of subjects.

3. An Illustration of Implementation of the Experimental Procedure

To clarify the experimental procedure, it is now illustrated by a more in-depth description of the implementation, instructor responses, and measurement of learning achievements for the "Moving Charge" data reported later. The simulation models radiation from a moving charge and can be found at:
http://www.cco.caltech.edu/~phys1/java/phys1/MovingCharge/MovingCharge.html.

The moving charge learning objectives were for the student to:

(1) understand that the field lines of a charge moving at constant speed compress along the direction perpendicular to the motion;

(2) understand that acceleration of the charge generates radiation;

(3) understand that the amplitude of the generated wave decreases with distance;

(4) understand that the finite speed of propagation leads to the kinks in the field when the charge accelerates.

The students were not formally exposed to objectives (1) and (4) in pre-requisite courses.

At the beginning of the semester the following pre-test question was asked: "What are some properties of the electric field from an accelerating charge? Justify you answer." Later in the semester the students were assigned to independently explore the simulation. In this free exploration, the students were able to navigate through the simulation, from moving the charge at constant speed to applying user control to accelerate the charge, thereby generating waves.

Before the subsequent intervention, the students were asked the post-exploration question: "What does this simulation illustrate about moving charges?" In responding to this via *InkSurvey*, some students had trouble expressing their thoughts. For example, the compression of the field lines was described as, "The electric field lines generated ahead of a moving charge are different than those generated behind the moving charge." Some students thought these were magnetic field lines. However, only the electric field was sketched in the simulation. Insightful comments about the field of the moving charge retaining some aspects of static charges, such as a radial field, were noted by a few students.

Intervention was initiated by the *InkSurvey* question, "What questions do you have about this simulation?" As the instructor responded to these questions in a "Socratic dialogue" with the class in general (rather than toward any particular person), students were encouraged to run the simulation again to refine their understanding. The magnetic field misconception reappeared in these questions. To correct this, the instructor verbally asked the class about the source of magnetic field lines. The students were led, in the ensuing discussion, to notice that the field lines emanate from a point, which is only true for electric field lines. Now, many students noticed the compression of the electric field lines as the charge moved at high constant speed and were curious why this occurred. Fewer noticed that the finite speed of light led to travelling waves. Others were able to manipulate the simulation to demonstrate the Doppler Effect.

Some students were curious about the moving kink in the field due to acceleration of the charge, wondering why it occurred. They also had concerns about the magnitude of the kink. One student submission stated, "It appears the field gets bigger while the particle is accelerating but then stays the same when the velocity is constant. That doesn't make sense to me yet." The instructor asked the class if the field amplitude gets smaller as it propagates further from the accelerating charge. Most students contended that the field amplitude increased with distance; this started a lively class discussion. Many students did not understand why the field amplitude should get smaller. The simulation either instilled the idea that the field amplitude gets larger or it reinforced a previous misconception. The simulation does indeed show the kink getting larger with distance from the accelerating charge (to see this effect, set the pull down menu to saw-tooth wave with speed zero). However, the field line density, which is proportional to the field amplitude, gets smaller. Only when it was mentioned that ripples from a rock dropped into water get smaller as they move away from the rock did student attitudes slowly begin to change. Radiation from the sun, another example of a decrease in amplitude with distance, helped reinforce the idea that the amplitude decreases with distance. Surprisingly, this was a concept covered in a pre-requisite physics course.

The summative assessment consisted of the following exam question at the conclusion of the unit: "Explain how the moving charge simulation relates to your understanding of electric fields." Table 1 shows the scoring rubric for the pre-test, post-exploration, and summative assessment.

Table 1: Scoring rubric for measuring student learning of radiation from a moving charge

Criteria	Unsatisfactory	Satisfactory	Excellent
(1) Understands field lines compress for moving charge.	No discussion of this relationship.	Notes the compression of the field lines.	Discusses dependence of this effect on speed.
(2) Understands acceleration generates radiation.	No discussion of this relationship.	Discusses acceleration as necessary for radiation.	Relates directions of acceleration and radiation.

(3) Understands that the wave amplitude decreases with distance.	No discussion of this relationship.	Notices a decrease in amplitude with distance.	Explains why the amplitude must decrease away from the source.
(4) Understands that a finite speed leads to kinks in the field.	No discussion of this relationship.	Mentions that kinks are caused by finite speed of propagation.	Explains how kinks form from acceleration and finite speed

4. Results and Discussion

This experimental procedure was applied to 5 simulations (16 learning objectives total) over the span of one semester. The results for all interventions associated with the targeted computer simulations are summarized in Figures 2 and 3, indicating strong learning gains after the intervention. The plots show aggregate mean learning gains, as determined using scoring rubrics such as Table 1; mean scores (0-4) have been converted to percentages.

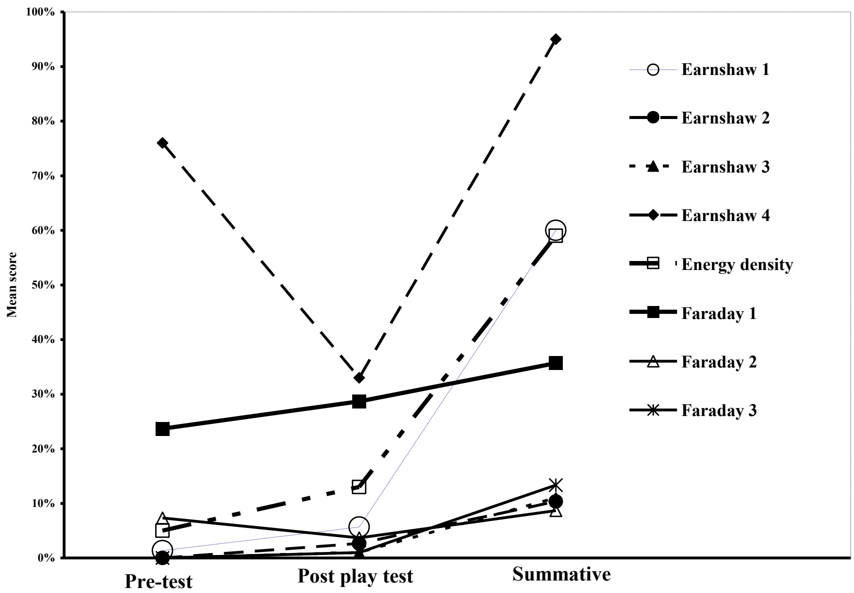

Figure 2: Comparison of mean student mastery of 8 learning objectives at 3 times: before exposure to the computer simulation ("Pre-test"), after independent exploration of the simulation ("Post-play test"), and after the intervention ("Summative")

Only students with all three data points for a particular learning objective were included in the mean. However, students did not need to have all data points for all objectives for data inclusion. Thus, even though the subjects for any particular learning objective were constant for all associated data points, every simulation had a slightly different set of subjects, depending on daily attendance. The reliability of the learning gains measurement was established in a similar study by the same researchers (Kowalski and Kowalski, 2012). There, the four-rater interrater reliability score (Ebel, 1951) over 9 random assessment questions was 0.82. (Reliability estimates can range between zero and one, with the larger value indicating more reliability between raters.)

To understand the change in student mastery over time, consider the Earnshaw 1 objective (data shown in figure 2) as an example. The learning objective was for the student to be able to apply potential energy concepts to determine if a "test charge" can be trapped with only a finite array of static charges. The simulation allowed the student to construct such an array of charges in two dimensions with the test charge moving in two dimensions. The test charge, when released, then moved under the influence of these static charges. Students could “experiment” with different static charge configurations to attempt trapping the test charge. With an appropriately placed array of static charges, the moving test charge could be approximately constrained to one dimensional motion. In the pre-test, only 5% of the students applied energy concepts. That jumped to 17% after independent exploration of the simulation; this is the point at which students had squeezed out of the simulation all that they could on their own. During intervention, potential energy concepts were stressed, along with a discussion of their application in 1, 2, and 3 dimensions. In particular, potential energy was used to show that while trapping can occur in 1 and 2 dimensions it is not possible in 3 dimensions. Student understanding in the summative assessment jumped to over 60% after this intervention. To document the effect of the simulation on their understanding of trapping, the Earnshaw 4 objective (understanding that no cage of charges can trap the particle in 3-D) was assessed. Students had used the simulation to construct a 1-D or 2-D trap; subsequent class discussion had addressed the 3-D case. Figure 2 shows that students’ independent exploration of the simulation encouraged the idea that a cage is a viable trap, while the intervention mitigated that misunderstanding.

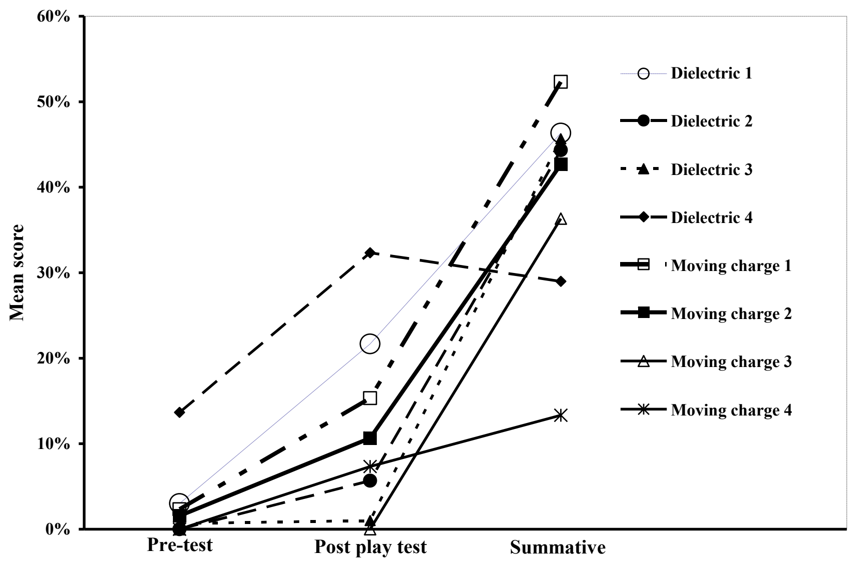

Figure 3: Comparison of mean student mastery of 8 additional learning objectives at 3 times: before exposure to the computer simulation (“Pre-test”), after independent exploration of the simulation (“Post-play test”), and after the intervention (“Summative”)

One notable exception to significant learning gains is shown in Figure 3 for the Dielectric 4 objective, which is to understand that the electric field inside a dielectric decreases due to surface bound charge. The pre-test indicated some understanding of this concept, which was either retained from the first year course in electromagnetism or inferred from an earlier discussion of fields in conductors. The simulation then reinforced this concept (although with low confidence). This concept was not mentioned explicitly during the intervention, which is perhaps why learning gains were not demonstrated in the summative assessment. This opens the door to further research into whether the mere mentioning of a concept during such an intervention somehow “flags” it as important in the minds of the students.

Statistical analysis of this data provides further insights. Table 2 displays the p-values for two inferential statistics, a two-tailed t-test and the Kolmogorov-Smirnov test, for the data in figures 2 and 3. The former inferential statistic requires normally distributed data whereas the latter does not. Table 2 also includes a descriptive statistic, Cohen's d (generating an effect size based on means, with larger absolute values indicating a stronger effect). The "Pre-Post" values address the statistical significance of the difference in learning gains before student exposure to the computer simulation and those after independent student exploration of the simulation—in other words, the gains by students without instructor guidance. The "Post-Sum" values address the statistical significance of the difference in learning gains after independent student exploration and those demonstrated in the summative assessment—in other words, the gains achieved with the intervention of the real-time formative assessment questions and the subsequent instructor response. The N/A values for Moving Charge 3 are associated with a zero score for all student responses for at least one of the samples needed in the statistic (i.e., all pre-test scores were zero), thereby limiting its validity. The tests in Table 2 confirm that the learning gains achieved in this study are statistically significant with medium to large effect sizes.

Table 2: Statistical analysis of learning gains achieved for 16 different learning objectives

		TTEST	KS TEST	Cohen's d	TTEST	KS TEST	Cohen's d
	Concept	**Pre-Post**	**Pre-Post**	**Pre-Post**	**Post-Sum**	**Post-Sum**	**Post-Sum**
	Earnshaw 1	0.14	0.99	0.35	0.00	0.00	1.92
	Earnshaw 2	0.08	0.35	0.24	0.04	0.93	0.54
	Earnshaw 3	0.32	0.54	0.09	0.01	1.00	0.54
	Earnshaw 4	0.00	0.00	3.50	0.00	0.00	-1.37
Fig. 1	Energy Density	0.16	0.99	0.36	0.00	0.00	1.15
	Faraday 1	0.13	0.91	0.34	0.02	0.76	0.56
	Faraday 2	0.23	0.81	0.27	0.13	0.64	-0.21
	Faraday 3	0.32	1.00	0.12	0.00	0.06	0.74
	Dielectrics 1	0.00	0.00	1.27	0.00	0.00	0.79
Fig. 2	Dielectrics 2	0.02	0.00	0.82	0.00	0.00	1.58
	Dielectrics 3	0.33	0.00	0.08	0.00	0.00	1.54
	Dielectrics 4	0.06	0.96	0.76	0.70	0.96	-0.08
	Moving Charge 1	0.00	0.03	0.86	0.00	0.00	1.49
	Moving Charge 2	0.01	1.00	0.65	0.00	0.00	1.09
	Moving Charge 3	N/A	N/A	N/A	0.00	0.00	1.34
	Moving Charge 4	0.00	0.42	0.86	0.04	0.08	0.43

Overall, Figures 2 and 3, along with this table, show that the intervention (coupling interactive simulations with real-time formative assessment facilitated by open-format questions using tablet computers) results in significant improvement in learning. Learning improvements, however, varied with each simulation. More research is required to address the issue of how to improve learning with all simulations. Here, the coupled model was used only once per learning objective. A more effective method might be to deliver a series of scaffolding *InkSurvey* questions over different class periods, the number of which is determined by the previous assessment and the complexity and significance of the concept.

Although the student responses to the open-format scaffolding questions were submitted on tablet PCs, the digital ink capabilities on many student-owned mobile devices, including smart phones, could be used similarly. When using pen-enabled, student-owned mobile devices and free, browser-based software such as *InkSurvey*, the resulting institutional infrastructure budget requirements for implementing this pedagogical model would be zero.

5. Conclusions

This study confirms that student exploration of interactive computer simulations without guidance often results in student misconceptions and/or little improvement in learning. However, when student explorations are guided by open-format questioning, written student responses are electronically collected in real-time, and there is subsequent appropriate instructor response, students display statistically significant learning gains. This coupling of interactive computer simulations and real-time formative assessment is facilitated by pen-enabled mobile technology, in this case tablet computers. We believe this instructional model initiates student metacognition, provides the instructor with insight into misconceptions, forces the students to communicate the misconceptions, and allows the instructor to then build an effective intervention in real-time.

Perhaps it comes as no surprise that coupling the advantages of several effective instructional strategies with broad theoretical grounding (interactive learning using computer simulations, real-time formative assessment, and open-format *vs.* multiple choice questions) results in improved learning. Our surprise, however, was in the richness of the window into student thinking, provided by *InkSurvey*. This challenged us to design innovative interventions, both in real-time and later in considering different ways the simulations could be used or modified. The increasing availability and affordability of pen-enabled mobile technology (including tablets, slates, iPads, and smartphones) underscore the potential for widespread utilization of this effective pedagogical strategy.

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