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# Learning Physics with Digital Game Simulations in Middle School Science

**Janice L. Anderson · Mike Barnett**



**Abstract** The purpose of this work is to share our findings in using video gaming technology to facilitate the understanding of basic electromagnetism with middle school students. To this end, we explored the impact of using a game called *Supercharged!* on middle school students' understanding of electromagnetic concepts compared to students who conducted a more traditional inquiry-oriented investigation of the same concepts. This study was a part of a larger design experiment examining the pedagogical potential of *Supercharged!* The control group learned through a series of guided inquiry methods while the experimental group played *Supercharged!* during the laboratory sections of the science course. There was significant difference, $F(2,91) = 3.6$, $p < 0.05$, $\eta^2 = 0.77$, between the control and experimental groups on the gains from pre- to post-assessment. Additionally, students in the experimental group were able to give more nuanced responses about the descriptions of electric fields and the influence of distance on the forces that charges experience due to their interactions with the *Supercharged!* game. Results of this study show that video games can lead to positive learning outcomes, as demonstrated by the increase in test scores from pre- to post-assessment and the student interviews. This study also suggests that a complementary approach, in which video games and hands-on activities are integrated, with each activity informing the other, could be a very powerful technique for supporting student scientific understanding. Further, our findings suggest that game designers should embed metacognitive activities such as reflective opportunities into educational video games in order to provide scaffolds for students and to reinforce that they are engaged in an educational learning experience.

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## Background and Introduction

Many scientific domains deal with abstract and multi-dimensional phenomenon that present difficulty for students to both comprehend and apply the knowledge. In order to master abstract scientific concepts, students need to be able to build flexible and testable mental models (Barnett et al. 2000; Redish 1993). This is in contrast to past practices of science education that often focused on facts and behaviorist approaches to learning (Clark et al. 2009; NRC 2011). Frequently, however, students are asked to develop accurate scientific mental models that have no real-life referents and to incorporate invisible factors and complex abstractions (Chi et al. 1991).

Historically, scientists and educators have used computational models to investigate and explore complex systems and phenomena. Tools that practicing scientists use to build computational models intended to visualize complex concepts and phenomena have been integrated into K-12 classrooms in order to help students learn and understand complex science topics (Edelson et al. 1999;

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Linn et al. 2006; Shen and Linn 2011; Korakakis et al. 2008). This is due, in part, to educators recognizing that model-based reasoning can facilitate the development of mathematical-scientific understanding of the natural world (Gobert and Buckley 2000; Keating et al. 2002; Lehrer and Schauble 2006; Lehrer et al. 1994; Passmore et al. 2009; Penner et al. 1998; Sabelli 1994). Further, the growing power of computers, coupled with a reduction in cost and the availability of inexpensive or free modeling software, have created opportunities to engage students in scientific inquiry through constructing computational models of scientific phenomena (Sabelli 1994; Passmore et al. 2009; Jackson et al. 2008; Hestenes 2010).

## Leveraging Games in Science Learning

Support for games to learn has grown into a major focus of research over the last decade (e.g. Gee 2003a, b, 2008; Dumbleton and Kirriemuir 2006; Kirriemuir and McFarlane 2004; Mayo 2009; NRC 2011; Young et ala 2012). In reviewing the literature, we looked for specific instances of research-based games, which differ from virtual worlds. Games take advantage of goal directed advancement within game play, while 3D virtual worlds are more immersive, academic play-spaces that allow for inquiry and discovery learning (e.g. Barab et al. 2007; Kettelhut et al. 2006; Dede et ala 2005; NRC 2011). Our review of the literature involved a two phase search. The initial search examined the field using a variety of library databases (e.g. ERIC, Academic Search Premier, Psyc ARTICLES, Psychology and Behavioral Sciences Collection, PsycINFO) and back searches from the reference lists of gathered articles (i.e. examining the reference list from one article to additional articles). The search terms that were utilized included video game, game, education, science education, and gaming. The second phase of the search included online searches (e.g. Google Scholar). We eliminated all studies that involved virtual environments including studies that pertained to *Quest Atlantis* or *River City*.

What we found was that research has demonstrated that games that are well designed can provide effective scaffolds for students' learning (Clark et al. 2009; NRC 2011; Young et al. 2012). Other studies argued that computer games can promote higher order thinking and learning through interactive play and dialog (Annetta 2008; MacDonald and Hannafin 2003; Mayo 2007, 2009; Young et al. 2012); promote learning and engage students in a way that helps them to make sense of their world (Anderson 2010; Willamson and Facer 2004; Mayo 2007, 2009; Young et al. 2012); and yield a potential increase in positive learning experiences (Anderson and Barnett 2011; Collar and Scott 2009; Kettelhut et al. 2006; Kebritchi and Hirumi 2008; Mayo 2009; Young et al. 2012). The National Science Foundation's *Panel on Cyberlearning* (2008) and the American Federation of Scientists (2006) further supported these ideas through their reports that digital games offer a powerful tool to support student learning, transforming both STEM disciplines and K-12 education. Their findings were re-iterated in a special issue of *Science* (Hines et al. 2009).

According to the report in *Science* (2009), the stakes and potential for the use of games in science education are high; while approximately 450,000 students graduate with STEM bachelors degrees, WHYville engages over 4 million subscribers with the dominant demographic being 8- to 14-year-old females (Mayo 2009). In this context, a single video game application has a much more expansive outreach than traditional education. This posits the question "is it possible to expand the reach of STEM education with the use of video games as the medium (Mayo 2009, p. 79)" particularly with respect to middle school students?

## Games, Simulations, Complex Phenomenon, and Middle School Physical Science

One area where games have great potential to impact student science learning is in middle school physical science. Engaging middle school students in complex physical phenomenon is challenging due to its abstract nature; however, computer simulations and games provide a mechanism to immerse students in the study of these complex scientific concepts (diSessa 2000; Dede et al. 1999; Clark et al. 2009; Lindgren and Schwartz 2009; NRC 2011). There is a growing research base (e.g. Yair et al. 2001; Barak 2007; Cooper et al. 2010) that claims students need to be able to view and interact with phenomenon in three-dimensions. It is difficult for students to mentally transform 2D objects into 3D objects, something that is often required for them to have a deep conceptual understanding of many complex scientific concepts including electrostatics (Winn et al. 2001; Franco et al. 2008; Hauptman 2010).

The affordances of digital technologies allow for the student to immerse themselves in worlds that not only represent specific scientific phenomenon, but behave according to the natural laws of physics by either Newtonian or Maxwellian rules (Dede et al. 1999; Mohanty and Cantu 2011). The immersive nature of gaming environments provides students with experiences that allow them to draw upon thinking about scientific concepts, using intuitive knowledge developed during play to interpret complex physics problems.

By leveraging the affordances of digital gaming conventions, educators can potentially increase engagement and foster deeper learning as the students engage in recursive and critical game play, whereby hypotheses about the game system are generated, plans and strategies are developed, observations are created, and ultimately hypotheses are adjusted based upon game play (Cordova and Lepper 1996; Gee 2003a, b; Squire 2003, 2006, 2008). Video games have often organized their play around core scientific content (e.g. Newton's Laws, Electrostatics) where students are able to develop tacit, intuitive understandings about topics such as kinematics. However, game structure does not always allow for the students to articulate or extend the ideas that emerge through their game play. Research suggests (e.g. Masson et al. 2011) that off-the-shelf commercial games, not designed specifically for science learning, require scaffolding supports from the teachers or other participants in order to support learning (Gee 2008). Games that are well designed allow students to build upon intuitive understandings of these complex physical phenomena due to the situated and enacted nature of the environment (e.g. Gee 2003a, b, 2008; Clark et al. 2009). Games also have the potential to support students in integrating their tacit conceptual knowledge with instructed knowledge (Clark et al. 2009; NRC 2011). This is accomplished through the specific design of the game that allows students to make choices that affect the state of the models being simulated. Complex scientific content that is represented through tangible, experienced, non-textually-mediated representations, games, and simulations may serve to engage reluctant learners in the study of science.

However, even advanced science students have difficulty in grasping non-intuitive abstract concepts such as those associated with electrostatics and electromagnetism (Furio and Guisasola 1998; Singh et al. 2010). Digital visualizations have helped physics teachers to alleviate this problem when teaching conceptual physics. According to John Belcher (2003), animations:

> can give you access to levels of abstraction that you just can't get to with the math alone. It's particularly valuable for students who are trying to understand things at a conceptual level, because there is not too much intuition about electromagnetism… electromagnetism is largely hidden from their reality. Animations help my students visualize vector fields and other electromagnetic phenomena that they have a hard time conceptualizing from just the mathematics. When the students look at the topology of the moving field lines, they can understand intuitively many properties of the Forces transmitted by the fields (p. 2).

The esthetic dimensions of these animations (Fig. 1) can also help to capture some of the beauty of electrostatics and in doing so, make physics more accessible to the broader public audience (Belcher et al. 1999; Zahn 1999). As representations of electrostatic concepts, animations, and visual depictions are not only tools for understanding physical phenomenon, but also they are objects that can engage students in learning.

In the sub-field of electrostatics, electric fields and their associated representational formalisms are three-dimensional, abstract and have few analogies to learners' everyday experience (Furio and Guisasola 1998). As a result, students have trouble understanding the relationship of abstractions about electric fields to phenomenological dynamics (Chambers and Andre 1995; Andre and Ding 1991; Viennot and Rainson 1992; Viennot 1994). In addition, learners often have trouble understanding how the electric field would propel a test charge through the field if it were free to move (Dede et al. 1999). This lack of understanding is because students are unable to visualize the distribution of forces throughout a vector field. Students are not able to relate how that distribution of force translates into the motion of the test charge or even to understand the concept of superimposed forces-at-a distance (Dede et al. 1999). In short, research suggests that students lack a qualitative understanding of the highlighted electric field concepts (Andre and Ding 1991; Bagno and Eylon 1997; Mualem and Eylon 2010). Such qualitative mental models are believed to lay the foundation for students' development of a more scientific, abstract understanding of these electric field models (White and Frederiksen 1998). To meet this need, researchers (e.g. Erickson 1993; Psotka 1996; Bruckman and Resnick 1995; Gordin and Pea 1998) have been exploring how to use computational simulations (virtual reality) to assist students in visualizing basic electrostatic concepts (Anderson and Barnett 2011; Bivall et al. 2011; Dede et al. 1996; Maier et al. 2009).

Some science educators currently advocate for conceptual or qualitative physics; the notion that physics is best taught not by mathematical formulae, but through experimentation, demonstrations, and visualizations that allow

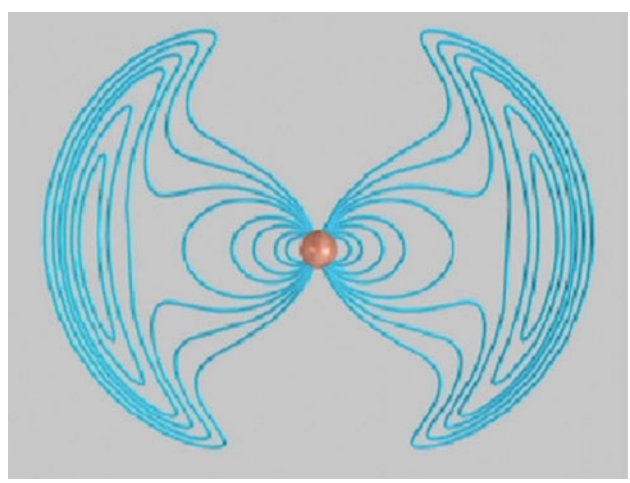

**Fig. 1** Creating a dipole image courtesy of John Belcher

students to begin to develop a conceptual understanding of physical phenomenon (diSessa 2000; Forbus 1997; Hewitt 2002; Rosen et al. 2009). This perspective, consistent with the *Physics First* curricular movement (American Association of Physics Teachers 2006), maintains that a deep fundamental conceptual understanding of physics provides a solid foundation for future learning in science.

Students have particular difficulty in conceptually understanding complex physics topics (e.g. electrostatics), which have few real-life referents and incorporate invisible factors, forces operating at a distance and complex abstractions (Chi et al. 1991). Students often have ideas about science concepts that are disconnected (Casperson and Linn 2006). Research (e.g. Casperson and Linn 2006) has demonstrated over time that students will maintain misconceptions such as the failure to realize that static cling and shocks from touching an object are similar events. By using visualizations, simulations, and games, students can begin to integrate discrete ideas, allowing them to begin to make connections between macro- and micro-experiences (diSessa 2000; Linn and Eylon 2006). Others (e.g. Miller et al. 1999; White and Frederiksen 1998; Guruswamy et al. 1997) have demonstrated that students are able to improve understanding of principles such as forces between charged particles and conduction when they are provided with the opportunity to interact with technology-enhanced visualizations or games. We believe that gaming structures could be used by educators to create powerful learning tools by coupling the rewards structures found in games with the pedagogical power of simulations in order to teach complex phenomenon (e.g. Cordova and Lepper 1996).

## Methodological Framework

### Design-Based Studies

Design-based research emerged from the dialectic between theory and design in research, with theory suggesting an improved design and design suggesting new dimensions to theory. While theory and design can and do exist independent of one another, there is still an inherent connection between them. Design-based research is an iterative process that is based upon outcomes that can impact the modification of instructional practice through monitoring and self-regulation (Schoenfeld 2006).

According to A.L. Brown (1992), the goals of design experiments are important educational objectives. Students in classrooms that utilize design-based curriculum are researchers, teachers, and monitors of their own progress. Design-based curriculum emphasizes the use of recurring themes of a topic as opposed to a breadth of knowledge, allowing the students to recognize and understand deeper levels of explanatory coherence. With the help of technology, students facilitate learning, collaboration, and reflection through their use of computer databases and communication tools such as chat spaces and e-mail. As a result, these experiments are able to produce data that enable the researcher to draw warranted conclusions about student learning and what contributes to it, focusing on how the students use rather than merely retain their knowledge (Brown 1992). In numerous studies, Scardamalia and Bereiter (1991), Scardamalia et al. (1994), Scardamalia (2002), Bereiter and Scardamalia (2010) demonstrated that when instruction includes the students' collective responsibilities for knowledge generation and content understanding, students feel empowered to take ownership in the discovery and refinement of information. It was the goal of this study to design such an environment utilizing the video game *Supercharged!* as the pedagogical tool with which the students generated their content understanding.

The purpose of this study was to examine what occurs when a 3D simulation computer game, *Supercharged!,* is used to support the teaching of electrostatics in a middle school classroom when compared to traditional classroom methods. Specifically, we examine: *What is the impact of learning with Supercharged! on students' conceptual understanding of electrostatic concepts?*

## Methods

This study was a part of a larger design experiment examining the pedagogical potential of *Supercharged*! (Brown 1992). We examined what classroom practices emerged when *Supercharged!* was used as the basis for an electrostatics unit in three middle school science classrooms. This experience was compared with learning in two classrooms where traditional, inquiry-based learning experiences were implemented. The study occurred in an urban middle school in the northeastern United States. Chamberlain Middle School has 700 students with only a 7th and 8th grade student body. The student body makeup is 30 % Latino, 20 % African-American, 15 % Asian-American (primarily Indian and Vietnamese), 25 % Caucasian, and 10 % Eastern European. In addition, 17 % of the student population has been identified as students who require special needs or care. This study occurred in one 8th grade teachers' classroom and included a total 91 students in five separate classes over seven class periods. In coordination with the teacher, we identified two classes to serve as a control group ($N = 32$) which left the other three classes to play *Supercharged*! and to serve as the experimental group ($N = 59$). Each group (control and experimental) was expected to learn the same content.

While the experimental group used *Supercharged!* as their learning experience, the control group participated in a series of scientific guided inquiry investigations that were designed to help them learn the same concepts as their experimental group peers. In this context, guided inquiry is being defined as the instructor providing the guiding question and materials for the investigation with the students responsible for determining the method of investigation and the interpretation and explanation of the resulting data. These investigations included understanding the force of a magnetic field on a charged particle, the relationship between force on a test charge and distance, and the impact of electric fields on charges. To this end, the control group was taught about electromagnetics and electrostatics through guided inquiry methods such as interactive lectures, experiments, observations, and demonstrations of the teacher's design as well as access to supplemental content materials. The supplemental materials used by both groups included various simulations from the web including the interaction simulations developed by the University of Colorado (http://phet.colorado.edu/index.php), web resources such as Teacher's Domain (http://www.teachersdomain.org/collection/k12/sci.phys.maf.electric/), and content background reading for the laboratory. These materials were meant to provide supplemental resources for the students to access as needed.

The first investigation in the control group required students to determine the impact of negative and positive charges on balloons and how charges transfer from one substance to another through the rubbing contact of glass and plastic rods with different materials such as wool, silk, and fur. For example, a student group would rub a balloon against a group member's hair to charge the balloon and then test whether the balloon was attracted or repelled from the rods. During this activity, the students had to pay careful attention to the distance between the rod and balloon and the impact of distances on the balloon. Afterward, students were expected to charge up their balloon and hold it over torn shreds of paper; they evaluated the reaction of the balloon as it moved closer and closer to the paper. The students then followed up this investigation by evaluating the repulsive force between two balloons by bringing two balloons together and measuring the force of repulsion between them. In their final set of investigations, the control group students examined the structure of a magnetic field, the impact of moving a magnet through a coiled wire by examining whether the speed at which the magnet moved impacted the magnitude of the current generated, and if a magnet would impact a stationary charged object such as their charged balloon.

The experimental group primarily played *Supercharged* ! during their class time with interactive lectures from the same teacher. The only required reading for the students was the laboratory documents which contained two–three pages of background content and the instructions for each laboratory. Students also had access to the same supplemental materials as the control group. Different from the traditional hands-on experiments conducted by the control group, the experimental group completed five levels of the *Supercharged!* game where they encountered the introduction of a new concept and/or increased difficulty at each level. The number of times these materials were accessed varied among the students in both the control and experimental groups, but were typically one to two times over the course of the study. Because access was so infrequent, we did not account for the use of the materials in the analysis.

## Game Context: Enabling Technology-Supercharged!

*Supercharged!* is a 3D action/racing game. The premise is that players are in a spaceship trying to maneuver through a set of obstacles to obtain a certain goal. In Fig. 2, the goal is to maneuver the ship to the black hole in the middle of the screen, which represents "the way out", the goal for this level. Players may adjust the type of their ship's electric charge (positive, negative, or neutral) and the magnitude of the charge. The relationship between the ship's charge and different objects throughout the level determines the ship's motion (e.g. rapidly imparting a positive charge onto the ship when the ship is close to a negative point charge would result in a strong attraction between the ship and the negative point charge). Players also have a limited number of point charges they may place anywhere within the level to further help them maneuver.

Different levels have varying types of obstacles and goals, increasing in difficulty. Starting with the simple screen in Fig. 2 representing level one, the only obstacles are two positive point charges, more complex obstacles emerge, including planes of charge, magnetic planes, solid

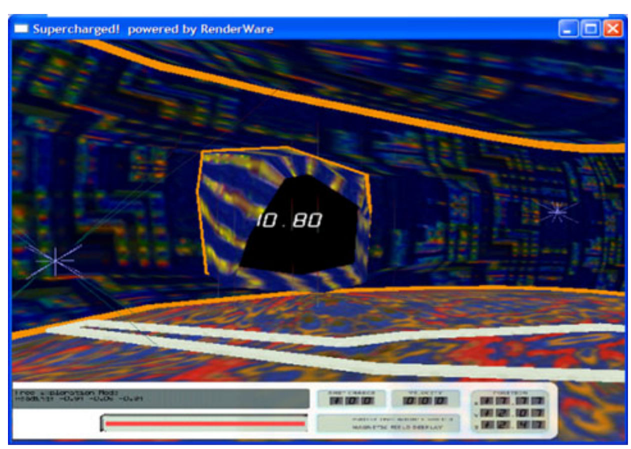


**Fig. 2** Screen shot of Level 1—*Supercharged!*

magnets, and electric currents. By level five, students were expected to navigate their ship through a maze that was filled with a magnetic fields and static electrostatic charges in order to exit the maze. The game has been designed in accordance with the laws of electrostatics. In short, the goal of *Supercharged!* is to help learners build stronger intuitions for how charged particles interact with electric and magnetic fields and use the laws of electromagnetism to solve novel problems in a variety of contexts.

### Data Sources

This study uses both quantitative and qualitative data, a mixed methodological approach, to provide a holistic view of the course and reciprocally identify patterns in order to uncover meanings into how students learn, process, and understand concepts in electromagnetism. Prior to the intervention, each group was administered a conceptual electrostatics and electromagnetism exam created by the project researchers. The exam consisted of twelve questions with space provided for the students to describe why the chose their particular answer. The content exam was determined to have an internal consistency (Cronbach) of $\alpha = 0.72$ for the instrument which, while low, is within acceptable range. The exam was also reviewed by two physicists to ensure that the questions were appropriate and that the questions were not confusing or misleading.

Additionally, a subset from each group ($N_{\text{control}} = 15$, $N_{\text{exp}} = 36$) were randomly chosen and interviewed. The interview was constructed to specifically elicit student responses that would provide the researchers with a better understanding of students' performance on the pre-test. The interview was semi-structured and focused on better understanding of students' comprehension of electrostatic forces and electromagnetic fields. During the interview, students were asked to draw pictures of their ideas regarding these fields and were provided with manipulatives to demonstrate their understanding of how charges interact with one another.

Along with the quantitative methods, naturalistic strategies were leveraged to better understand how the students used and interacted with *Supercharged*! and each other as they engaged in the game play. Each class was videotaped with five video cameras. One camera was focused on the teacher to track the teacher's movements and comments. Another camera was a "roving" camera moving around the room to capture "interesting" classroom moments. The other three cameras were focused on a specific group of students who were playing *Supercharged!*. In addition, two researchers were always present recording their observations concerning student discussions, interactions with each other and the game, and students' frustrations and successes with the game into a database. At the conclusion of the intervention, the students were again administered the conceptual electrostatics and electromagnetism exam and students from each group were interviewed again ($N_{\text{cnt}} = 16$, $N_{\text{exp}} = 33$). Given the constraints of the school structure, it was difficult to always post-interview the same students that were pre-interviewed. However, we did successfully to conduct 25 pre-post experimental pair interviews and 12 pre-post control pair interviews.

### Data Analysis

The quantitative data were analyzed using SPSS and analyzed using two-way ANOVA. Concurrently, the qualitative data was entered into a database and correlated with the appropriate question on the conceptual assessment. This analysis allowed us to look across the data to understand how students think about physics on both a macro- and micro-level. In order to develop a more fine grained understanding of how students' conceptions of electrostatics changed, we purposively selected a subset of students whose scores increased (3), decreased (3), and stayed about the same (3) for a more detailed analysis of their understanding.

The qualitative data were analyzed using naturalistic methods (Lincoln and Guba 1985) techniques to examine the classroom practices that emerged through game play, how students approached the game, and how learning occurred through game play. Researchers met informally between class sessions, and in three data analysis sessions following the program. Using the constant-comparative method (Glaser and Strauss 1967), researchers generated themes from the data, consulting video tapes and field notes to search for supporting and disconfirming evidence.

Findings are reported as described by three themes: (1) content understanding, (2) game design and conceptual learning, and (3) instructional practices in game-based learning environments. The following section will elaborate on these in detail.

## Results and Discussion

### Content Understanding

Evaluating the quantitative assessment data, the experimental group generally outperformed the control group (see Table 1) on the conceptual electromagnetic questions. To measure the treatment effect, the researchers calculated the effect size using a pooled standard deviation (mean square of the two standard deviations) for both the control and experimental groups. The control group demonstrated a moderate effect of $d = 0.54$ while the experimental group demonstrated a large effect where $d = 1.04$ (Cohen 1988).

**Table 1** Pre-post data

| | Control group | | | | | | Experimental group | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $N_{Cnt}$ | Pre-test | SD | Post-test | SD | Δ | $N_{Expt}$ | Pre-test | SD | Post-test | SD | Δ |
| Females | 12 | 5.33 | 1.377 | 5.33 | 2.22 | 0 | 26 | 4.84 | 1.75 | 5.92 | 1.35 | 1.08 |
| Males | 20 | 4.65 | 1.75 | 6.25 | 2.07 | 1.6 | 32 | 4.46 | 1.98 | 6.66 | 1.56 | 2.20 |
| Overall | 32 | 4.90 | 1.63 | 5.90 | 2.15 | 1.0 | 58 | 4.64 | 1.88 | 6.33 | 1.50 | 1.69 |

A two-way ANOVA was also calculated with post-test scores as the dependent variable. Intervention (Experimental or Control) and gender (Male or Female) were between-subject variables. There was significant positive difference between the experimental and control groups, $F(2,91) = 3.6$, $p < 0.05$, $\eta^2 = 0.77$ and no significant effect due to gender. That is, though modest, the students in the experimental group outperformed the control group on the conceptual exam. Interestingly, the males in both the control and experimental groups showed a greater increase than the females with the females in the control group showing no increase at all. Both the males and females in the experimental group showed a difference in scores that was statistically significant. To understand these differences, the researchers examined the student open-ended responses where the students justified their answer on the multiple-choice questions, the nature of the discussions in each class, and the semi-structured interviews. These results are presented in the following section.

When examining the pre-post interviews and student comments, a number of misconceptions about the nature of electrostatics emerged. For example, one female student, Maria, who was a part of the experimental group, gave a comment in the pre-interview that was representative of the majority of the students' beliefs regarding how two like charges interact with one another:

> *Interviewer*: Now lets imagine we have two positive charges next to one another. What is going to happen when I let them go?
> *Maria*: They are attracted because they are the same, so they will want to go toward one another.

In addition, Alex (control group) believed that electric fields simply consist of like charges around a charge (see Fig. 3) as seen below:

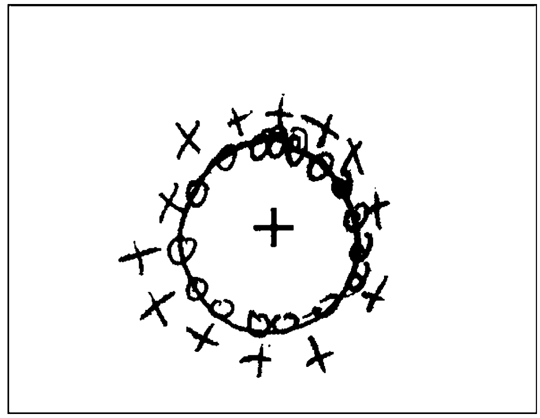

**Fig. 3** Alex's representation of electric fields

Other students, like Janet (experimental group), called upon her knowledge of atoms as noted in the following pre-interview excerpt:

> *Interviewer*: Ok, now what do you think the electric field looks like around a positive charge?
> *Janet*: Well, it probably looks like this (draws circles around the positive charge)
> *Interviewer*: Why do you think it looks like that?


**Fig. 4** Janet's representation of an electrical field

> *Janet*: It looks like the picture in the book from last year. You know, like an atom. The negatives are out here [pointing to her drawn circles] and the positive are in there [pointing to the center positive charge].

Furthermore, when students were asked to place a positive charge between two positive charges, nearly all of the students indicated the charge would go in the middle. However, when asked to explain why this was occurring, they could not respond. When asked what would happen if the charge was placed slightly off center, some students hypothesized that it would move toward whichever charge was closer (See Figs. 4, 5). For example,

> *Interviewer*: Ok, so what would happen if the charge landed a little bit off center?
> *Jose*: Well, it probably move toward whichever one was closer.
> *Interviewer*: Why do you think that?

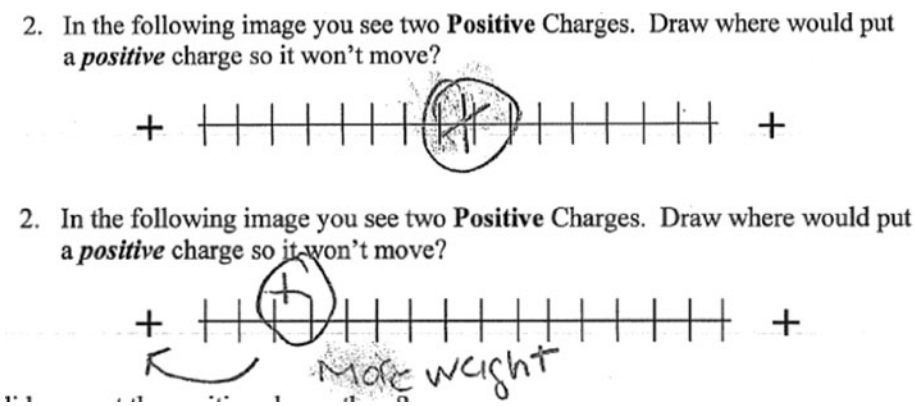


**Fig. 5** Position of positive charge—two different responses

> *Jose*: It is closer so it is easier to get to and because there would be more weight on one side, it would make the charges want to move to the side it was on.

It became clear from these pre-interviews that students whether in the control or experimental group did not have an understanding of electrical charges beyond a tenuous assertion that it was related to energy. Additionally, most students could not articulate that positive and negative charges were attracted to each other; those that could identify this concept typically could not provide evidence for why this was occurring.

When students were given a diagram with three fixed negative charges and asked what would occur if a free positive charge were added, students provided a variety of creative responses. For example, one student thought that the free positive charge would move directly toward the two negative charges where it would stop to get "recharged" and then move on to the other negative charge before moving back to its original starting point (See Fig. 6). This same student also thought that when two positive charges were put next to one another, they would "dance around" because they had all the "energy." The negative charge, on the other hand, they thought would not do anything since it contained "no energy."

The post-interviews revealed that both set of students had improved their understanding of basic electrostatics. However, there were some qualitative differences between experimental and control group students. The most striking differences were in students' descriptions of electric fields and the influence of distance on the forces that charges experience. For example, Maria during her post interview described an electric field as:

> The electric goes from the positive charge to the negative charge like this [drawing a curved line from a positive charge to a negative charge]. I know this because this is what it looked like in the game and it was hard to move away or toward it because the two charges are close together so they sort of cancel each other out (See Fig. 7).

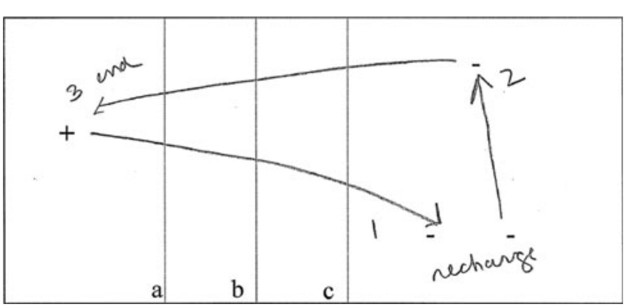


**Fig. 6** Movement of charges

In the control group, the students also performed well in drawing an electric field diagram though their explanations revealed a different type of thinking than the experimental group (See Fig. 8):

> *Interviewer*: Ok, what do you think the electric field looks like around a positive charge?
> *Alex*: It has lines going outward from it like this [drawing lines with arrows pointing outward]
> *Interviewer*: Why do you think it looks like that?
> *Alex*: I don't know. The teacher said so and showed us a picture and that was what it looked like.

From the above interview excerpt, it appears that students in the experimental group were recalling experiences and challenges that were a part of design of *Supercharged!*, whereas students in the control group were relying more on their ability to memorize information presented by the instructor. Playing *Supercharged!* enabled some students to confront their conceptions of electrostatics, as they played through levels that contradicted their understandings. Students used *representations* of electric fields depicted in the game as *tools for action*. While at first glance, it may appear that Maria's comment, "what it looked like in the game" and Alex's comment, "the teacher said so" are similar, what was distinctly different was Maria's ability to understand and articulate why it was difficult to move the

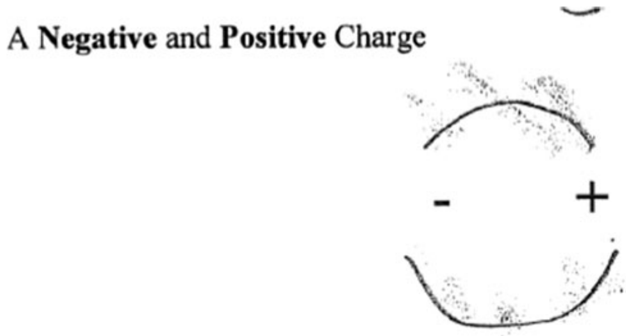


Fig. 7 Maria's representation of an electric field post-game play

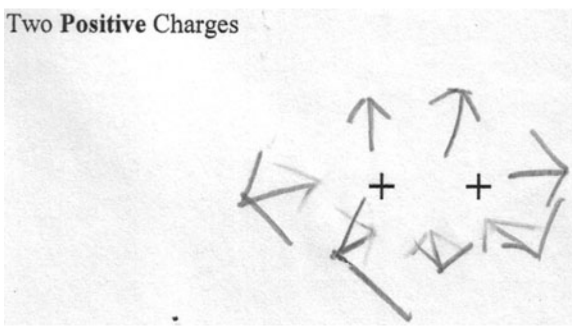


Fig. 8 Alex's representation of the lines drawing out from the positive charges

charge through the field. Alex, on the other hand, was unable to provide any substantial reason beyond his initial comment. These initial findings suggest that the primary affordances of games as instructional tools may be their power for eliciting students' alternative conceptions and then providing a context for thinking through problems. Adept game players appropriate game representations as tools for thinking, which, for some students such as Maria, were later taken up in solving other physics problems.

### Appropriation of Games in Classroom Environments

Many students in the experimental group were somewhat confused by the *Supercharged!* activity and sought more specific guidance about how to navigate the learning experience. After just 15 min of playing *Supercharged*!, students complained that they did not understand the point of the activity, or how they were learning physics through the game. Similarly, many students were reluctant to engage in discussions, with one student commenting, "We're just not really used to talking in class." For these students, learning science through exploratory activities was uncommon, and students had little reference (or no script) for how to participate in non-teacher led or teacher centric science activities. It was clear to the researchers that consistent with previous studies of digital tools in classrooms (Squire et al. 2003), the classroom culture was impacting how the tool was appropriated in significant ways.

By the second day, the teacher and researchers recognized that students were playing *Supercharged*!, but few were critically reflecting on their play in meaningful ways (Gee 2003a, b). As a result of this observation, the teacher created log sheets for students to record their actions and make predictions, which reinforced the purpose of the activity and encouraged students to detect patterns in their game play. By Day 3, as students continued to struggle, the teacher provided even more structure, using the projector to display game levels, encouraging the class to interpret the events happening on screen and make predictions about how they thought the game simulation would behave. This added structure generated a greater focus on students' play and allowed the teacher to prompt deeper reflection on game play as it was occurring. The teacher's move to adapt *Supercharged!* re-enforces the importance of designing tools transparent and flexible enough to be appropriated by teachers in response to local needs and conditions (Masson et al. 2011; Gee 2008). This also suggests that games do not replace instruction, but should be used to support inquiry teaching in the classroom.

### Impact of Game Design on Student Understanding of Electrostatic Concepts

The level design provided opportunities for students to intuit some electrostatic concepts which they used as tools, but most students did not readily adopt the game vocabulary or interpret game events in terms of electrostatic concepts. Students readily understood concepts such as the attractive force between opposite charges, and like charges exerting repulsive forces, concepts which many students had difficulty with in pre-interviews (many students used intuited algebraic meanings on positive and negative charges). Results from interviews and post-tests show that most students also discerned that charges experience force over distances and that this force grew weaker over distance. Some students, such as Maria, also used the concept of field lines, which were visual representations in the game as a tool for solving post-interviews. In general, students readily discerned the *kinetic* elements of the game and developed intuition about the general nature of electrostatic forces.

Results from interviews and post-tests also revealed that students did not infer some of the more complex concepts depicted in *Supercharged!*. Few students appropriated terminology presented in game and misconceptions persisted about the interaction among charged particles within an electric field. Most likely, this is because physics terminology is introduced in cut scenes (which many students skipped or ignored) and is not instrumental to the game play. Post-interviews revealed that students had idiosyncratic methods for interpreting game events, and this interpretation was mediated by play styles and social discourses.

## Limitations

There are several limitations with respect to the findings that should be noted. First, the number of questions included in the assessment is relatively small. While the internal consistency among the test items was acceptable, it was low. Additionally, the scores on the post-assessment, while demonstrating improvement, were still very low. Assessments need to be re-evaluated to better correlate to the content being presented. Second, a more thorough accounting of the use of the supplemental materials by the students should have been considered. These concerns will be addressed in future studies.

## Summary and Conclusions

Results of this study show that video games can lead to positive learning outcomes, as demonstrated by the increase in test scores from pre- to post-assessment. Additionally, this study also suggests that a complementary or mixed approach, in which video games and hands-on activities are integrated, with each activity informing the other, could be a very powerful technique for supporting student scientific understanding. One may consider this suggestion as a common sense approach, however, as found by a recent NSF workshop and the recent report on the research agenda for cyber-infrastructure development there needs to be significant work that investigates how emerging visualization technologies (like video games) can be leveraged to support "real-life" scientific investigations and vice versa (Computing Research Association 2006; NSF Task Force on Cyberlearning 2008; NRC 2011). Further, our findings suggest that video game designers should embed metacognitive activities such as reflective opportunities into educational video games to provide scaffolds for students and to reinforce that they are engaged in an educational learning experience. For example, most educational video games that are being used in classrooms have an implicit assumption that learning and skill development, such as scientific argumentation practices, will unfold organically. This notion is supported in the literature. Steinkuhler and Duncan (2008) found that game-related forums were rich sites for social knowledge construction where "discursive practices include argument, counter-argument, and the use of evidence to warrant one's claims"(p. 541) was prevalent and where "the predominant epistemological disposition exhibited in the forum posts was "evaluative" and therefore appropriate to science" (p. 541). This study supports these notions but we include the caveat that learning would be supported if appropriate supports are purposively built into video games. While this may detract from the "game-like" nature, it would provide the important learning scaffolds that students need to develop the appropriate conceptual understanding.

Additionally, we found student learning improved, as evidenced by the pre- to post-assessments and laboratory notebooks; however, we were concerned that the experimental group of students did not find playing *Supercharged!* to be a learning experience. This perspective could have been for many reasons, such as the relatively unpolished graphical interface of the game compared to what students may experience through game consoles, television, or movies. Another could be that the game-based laboratory was vastly different from their expectations and experiences of a typical laboratory; this might have resulted in the students being disconnected from the learning aspect of the game. However, the students' comments suggested that their discomfort with the video game was due to the fact that they did not perceive that a video game could really be educational. The game became a disruption to their traditional ways of science learning (e.g. Hall et al. 2002) and interfered with how they perceived the learning experience. This perspective is potentially problematic as it suggests that pedagogical disruptions such as video games that are designed to be powerful learning tools simply may not work for all students.

From our analysis, it appears that students in the experimental group were recalling experiences and challenges that were a part of the design of *Supercharged*!, placing themselves "in" the game. We base this placement of self upon the first-person language that experimental group students used in their descriptions of the ship movement in both post-assessment and laboratory notebooks. Thus, it appeared that through the playing of the first-person *Supercharged!* game, students were able to place themselves in the role of an electric change and experience how their actions impacted their motion. This approach of "placing oneself" in a visual representation is a typical scientific practice that many scientists use to help them conceptualize or solve a problem (e.g. Ochs 1990). Hence, our results reinforce the emerging findings that video games (e.g. McFarlane et al. 2002; Rosas et al. 2003; NRC 2011; Young et al. 2012) provide a natural venue to engage students in scientific practices. These initial findings suggest that the primary affordances of games as instructional tools may be their power for eliciting students' misconceptions and then providing a context for thinking through problems. The challenges that become apparent are that the middle school students do not always perceive that this learning has occurred, nor do they always see the game as a learning experience. While this was often the perception of the students, when analyzing the learning gains from pre- to post-assessment, it was clear that the experimental group out performed the control group on most measures. The key becomes helping these middle school students recognize the power of games as a learning tool.

Gee (2003b) stated: "when kids play videogames they experience a much more powerful form of learning than when they are in the classroom" (webarchive). Gee's statement reflects not only about the potential impact that videogames can have on learning, but also about the increased interest by educators to develop new and innovative tools to support learning (Gordin and Pea 1998; Yair et al. 2001; NRC 2011). This study provides evidence regarding how computer video games can be used to support or inhibit student learning of complex physics concepts. It also describes the challenges that students and teachers experience when attempting to use computer video games in a classroom context. In post-assessments, students used game concepts to solve complex Physics problems.

In closing, this study suggests that the active nature of computer game play, the goal-based nature of using the game structures, and the manner in which the students utilized the visual representations within the game context may be beneficial in getting students to think about and understand scientific phenomena, such as electromagnetism, that are often difficult to comprehend. This study also suggests that digital games can support science instruction and learning when they are appropriately designed and implemented within the classroom, but they do not take the place of science instruction. As demonstrated in this study, a mixed approach with games integration and inquiry teaching would be the most appropriate instructional strategy. Additionally, classroom implementation requires a purposeful design in order that the teacher can create the socio-cognitive learning supports that go beyond what the game can provide to the students. Games like *Supercharged!* have the potential to individualize and contextualize learning in an engaging environment creating the opportunity for improved access to high quality learning for all students (NRC 2011).

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