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DEVELOPMENT ARTICLE

Development of a design-based learning curriculum through design-based research for a technology-enabled science classroom

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Abstract This exploratory study provides a deeper look into the aspects of students' experience from design-based learning (DBL) activities for fifth grade students. Using design-based research (DBR), this study was conducted on a series of science learning activities leveraging mobile phones with relevant applications and sensors. We observed 3 different DBL workshops to understand potential learning effects and develop a curriculum to be reiterated as part of the DBR. The students who participated in this study were (1) provided with resources for their own experiment design, (2) encouraged to engage in problem solving by collective reasoning and solution designs, and (3) scaffolded in documenting, evaluating, and reporting scientific phenomena embedded in a thematic integrative education setting. This exploratory research model may be appropriate in addressing the issues of making science learning more approachable, interesting, enjoyable, and contextual while determining the efficacy of the pedagogy, resources, and conditions needed for the continuous curriculum enhancement process. Key findings suggest that emergence, evolution, and permeation could be promoted in the DBL environment as a pedagogical perspective.

Keywords Design-based learning · Design-based research · Science education · Mobile technology

Introduction

This study reports findings from a design-based research (DBR) project for a fifth-grade science class integrating design-based learning (DBL) activities. The aim of this study is to incorporate science in a DBL setting while facilitating cooperative curriculum

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development processes involving constituencies (i.e., teachers, students, and researchers) in a real-world context. The study evolved over three science activities, anchored on scientific concepts around wind, motion, and energy, leveraging mobile phones with relevant applications and sensors. A DBL approach was utilized in this study to help students engage in hands-on (i.e., kinesthetic), minds-on (i.e., cognitive), and attitudes-on (i.e., self-directed) science learning through iterative processes of students' creative design. This approach was used to help students explain scientific phenomena and solve relevant problems.

The DBR process involves multiple stages (1) diagnosing a learning problem, (2) designing DBL activities, (3) facilitating classroom activities, (4) evaluating student interactions and design artifacts, (5) specifying learning evidence over three separate activities, and (6) suggesting the next steps to enhance the continuous cyclical research process. Students who participated in this study were provided with resources to conduct their own experiment designs, encouraged to engage in problem-solving by collective reasoning and solution designs, and scaffolded in documenting, evaluating, and reporting scientific phenomena embedded in a thematic integrative education setting.

Background

According to an analysis of education by the Organization for Economic Co-operation and Development (OECD), there are four desirable types of learning (1) conceptual understanding (i.e., rather than superficial facts and procedures), (2) connected and coherent knowledge (i.e., rather than knowledge compartmentalized into distinct subjects), (3) authentic knowledge in the context of use (i.e., rather than decontextualized exercises, and (4) collaborative learning (i.e., rather than in isolation) (Organisation for Economic Co-operation and Development (OECD) 2008). However, science classrooms have become an authoritative discourse without deep considerations of how to address those significant aspects in students' learning (Osborne 2010). Science teachers have been concerned with the delivery of superficial facts and decontextualized exercises (Lyons 2006).

As Anderson (2012) points out, science education moves from "constructivism to direct instruction, and from local accountability to national standards" (p. 105) though scientific organizations (e.g., AAAS 1989; NRC 1996) have encouraged the use of inquiry-based instruction and constructivist learning. Legislation placed substantial burdens on teachers to conform only to a standard curriculum, leaving no room for innovative pedagogies (Wissehr et al. 2011). As a result, teachers reported less frequent use of inquiry-based lessons (Coble 2006; Katzmann 2007) as science curriculum became more fact-based (Smith and Southerland 2007; Taylor et al. 2008).

Design-based learning (DBL) in science education

Design-based learning (DBL) has been suggested for making science learning more engaging and relevant for students. DBL is an inquiry-based pedagogy combining the merits of project-based learning and problem-solving through students' creative designs. The DBL approach aims to help students construct scientific understanding and real-world problem solving skills by engaging them in the design of artifacts (Fortus et al. 2004). A number of researchers have noted the advantages of DBL as a means for increasing student motivation, developing higher-order cognitive skills, and fostering personal and interpersonal traits (Barak and Raz 1998; Doppelt 2003; Marulcu and Barnett 2013). When students are given the opportunity to creatively devise something that fits their needs and solves a problem, they gain self-esteem and a greater sense of responsibility for their learning (Beetham and Sharpe 2013; Waks 1995). This type of exploration and discovery helps to promote students' self-regulated behaviors (see Neber and Schommer-Aikins 2002). Furthermore, emphasis on reflective thinking and drawing conclusions from the data collected by students are significant predictors of increased conceptual understanding of science content Minner et al. (2010). The iterative process of DBL (i.e., generating questions, designing experiments, collecting data, drawing conclusion, and communicating findings, which lead the evolution of design) supports students' reflective thinking and visualizes their active thinking (Loh et al. 2001).

Previous studies reported empirical evidence that DBL enhances students' learning outcomes. Duran et al. (2014) examined the impact of collaborative design-based learning on 77 high school students' science, technology, engineering, and mathematics (STEM) learning. It was found that the DBL program had a significant impact on students' STEM skills and understanding of the instructional topic (Duran et al. 2014). Also, Fortus et al. (2005) investigated the impact that design-based science had on 149 students' understanding of the curricular content. The results showed a significant increase of scores between the pre- and post-test that measured students' science content knowledge. Silk et al. (2009) also studied the impact of design-based learning on 177 eighth grade students' domain-general science reasoning. Their results showed a significant test score increase in science reasoning.

Though most of the studies focused on the impact of DBL on students' learning gains, there is a dearth of studies addressing the open-ended nature of design, as well as how to scaffold students' imagination for creative design. It is important to note that DBL tasks including content exploration, iterative design process, and collaboration could potentially overburden students (Doppelt et al. 2008). Thus, it is essential to adequately encourage students to improve their designs while methodically facilitating their reflection process and appropriate documentation of their creations (Doppelt 2009). In addition, many science teachers pointed out that students need ample resources and guides in order to organize and communicate ideas in a creative and scientific way (Taylor et al. 2008).

Mobile technology as a scaffolding tool

Recent studies report that mobile technology works as a scaffolding tool in inquiry-based learning. Laru et al. (2012) investigated the use of mobile phones to provide meta-cognitive and procedural support for primary school students during a biology field trip. It was reported that mobile phones promote students' argumentative interactions during inquiry-based learning. Laru et al. (2012) claim that a peer-to-peer messaging application provides procedural and metacognitive scaffolding. Looi et al. (2010) examined the support of mobile technologies in inquiry-based science learning for primary school students. They report that the use of mobile phones support students' engagement in science learning. Moreover, Looi et al. (2010) pointed out that the availability of multiple applications on mobile phones can help students to better observe the world, record significant moments, and synthesize their ideas. Nouri et al. (2013) also examined the use of mobile phones in inquiry-based science learning. It was reported that mobile phones provide both conceptual and procedural scaffolding, which correlates with students' performance scores. Previous studies have used mobile devices as a scaffolding tool in order to provide opportunities for instant access to information and enable instant communications. Beyond that, mobile applications increasingly offer intensive computational tools for learning (e.g., semantic mapping, 3D graphing, simulating scientific phenomena, etc.). Nonetheless, researchers examining the role of mobile phones to support DBL are scarce to date.

Purpose of the study

This study adopts design-based research (DBR), which is a method suitable to both research and design of technology-enhanced learning environments in real-world settings (Wang and Hannafin 2005). With the specific goal of linking theory and practice, DBR has been used in research on inquiry-based science learning (Annetta et al. 2013; Barab and Dede 2007; Ketelhut et al. 2010; Shen et al. 2014).

Towards a theoretical model

This study investigates students' iterative design and learning processes in a DBL environment utilizing various resources including mobile technologies. We assume that new ideas from curiosity and creativity may emerge from the students' DBL process (i.e., evolutionary designs and experiments). Also, we expect that students may learn from observing designs and experiments of their own as well as peers' (e.g., vicarious learning). At the same time, an innovative design concept, discovery from an experiment, and demonstrated understanding of one student might influence the entire class as a process of collective knowledge building. Therefore, we attempt to identify the relevant and supporting evidence of idea emergence, design evolution, and vicarious learning in DBL through a cyclical process of DBR.

Mobile phones

Mobile phones with sensors and diverse applications may provide the necessary scaffolding for student learning in DBL. Specifically, the use of particular application features may play a supportive role in increasing students' imagination, creativity, and design improvement. Although computer devices like desktops provide a variety of applications and tools, mobile phones offer as much or more useful tools. A major advantage of mobile phones is its portability and ease of use as students, engaged in DBL, can fluidly shift from one design phase to another. In addition, mobile applications can be used to search various databases on the Internet, verify information offered by experts with authorities, compare scientific facts, design solutions, and share findings with the larger community. Mobile technology can be devised to support students' overall creative design production. This study is designed to analyze such unique learning opportunities in DBL.

Method

Participants

The participants included 30 fifth-grade students (i.e., 14 male, 16 female) from a public school located in a middle-low income class suburb in Northern California. The student population consisted of diverse racial and ethnic groups. Students were randomly assigned into 6 teams of 5. All participants either owned or had access to mobile phones. The teacher had over 10-years of science teaching experience especially interested in developing students' positive attitudes towards science learning. In a series of interviews the teacher indicated that "students generally find science learning as memorizing a vast arrays of facts and solving problems well on tests.” The teacher wanted to shift students’ attitudes to make science relevant, exciting, engaging, and interesting to her students.

Procedure

As shown in Fig. 1, the DBR process of this study involves dynamic interactions among all participants in an iterative fashion with five phases (1) (re)defining a problem, (2) planning action, (3) implementing, (4) evaluating, and (5) specifying findings.

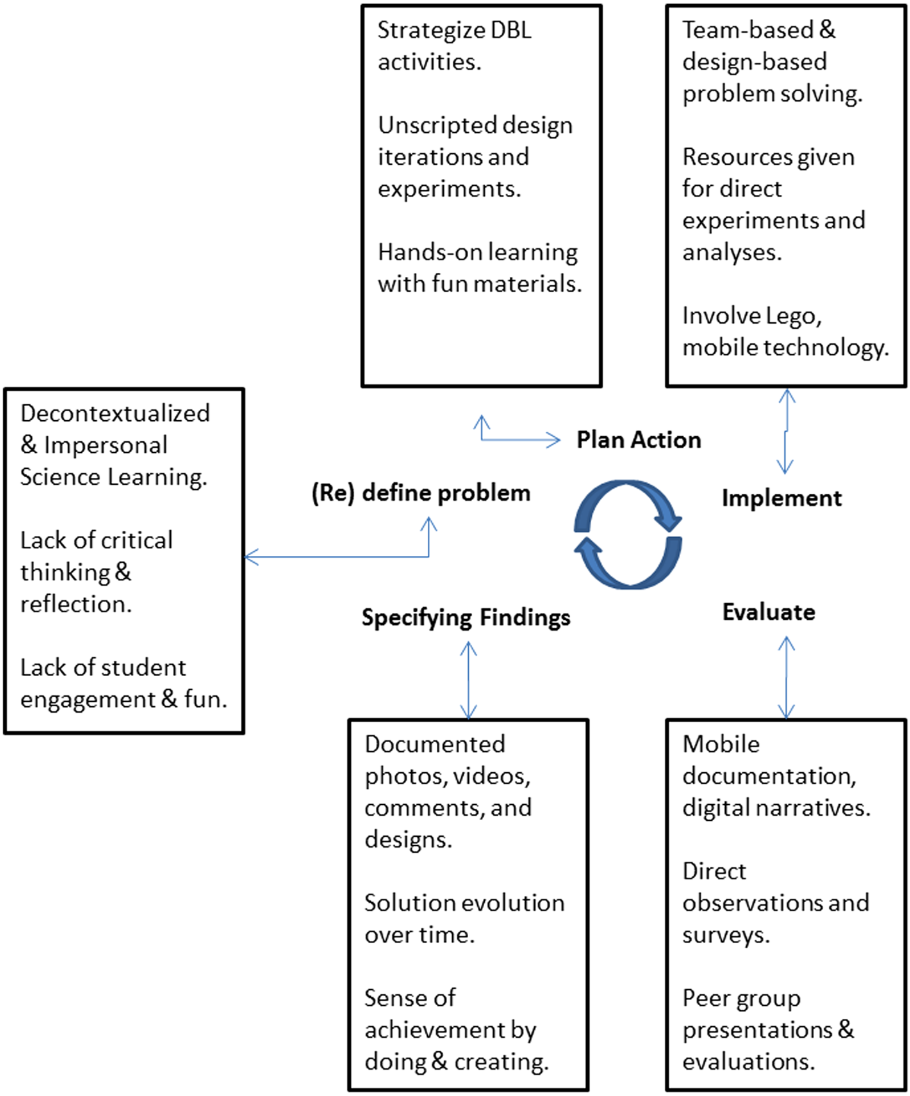

Fig. 1 The cyclical process of the study: (Re) define problems, plan action, implement, evaluate, and specifying findings

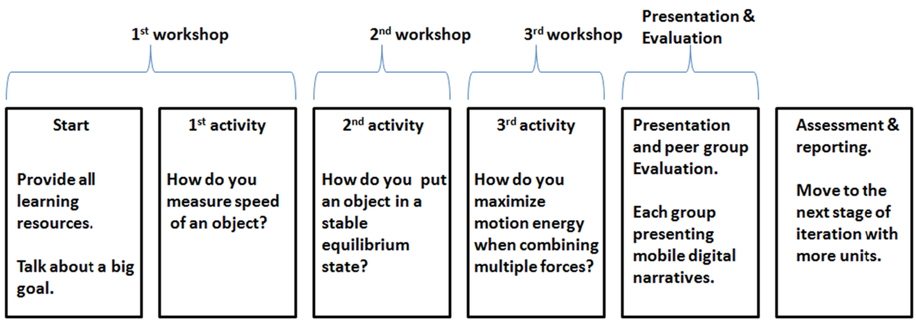

Fig. 2 The workshop and research process

With the teacher's input, we developed three workshops dealing with students' learning to analyze natural phenomena while uncovering characteristics of air, wind, motion, force, and energy. In order to increase the challenge for the student participants, upper grade topics (i.e., comparable to the eighth grade California science standards on Forces, Motion, and Scientific Investigation) were incorporated into the workshops. The workshops spanned a 2-week period in which students spent the remaining 2 h of each school day engaged in tweaking their designs (see Fig. 2).

The students were given a specific challenge for each workshop as shown in Table 1. As a team, the students used the provided materials to design solutions and demonstrate how their designs responded to the challenge. The teacher and researchers assisted students in searching, designing, experimenting, analyzing, reflecting, and articulating their rationale for their design decisions. As an overarching instructional theme, we encouraged students to think about the knowledge required if they were to design a spacecraft 1 day in the future.

Resources

Prior to the present study, we conducted several pilot workshops with fifth grade students in a different school district covering the topic of force. One of the learning objectives was to understand how a multi-floor paper house withstands different types of force while learning the nature of earthquakes, types of waves, and methods of measuring the wave magnitude. In teams, students were asked to build a house with only a set amount of provided materials: a few sheets of papers, paper clips, and a limited amount of tape, glue, and index cards. A lesson gleaned from this pilot workshop is that students' designs are often persuaded by the types, quantities, and characteristics of learning materials.

In the present study, we expected similar implicit persuasion effects. Our goal was to provide materials that may have direct persuasion effects leading to efficient design innovations and a deeper understanding of the scientific phenomena linked to the learning objectives. To help students have more time for experimenting with different designs, we provided them with materials that would potentially save time in making specific parts for their designs. This change transpired from our observations made in the previous pilot study where students spent long periods of time constructing basic building-block pieces they needed for their designs. Thus, the students were provided with party balloons, string, measuring tape, glue sticks, sheets of heavyweight paper, masking tape, a helium tank,

Table 1 Overview of activities

Problems and directions	Resources provided	Description	Purpose
Workshop #1. How do you measure speed of an object?	Lego elements Android phones	Lego cars designed, built, and tested in iteration. Limited supplies used. Design specification: (1) attach mobile phone to car for recording distance (2) power car with balloon air Document design process with mobile phone Whole class competition: each team explains and tests their designs in front of class	Building with limited supplies was used to encourage creative and unexpected designs. Students consider various options to create wind in order to propel their designed cars travel much straighter and much further distance for getting better data to calculate. Through iterations, students experiment with various designs to create and sustain wind power for cars to travel the designated distance
Workshop #2. How do you put an object in an equilibrium state?	Helium balloon	Suspend helium filled balloon in mid-air Use different weight objects for suspension Measure weight of objects, height of suspended balloon and its circumference Record and graph above measurements Document design process with mobile phone Multiple iterations performed	Purpose was to learn about the characteristics of helium and effect of weights. Through this exercise, students become aware of the lifting power generated by helium, thus, creating enough "energy" to carry different amounts of weights. Students also learned to measure, record, and graph their collected data as well as sharing ideas for solutions
Workshop #3. How do you maximize motion energy?	Sail and slope	Designed, built, and tested in iteration: (1) cardboard sail car (2) slope Limited supplies used. Collect data: (1) car distance traveled (2) time it took to travel (3) varying slopes Various scientific mobile applications used for the activity Document design process with mobile phone Peer assessment completed	Demonstrate wind power by propelling their designed vehicles on different slope heights. This illustrates the inter-relationship among weight of car, slope height, and amount of wind power needed. Students learned to collect data and used these data to perform various calculations. Students learned to use various scientific mobile applications as part of the resource toolkit available to them

weight scale, rubber balls, and mobile phones. In addition, each team of students received 20 assorted Lego parts, consisting of wheels, panels, and blocks.

Two Android platform mobile phones were given to each team without specific instructions. The phones came with basic applications such as note, browser, calendar, map, camera, sound recorder, and calculator. If deemed necessary, students were able to install new applications.

Data collection and analysis

Various sources of qualitative data were collected. Researchers' daily observation notes focused on students' attitudes and behaviors, relationship dynamics in teams, student conversations, and other notable moments related to students' learning. Video recordings of each workshop were used to capture as much of the classroom activity as possible. We collected photos and videos retrieved from students' mobile phones, learning summary handouts assigned as homework after each workshop, data on student knowledge acquisition, and peer assessment of each team's final designs. Throughout the workshops, the teacher provided us with feedback and tips on how to manage the classroom and engage certain students.

Marshall and Rossman (1995) analytic scheme was used to iteratively review and organize data for generating categories and clustering segments of texts and scene descriptions. Transcribed data were summarized and designs were recreated in graphic illustrations to decontextualize, identify, organize, and extract overarching themes and meanings. Any unpredicted, unintended, and negative instances were also observed and discussed to challenge apparent understandings of the data.

Findings

Findings reflect six themes identified from the data (1) students' initial behaviors, (2) iterative designs, (3) student learning, (4) emergence, evolution, and permeation, (5) mobile technology, and (6) peer assessment.

Students' initial behaviors

The use of online resources

Though Internet browsing was not part of the planned activities, students set up the phones to access the school wireless network. The teacher later commented that her students frequently helped to troubleshoot various technical issues in the classroom. Before the end of the first workshop, all 12 mobile phones were configured for Internet access by the students. Review of their browser histories showed that students frequently visited sites such as Google (34 %), Wikipedia (27 %), Facebook (21 %), and others (18 %). They mainly searched for information on specific terms and relevant formulas throughout the workshop; often, photos taken from the workshop were posted on Facebook.

Role assignment

Students were broken up into teams at the beginning of the workshop. Though no one mentioned assigning specific roles to different team members, they did this of their own accord. Various roles were assigned to each other. Documenters used the phones to take notes, photos, and videos. Chief Engineers made main design decisions. Experimenters set up and conducted the experiment. Researchers searched for relevant information or "borrowed" ideas from other groups. Team Leaders managed the team as a whole and directed their activities. However, the roles were not fixed as they often switched or combined their roles. A sense of teamwork was prevalent throughout the workshops. One student indicated his familiarity with doing group projects: "We do many team projects … our teacher tells us to help each other … I think we can do more if we work together."

Iterative designs

Students' iterative design efforts were observed throughout the workshops. Most of their efforts revolved around self-directed learning.

First workshop

The primary instructional goal of the first workshop was to accurately measure the speed of an object. In the beginning of the workshop, students did not know how to calculate speed, although they were informed the teacher would provide the formula for speed if requested. However, students found the formula from an online search, as well as answers to questions that arose during the design process. When students figured out the formula for velocity, they proceeded to move objects as their first iteration shown in Fig. 3 left. There were heated arguments about the difference between speed and velocity among the students. However, in the end, they agreed to measure velocity instead of speed since they believed it is harder to accurately measure the distance of an object if it is not moving in a straight line. They realized that causing an object to move in a relatively straight line was not as easy as they thought.

In a subsequent design idea (see Fig. 3 middle), some students built a moving vehicle with Lego parts and tried to measure the time elapsed while pushing the vehicle in a given direction. They used the Stopwatch & Timer app, which they found and installed on their own. However, they realized that the vehicle often did not travel longer than 1 s or in a straight line.

To provide more constant motion, one team began using inflated balloons to cause the vehicle to travel farther. For example, one student controlled the wind with air from a balloon while another pressed the start/stop button on the stopwatch; a downfall to this method was the lack of clear point markers on the table. With this artificial wind energy,

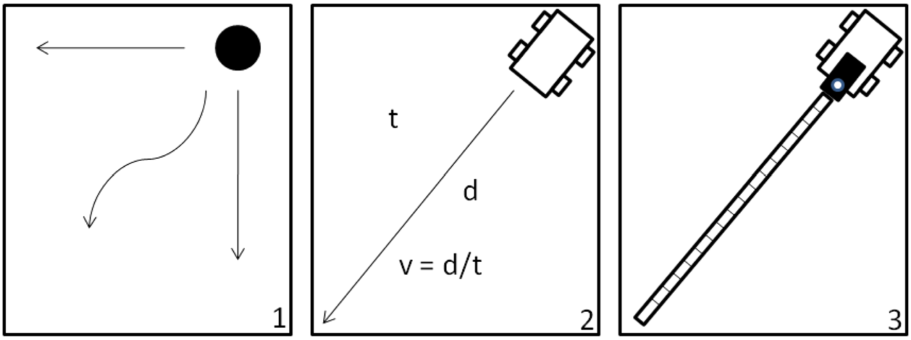

Fig. 3 Design evolution. 1st attempt: use of a rubber ball (*left*), 2nd attempt: use of Lego car (*middle*), 3rd attempt: mobile phone strapped to the Lego car with video recording application running, making the car travel over a tape measure (*right*)

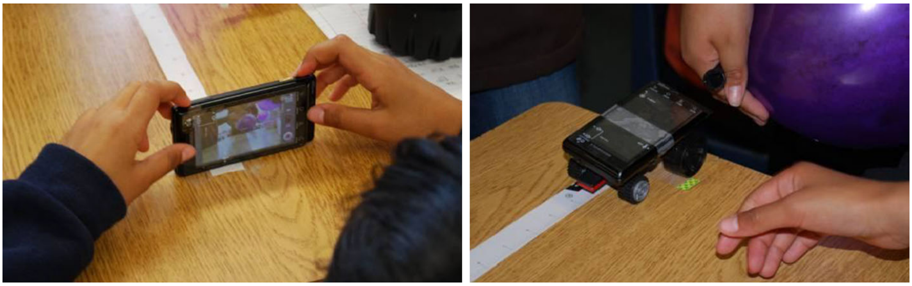

Fig. 4 Indirect video recording design (*left*), Direct video recording design (*right*)

they were able to make the vehicle travel much straighter and farther, from less than 1 s to more than 3 s in this iteration. However, when a researcher questioned the accuracy and reliability of this method, they brainstormed and came up with a more refined design.

As a result, one student decided to take a video image of the vehicle's movement while another student operated the stopwatch. The students placed a measuring tape on the table while pushing the vehicle straightforward with somewhat steady wind energy (see Fig. 4 left). Still, the video image was not in sync with the stopwatch and the video did not capture the entire action with distance pointers. To improve the latest design, another group strapped the phone on the vehicle by pointing its camera to the measuring tape (see Figs. 3 right, 4 right). With the video application, they were able to play, replay, or pause the video to calculate and analyze the average speed. Other groups quickly followed the latest strapped-phone method to obtain higher speed.

Second workshop

The goal of the second workshop was to make a helium-filled balloon stay afloat. One team attached a small rubber eraser to the balloon, but it made the balloon sink quickly to the ground. They then attached bigger, additional balloons, but it made the balloons float upward. After a few iterations without significant improvement in their designs, students were challenged to come up with an explanation of why a helium-filled balloon generally floats upward, yet sinks when weight is attached to it. Students quickly searched the Internet for general characteristics of helium gas and were able to explain several scientific principles: helium is lighter than air, breathing air is heavier than helium, breathing air contains many types of gas, and that gravity is a downward force which pulls down objects with mass. The students realized that any attached weight to the balloon created more downward force (Fig. 5 left) while more helium led to the opposite effect (Fig. 5 middle).

To better understand the balloon's buoyancy and its measuring method, students began to measure various units of different objects. The students were engaged in their experiments and created a chart showing the exact points of ascension and fall. The units measured by the students included the circumference of balloons filled with helium, number of balloons attached to the floating object, and the weight of attached objects. Interestingly, they graphed the relationship between different sizes of inflated balloons and weights of objects lifted by balloons. Though the students realized that their attempt to establish the relationship between measured circumference and buoyancy was not helpful to find the precise weight, they learned how to measure volumes of three-dimensional

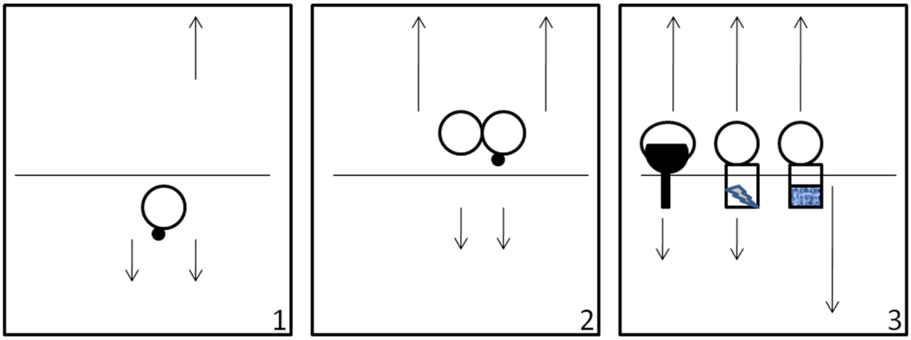

Fig. 5 Design evolution (the second workshop)

Fig. 6 One student experiments with a shredded paper in a clear plastic bag while his team member documents the experiment with the mobile phone

figures (e.g., rectangles, prisms, cones, cylinders, etc.) by finding its formulas on the Internet.

After several attempts, one student suggested that mixing the helium with breathing air would accurately control the overall weight of the balloon (see the left object in Fig. 5 right) and buoyancy. However, there was no surefire way to easily open and close the inlet of a balloon and mix air with helium.

Another team attached a clear plastic bag to the balloon with shredded paper inside; this method allowed them to precisely control and measure the weight of the paper (which they freely added or removed from the bag), as well as the overall weight of the floating object (see the middle object in Figs. 5 right, 6). Later, this team ingeniously punched holes in the pieces of shredded paper to reduce the overall payload of the flying object. Another team aimed to achieve equilibrium by adding or removing controlled amounts of water into a clear plastic bag with a plastic spoon (see the right object in Fig. 5 right). This design gave them more precise control of their overall weight and was able to achieve almost perfect equilibrium.

Third workshop

In this workshop, students were presented with a challenge of maximizing wind energy to fuel a vehicle. Some students attached the mobile phone to multiple balloons to create a source of combined wind energy (see Fig. 7 top left). In response to the abovementioned design, we asked them how they could modify their designs to maximize energy by providing a constant supply of energy more efficiently. One team decided to attach a paper sail to the car, and this new feature was refined by other teams through their design iterations. The initial sail was made of a flat piece of paper attached to a mast made of straw. By testing this design, students noticed that the vehicle moved in a wide range of directions with motion caused by wind. Seeing the vehicle travel in erratic directions, another team augmented this design by making their sail into a half-moon shape so it can capture more wind energy and minimize energy loss (see Fig. 7 top right). The lighter vehicles with this improved sail design traveled farther.

As students improved their designs and seemed content with what they made, we suggested experimenting with their vehicles on a cardboard slope. The intent was to explore a whole new set of principles related to force and gravity. As students tried to keep their vehicle in motion while going up steeper slopes, they realized more propelling force was needed. Otherwise, the vehicle tended to roll back down the slope. When students were asked to explain what forces were at play with the slope, they mentioned gravity as the downward force and wind motion energy as the source of propelling force (see Fig. 8). To help students reflect, they were asked to discuss the relationships of the measured angle,

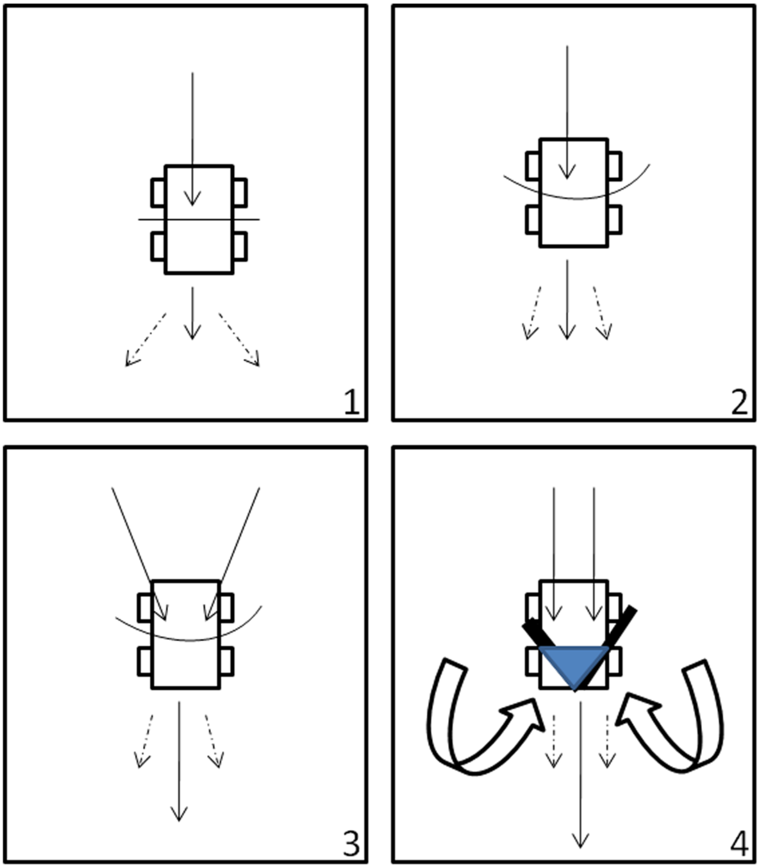

Fig. 7 Design evolution (the third workshop)

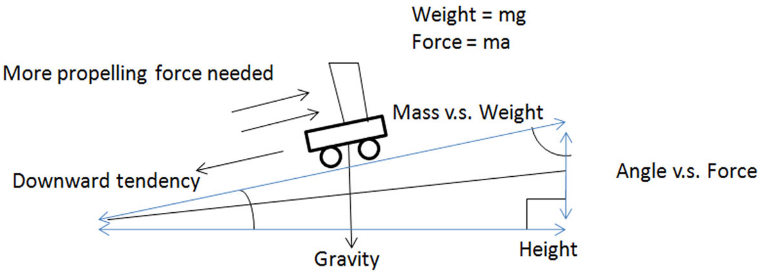

Fig. 8 Terms, phenomena, and relationships discussed during the activity

height at the tip of the slope, and the required wind energy needed to propel the vehicle to the top of the slope as they experimented with different sail designs.

Students created a graph indicating the relationship between the height of the slope versus balloon wind force needed to make the vehicle climb the slope. However, they realized that as the height increased, the angle of the slope also increased. Many students were eager to figure out the exact angle of the slope by applying the measured lengths of the sides of the triangle the slope formed. After realizing the complex and difficult nature of calculating the angle of the slope (i.e., Angles $A + B + C = 180$; $a/\mathrm{Sin}A = b/\mathrm{Sin}B = c/\mathrm{Sin}C$), one team decided to use the leveler application on the mobile phone to get the exact angle of the slope (see Fig. 9 bottom right). They pointed out that mass of the object does not change. However, they were not able to explain how weight might change on the slope as the vehicle moves up and down. Some students indicated that they heard the term, $F = ma$, but did not exactly know what it meant until they searched and read about the formula.

With this increased challenge, students had to come up with improved and more thoughtful designs. When two balloons were used (see Figs. 7 bottom left, 9 top left), students were not able to release the air in a specific direction. In order to increase the control of the vehicle, they tried to mount various shapes of sails at the front, middle, and rear. A dominant design was one in which the sail, made into a curvature shape, was mounted in the front. One team indicated that there is also a resisting force exerted on the sail (i.e., aerodynamics of the sail when it moves forward). This team designed a new sail (see Fig. 7 bottom right), which was almost a triangle shape with a cover on top of the sail to maximize capturing the combined wind energy forces while minimizing the aerodynamic drag.

Student learning

The impact of the DBL approach was shown in student learning from trial and error experiences across all workshops. Students articulated attitudes they found helpful in the design process, like “being patient” and “try and try again.” The latter comment made by Henry, the designated engineer on his team, emphasizes that perseverance achieves desired results. In the first workshop, for example, students searched the Internet for the formula they needed and learned that average speed is the total distance traveled divided by the total time elapsed. They also demonstrated ways to solve problems they encountered as they responded to the design challenge. Though all learning outcomes could not possibly be specified by simply referencing the standards, according to the eighth grade California

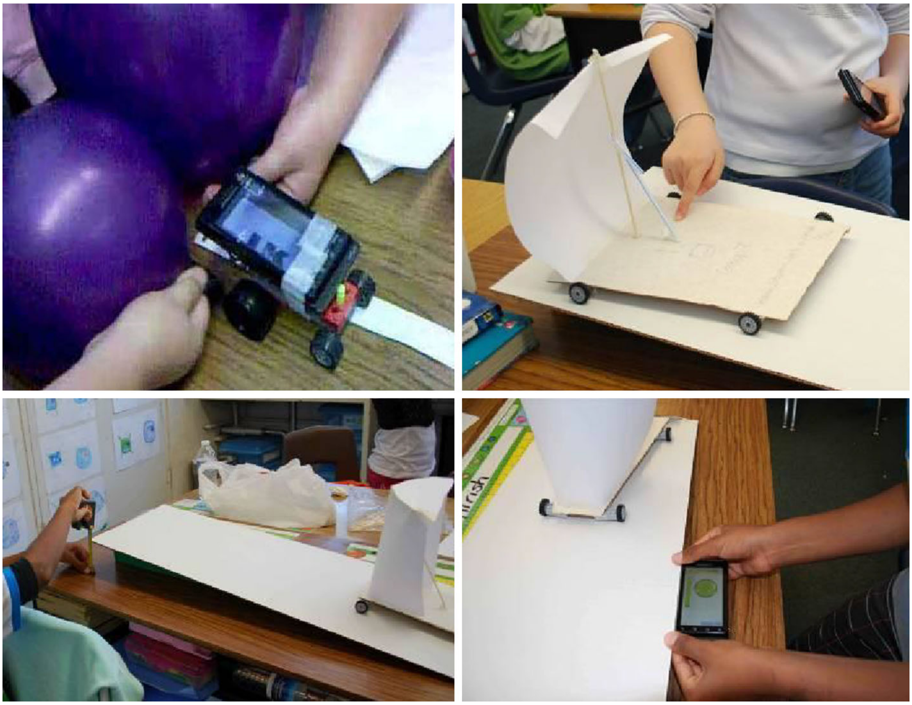

Fig. 9 No sail car (*top left*), Vehicle with improved mast support (*top right*), Measuring the height of the slope while experimenting a vehicle with an aerodynamic- considered sail (*bottom left*), and Experimenting with a later design while measuring the slope angle with a mobile phone application (*bottom right*)

science learning standards, it seems that students obtained specific rules on motion (California Department of Education 2000, reposted in 2009, p. 26) for the following reasons.

In the first workshop, the students understood that (1) average speed is the total distance traveled divided by the total time elapsed and that the speed of an object along the path traveled can vary, (2) changes in velocity may be due to changes in speed, direction, or both, and (3) when the forces on an object are unbalanced, the object will change its velocity.

In the second workshop, the students could identify (1) separate forces acting on a single static object (e.g., lift by helium balloon and gravity, and weights), (2) the greater the mass of an object, the more force is needed to achieve the same change in motion, and (3) when an object is subject to two or more forces at once, the effect is the cumulative effect of all the forces-equilibrium. These learning outcomes are consistent with the eighth grade California science learning standards (California Department of Education 2000, reposted in 2009, p. 26–27). In addition, the students understood that (1) when an object is subject to multiple forces at once, there is the cumulative effect of all the forces, and (2) when the forces on an object are balanced, the motion of the object does not change. They also learned to identify separately the multiple forces that are acting on an object. Further, the learning outcomes could also be relevant to the standard for the grades 9 through 12 on motion and forces because the students understood the relationship between the universal law of gravitation and the effect of gravity on an object at the surface of Earth (California Department of Education 2000, reposted in 2009, p. 31).

In the third workshop, the students had to identify the critical elements of exerting forces while making quantitative observations with instruments to make labeled charts and graphs. The students developed their own testable questions and performed investigations involving a series of complex physics scenarios. All groups designed their own solutions through continual testing, modifying, and learning from unsuccessful attempts. Kelvin shared his experience, “I have learned that if you make the sail bigger, it won’t go good, I learned that if you put the sail on the sides you go faster and better.” He realized that his car speed and direction were affected by sail shapes and their placements. The continual testing and modifying of vehicles led students to better understand the relationships of various factors working together. With the effects of aerodynamics on different shapes of sails and different levels of forces, students learned that if the forces on an object are unbalanced, the object will change its motion. Greater the mass of an object, more force is needed to achieve the same change in motion.

Throughout the DBL activities, the students learned to build designs, solve problems, discover relationships among many elements, and develop attitudes to continuously tackle emerging challenges. Overall, the iterative cycle reinforced the importance of revising their designs based on trial and error experiences, not only for the current task but to foster a positive attitude.

Emergence, evolution, and permeation

The common sequence and processes observed in the workshops were analyzed (see Table 2).

We found common themes: emergence, evolution, and permeation. The emergence of team behaviors (e.g., searching information on the Internet, replicating solutions, improving designs, documenting events and analyses, etc.) was not directed by the teacher. In the workshops, the teacher’s role consisted of exciting the students with the overall goal of ultimately making a flying spacecraft, prompting relevant questions tied to previous classroom learning, and verifying concepts as requested. The teacher’s participation evolved as workshops progressed and students’ understanding of relevant scientific concepts permeated the entire class through vicarious learning. The replication and improvisation of solutions were not discrete events by one individual student or a single team’s effort.

In the workshops, the teacher encouraged students to be active and collaborative team members. We observed that one team member’s moment of enlightenment permeated the whole team while another team’s innovative spirit permeated the whole class. If one team figured out something, others quickly followed to implement what seemed to be a good solution at the given moment. There was a lot of peeking, copying, imitating, replicating, and reusing ideas within the entire class. The workshops provided high levels of self-monitoring, self-explorations, creativity, design thinking, analyses, and articulations along with excitement and joy. It was an opportunity for students to participate in developing collective intelligence.

Mobile phones

In order to explore the supportive aspects of mobile phones in DBL, we identified five categories of usage (1) documenting design processes, (2) searching online resources, (3)

Table 2 The sequence and process observed

Sequence	Details	Workshop #	Supporting Data Sample (Student questions, comments, notes, behaviors)
Understanding of the problem or new problem	A prompt was given by the teacher	1	What is speed…oh…it is distance divided by time What is velocity then? Is it the same thing? No, velocity needs directional…take a look at this page I found
		2	Can we just put the good amount of helium to make it fly and stay in the air? Why these balloons even go up in the air?
		3	What is motion energy anyway? How do you combine forces?
Discussion of the context (problem and potential solution)	Students in team discussed the context of the problem	1	Where can we find the definition…Let's read them again How do we know if that is what we are looking for? Can we build something to test it? How do you give speed to an object to test?
		2	If we put a weight at the end of… it will stay in the air Do we need to know how much helium we need to put into a balloon?
		3	The blowing air from balloons is air force? Yeah…What other forces are there? Gravity? What else?
Verification of current understanding	Students discussed new terms, relevant information around the context	1	Velocity is speed. It's the same thing Does an object need to move in a straight direction?
		2	Let's figure out how to measure the volume of the air in the balloon Is helium lighter than air? Is that why it goes up?
		3	What resisting forces are there? How about the wheels? They have resisting forces, too?

Table 2 continued

Sequence	Details	Workshop #	Supporting Data Sample (Student questions, comments, notes, behaviors)
Searching for new information	Students searched necessary information on Internet	1	Let's Google it! How do they measure speed? Let's watch this Youtube video…Hey, there is a video… They show how to measure a moving vehicle's speed!
		2	Guys, we need to measure the three dimensional volume…That's too hard… Let me search for the formula…
		3	Is there any similar experiment on the web?
Augmentation of knowledge	Students augmented their current understanding of the context with new information identified	1	Is speed distance over time? You just need to get the total distance traveled and divide that by time it took The direction doesn't matter
		2	Actually, it's not necessary to measure the exact amount of air Oh!!! Helium is lighter than air…normal air contains oxygen…see oxygen and nitrogen are heavier than helium…
		3	The higher the slope is the more resisting force is there…We need more power! What if we use two balloons to blow at the same time? But still, we need something to catch the air
Ideation of solutions	Students divided the team and gave roles to come up with a potential solution	1	Can we make something that can move so we can measure the speed? We can make a car with these Legos
		2	How about using this zipper bag to make some weights! How about using this hole puncher to make tiny paper pieces?
		3	Let's put the phone on the Lego car. The smaller wheels must be the front wheels. That's too heavy…

Table 2 continued

Sequence	Details	Workshop #	Supporting Data Sample (Student questions, comments, notes, behaviors)
Construction of solutions	Students tried to come up with a possible solution	1	We can make a car, but we need wheels….The wheels are not good
		2	Don't tie the end too tight
			Make a hole on that bag so we can tie it with the balloon
		3	If you make the mast, it can catch more air force…
			Let's make a slope…This will be easier to show downward forces…
Replication of solutions	Students often copied from other team's ideas	1	They are making a car with Lego!
			Oh! They put wheels on the phone!
			We should use the measuring tape, too!
		2	Hey guys, they are using water drops to make the weight more controllable…Can we try that, too?
			What are they doing? They are breathing in their air…How does that help?
		3	Hey…they are adding a sailing thing on it…
			They are making it lighter to move better…
Improvisation of solution	Based on their findings, they improvised a solution with given resources	1	What if we just leave the video on the phone on?
		2	Using water drop is much easier than the air breathing technique…See they are losing all the helium…
		3	We can measure the slope with the phone. I know it can measure the angle
			Why don't we make the sail edge sharper?
Experimentation	Set up an experiment to try out their ideas	1	Why don't we push the Lego car and measure the speed?
			*Let's put the measuring tape on the table to measure the distance

Table 2 continued

Sequence	Details	Workshop #	Supporting Data Sample (Student questions, comments, notes, behaviors)
		2	Are you getting all these? Record this…See the balloon is almost still
			No, it is coming down eventually. We need to lighten up the weight bag….
		3	OK. Let's roll down to show the downward force and you release the air from the balloon to push it…
			I will record the video with my phone
Articulation of experimentation	Students explained steps involved while recording with mobile video camera	1	Now we need to make sure it.…travels on the tape in a straight line…
		2	When you release the balloon, it is supposed to stay still in the air…not going up…or…going down…
		3	Ah! We can measure the height of the slope, too. Angle and height!!
Observation of results	As a team, they observed how their experiment unfolded	1	Look! We are not doing it right. We need to use the time it traveled, not the time we recorded and stopped
		2	If we add more pieces in the bag, it sinks…fast…
			We need to make the pieces smaller to control better…
		3	See this needs a support otherwise it won't stand the air
Documentation	They took notes and created graphs and charts to record their measuring outcomes	1	Please put the formula on the notepad on the phone
		2	I am making the graph of the amount of the punched holes and the weight measure
		3	Write down the height and angle to make a graph
Explanation of experimentation	As events took place, they explained what was happening with their solution and setup	1	We cannot measure the distance accurately
			If we hold the camera like this, we can measure the time
		2	We cannot measure the amount of helium in the balloon. That's too hard…We need a different technique…to control the weight…

Table 2 continued

Sequence	Details	Workshop #	Supporting Data Sample (Student questions, comments, notes, behaviors)
		3	By letting the car roll down and pushing up by the air, we can show the forces…But why does it come down? What force is there?
Conceptualization of potential theories and principles	They linked with what they found on internet or asked the teacher about theories or concepts involved in their experiments	1	Wait a minute! Is this really the speed? Don't we need to find the average speed? What is the difference between the average speed and just speed?
		2	The more helium, the more power is added to the balloon to go upward. What's that called? Is that the same power as buoyancy?
		3	We found 5 different kinds of forces here. Is there more?
Examination of efficiency and effectiveness of solutions	By observing own experiments and others, they compared and analyzed the overall efficiencies and effectiveness of their solutions and setups	1	By using hands to move the object, the distance is messed up. Then, what do we do? I think the distance is the actual path it traveled so what we are doing is wrong because you are making the phone travel straight forward
		2	If we draw a circle on the balloon with and measure the diameter of the balloon, we may be able to measure the buoyancy better…Let's try to draw circles on all of our balloons and measure the helium…This way, we can have equal amount of helium…
		3	Make the sail V shape to capture more air force and it makes the front air resistance less…That's brilliant! Anything we can do about the wheels?
Consideration of third party opinions	When the teacher interjected opinions or corrected students' understandings, the students corrected their understandings of the concepts	1	Speed itself is an average number OK. OK. How are we going to get the phone travel straight forward without leaving the measuring tape? Velocity needs magnitude and direction information…

Table 2 continued

Sequence	Details	Workshop #	Supporting Data Sample (Student questions, comments, notes, behaviors)
		2	Downward force is gravity? If so, the upward force is buoyancy? Isn't it just in the water? No. Air, too. OK.… Ah! Hydrogen is also lighter than air…We can't use hydrogen because it is flammable…
		3	Weight itself is part of force? What formula is there about it? Ah! Weight is a kind of force?…wow…we have more forces
Enhancement of solutions	Based on new learning, they enhanced their solutions for further experiments	1	How do we make sure the phone is traveling at a constant speed? You cannot right now and it doesn't matter…We are using the average…
		2	OK…Punching holes can make it lighter, but it is not precise enough…let's use water… *We mix breathing air and it becomes more controllable…
		3	Let's use three balloons to blow air upward…make the sail larger with a V shape…

measuring elements, (4) analyzing experiments, and (5) sharing artifacts. The students used mobile phones to accomplish their roles in groups. They took turns exploring and using various functions, such as typing notes, searching for information on Google or Wikipedia, and attempting to upload pictures on Facebook. Many students stated the usefulness of documenting with mobile phones, especially when modifying design errors. A student commented, "It [mobile phone] was helpful because the other day we had a good idea and we had to look back on our pictures and videos, and we found it." Mobile phones provided visual reminders and evidence of their work.

In the final activity, students selected specific mobile applications to complete their designs. Four out of six teams stated that they would recommend mobile applications for their peers working on a similar design-based activity. The reasons varied from being useful to hoping their peers achieve the same level of success as they did. The ease with which they explored, selected, and utilized applications was noticeable. In addition, though the picture and video features of mobile phones were mainly emphasized in the workshop, we found that some students were eager to explore and experiment with other feature on their own; if a resourceful feature was found, students tried to use it to solve a problem or answer a question without getting any input from the teacher.

In all, we observed that students, with specific tasks in mind, can become more self-directed and discovery-oriented learners by using smartphones for educational purposes. In addition, the phones worked as an analytical tool to help researchers examine for which purposes students used the phones and better understanding the significance of the photos and videos they captured.

Peer assessment

In reviewing common ideas across the peer assessment responses, three top criteria were identified (1) imagination, (2) creative features, and (3) function (see Fig. 10).

For imagination, students appreciated designs that were unique and unprecedented. Students attributed words like original, different, cool, and imaginative to describe their favorite designs. The second criterion, creative features, represents students' appreciation for the construction and specific features of the car. Creativity is one of the significant criteria when evaluating a design or a design solution (see Christiaans and Venselaar 2005). Again, most students identified the winning design as the one which showcased a unique wheel placement and large awning type sail. The third criterion, function, describes how fast and smoothly the car traveled on the slope. Emphasis on functionality was apparent in one student's comment: "It did not look so pretty, but it did go up the hill pretty well. It was one of the best." Few students elected non-functioning cars as favorites while rewarding peers for their effort and persistence.

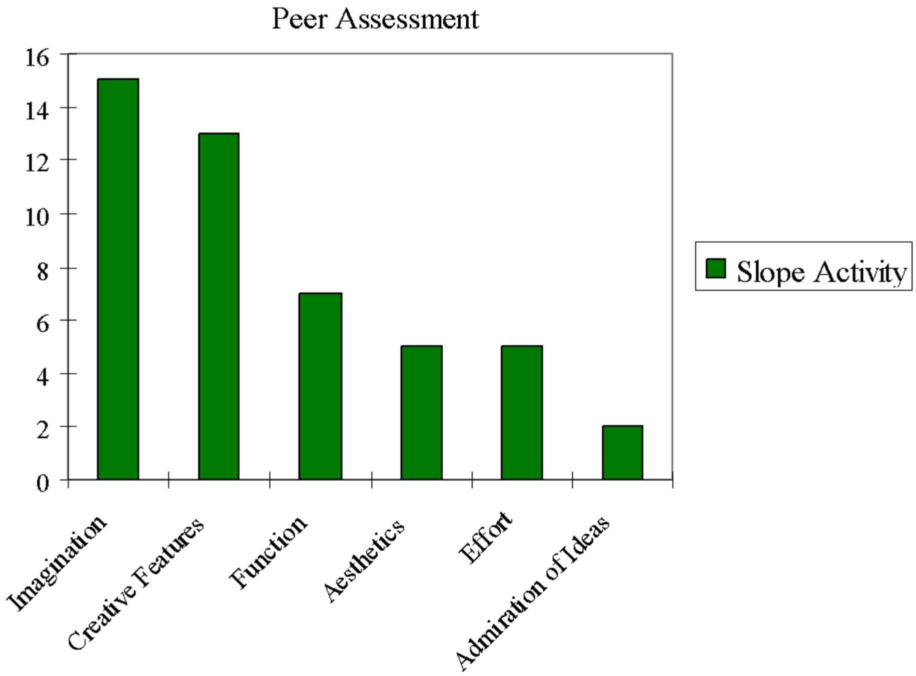

Fig. 10 When asked to provide top three reasons for selecting favorite design, 30 students described range of criteria as shown above

Discussion

We used a DBR approach to understand more about DBL with the support of mobile technology and to improve practice during the process. The results provide a window of what happened with fifth grade students working on engineering design activities with the use of mobile phones. We contend that emergence, evolution, and permeation can be promoted in the DBL environment as a pedagogical perspective. New ideas stemming from curiosity and creativity emerged from the students' DBL process. In addition, students realized the need for a better understanding of math and science concepts in the learning process of DBL. Given these findings, educators need to provide students with learning opportunities that include elements of self-discovery, self-learning, and self-monitoring. This will allow new discoveries and understanding to emerge while students are progressing in their evolutionary designing and learning path. In this study, one student's or one team's discovery, design, realization, and learning permeated the entire class. Therefore, we claim that pedagogies particularly in science education need to allow opportunities for emergence, evolution, and permeation.

The results of this study show that DBL is aligned with the direction suggested by Organisation for Economic Co-operation and Development (2008). First, DBL supports students' efforts in acquiring conceptual understanding. The hands-on and minds-on approach of this study developed students' conceptual learning and a sense of ownership as they created and built their designs. The overall context of the workshops allowed students to "learn science by active doing" (National Research Council 1996; Svihla and Linn 2012).

Second, students' effort to make connections between what they designed and the results they achieved contributed to building a coherent knowledge structure. This hands-on experience for obtaining relevant knowledge has been shown in previous research as having impact of simulation on science learning (Anderson and Barnett 2013). Throughout the modification process of their designs, students explored more relevant and connected knowledge areas, such as searching the Internet for science formulas, learning about the general characteristics of helium gas, or attempting to measure volumes of three-dimensional figures.

Third, the hands-on design experiments facilitate students to acquire authentic knowledge in a real life situation. Through the iterative investigation cycle, students learned to revise their work based on trial and error experiences (Barron et al. 1998). These experiences have become applicable for both classroom learning and real-world problem solving, as well as providing immersive experiences with inquiry and design processes giving students the opportunity to work and think like scientists and engineers. Their efforts to tackle challenges through a series of experiments support authentic knowledge building.

Lastly, the results of this study show how DBL promotes collaborative learning because teamwork comprised a major part of students' design experiences. In this study, it was observed that students' teamwork made learning processes more systematic. Though some students expressed frustration in working with a team, others praised their team's effort and persistence in completing the design tasks.

While working on tweaking their designs, students were watchful of what other teams were doing. They often copied ideas from other teams if they thought it would improve their designs. The team who developed the first solution did not always send up with the best solution. With freedom to iterate on their own, students were open to making adjustments, restarting their designs, and experimenting with new materials and models.

Overall, the results of this study align with Duschl's (2008) view that science education needs to provide active learning experiences and promote integrative knowledge building opportunities. In the third workshop, students kept on experimenting with their designs even after the school bell rang for the day. Such attitudinal outcomes show the benefits of hands-on, minds-on, and attitudes-on integrative science learning. In this study, the teacher was able to observe students' thinking processes through their designs and give feedback on their artifacts. This process led students to take responsibility for their learning and deepen understanding of science content and concepts. In addition, students recognized that achieving success in their design efforts rested on cultivating virtues like patience and perseverance. By implementing design improvements through iterative testing, students became more comfortable with the trial and error process.

Moreover, the issue of teamwork dynamics received considerable attention from students as their working experiences both encompassed the advantages of working with others and the challenges of working through interpersonal issues and differences. Although some group dysfunction challenged students, they were able to overcome problems and set them aside for the sake of completing their designs successfully within the allotted time.

The peer assessment criteria developed from students' responses deepens our understanding of which design element they recognize and appreciate. Students' abilities to not only effectively assess themselves but also others in group situations with proper training have been recognized (e.g., Bransford et al. 1999). As a result, the peer assessment approach has great promise in their ability to facilitate and advance design activities and potentially recognize creativity and radical innovations versus incremental innovations in design features (Atuahene-Gima 2005). Though peer assessment was used for summative purposes in this study, future studies could implement peer-based formative assessment more frequently. The affordances of peer evaluation activities not only require students to fully understand the criteria for assessment, but they also invite learners to partner in the process of defining quality work in DBL activities. Students were generally empathic in their assessments, and they overlooked design to praise team effort.

The results of this study show that during the design improvement process students fluidly moved back and forth from collecting data, documenting with their phones, exploring relevant information, and sharing ideas with others. Thus, we argue that DBL encourages students' process of emergence, evolution, and permeation toward self-directed learning. Many participants in this study commented that mobile phones were an effective tool for supporting their imagination and creative design. The results seem to suggest that by performing design projects with the contextually-relevant information and tools, mobile technology can be used as a scaffolding tool for students' imagination, creativity, and finally improved designs.

Suggestions

We suggest that this exploratory research model is appropriate in addressing the issues of making science learning more approachable, interesting, enjoyable, and contextual while determining the efficacy of the pedagogy, resources, and conditions needed for the continuous curriculum enhancement process. Working with the teacher, the iterative design and formative evaluation focused on helping us identify and tackle obstacles in the implementation of effective instruction. Throughout the reflective phases in this DBR study, the following suggestions were developed.

First, we need a more appropriate assessment paradigm for DBL. The traditional assessment has been bound by grade-specific curriculum standards. This assessment aims to measure knowledge by requiring students to recall discrete science facts, concepts, and theories. In this situation, it is almost impossible for science teachers to introduce wide topical knowledge (Minner et al. 2010). New assessment strategies are needed for complex teaching and learning environments. In this regard, there is a need for creating more flexibility into the curriculum where students and teachers have the freedom to explore and examine new ideas and inquiries.

Considering limitations stemming from standards and assessment gridlock, today's grade-school science education programs need to make room for innovative and stimulating science learning to occur in classrooms. Under current circumstances, even those heavily-researched pedagogies of inquiry-based learning, supported by the latest technological innovations, would be neglected in the overwhelming pressure to conform to grade-specific standard curriculum and to excel on standard tests. We believe that challenging students to inquire and explore scientific phenomena, as would an engineer or a scientist, would broaden their understanding of how science is all around them and that learning about it is relevant to their lives, which are areas that standardized testing does not adequately cover.

Another suggestion is that teachers provide more guidance for students in their learning, which is consistent with the recent suggestion made by DBL researchers in science education (e.g., Gómez Puente et al. 2013). We realized firsthand the significance of this suggestion from our observations and experiences with the iterative research cycles of our workshops.

In the first workshop, teacher intervention at the proper time was important for students to measure and calculate the proper element. In the second workshop, the teacher's challenging questions motivated students to articulate their observations and understanding of the scientific phenomena at hand. Learning from the previous iteration that teacher's questions encouraged students to slow down and reflect on their design activities, the third workshop included more teacher participation in asking students to explain the relationships of the concepts and measured data. Towards the last end of the workshop series, the teacher became more accustomed to her role as a coach and facilitator. An implication for teacher training programs would be to focus efforts on helping teachers to become comfortable as active inquirers with students rather than deliverers of static knowledge. This kind of training would make teachers more amenable to incorporate DBL activities in the classroom, thus making the activities enjoyable and exploratory for both teachers and their students.

Mobile technology seems to play an effective role in DBL classrooms. In this study, mobile devices were perceived by students as useful measuring and learning tools. The inclusion of mobile technology in activities not only generates a high level of enthusiasm and interest in students (Kim et al. 2008), but it also helps students achieve higher accuracy in measuring various scientific phenomena. Student-recorded notes, photos, and videos offer students the opportunity to discern which information is pertinent to record; also, it gives them the security and assurance that valuable information, insights, observations are stored for review for future purposes. From a research standpoint, these student-recorded data deepens our understanding of student learning processes, learning outcomes, and the effects of educational interventions.

For future implementations, an improvement to consider in these DBL workshops is to have students begin the activities by recording a couple of predictions of possible outcomes that may result from their experiment. In this way, more real-world scientific experimentations can be emulated while triggering students to think more critically about the scientific phenomena they are about to witness and learn.

Future research

Future studies on DBL implementations in the classroom would include more precise measurements of students learning outcome. Pre- and post-test scores of individual students and teams would highlight specifically which and how much of the content was learned. In addition, the next iteration of a related study can provide articulation, presentation, argumentation, and self-evaluation opportunities for students and teams to create digital narratives of their design process. These activities would help students to reflect on experiences and practice presentation skills. Given the fact that many students often posted photos collected from the workshop on their Facebook page, future studies are needed to investigate if there might be an opportunity to leverage the motivating power of social media networks in design-based learning activities (e.g., posting a design idea or a successful solution for crowed feedback gathering and knowledge augmentation).

Conclusion

This exploratory study on DBL using mobile technology provides evidence that student learning by hands-on iterative designs can be expanded beyond a grade-level curriculum. DBL in science involves the cyclical processes of generating and improving different designs to solve problems anchored in a real-world context while investigating and measuring the efficiency and effectiveness of each design. For DBL to take place successfully, teachers need training to become fellow inquirers and designers with students while guiding them with challenging questions to understand scientific phenomena beyond the specific grade level material. This change may be more difficult to adopt in elementary school structures as that would cause a major shift in classroom activities and a role change in traditional teacher student relationships. Nonetheless, what seems counter-intuitive is that the current educational structure pushes students to memorize facts for standardized tests when students would gain more from asking and examining questions on what they find as interesting scientific phenomena. Perhaps, it is necessary to leverage today's research findings and appropriate technology to create a new learning environment where students engage in real science experiments with the freedom to explore their inquiries when they are younger and more curious.

References

American Association for the Advancement of Science (AAAS). (1989). *Science for all Americans: A project 2061 report on literacy goals in science, mathematics, and technology*. Washington, DC: AAAS.

Anderson, K. J. (2012). Science education and test-based accountability: Reviewing their relationship and exploring implications for future policy. *Science Education, 96*(1), 104–129.

Anderson, J. L., & Barnett, M. (2013). Learning physics with digital game simulations in middle school science. *Journal of Science Education and Technology, 22*(6), 914–926.

Annetta, L. A., Frazier, W. M., Folta, E., Holmes, S., Lamb, R., & Cheng, M. T. (2013). Science teacher efficacy and extrinsic factors toward professional development using video games in a design-based research model: The next generation of STEM learning. *Journal of Science Education and Technology, 22*(1), 47–61.

Atuahene-Gima, K. (2005). Resolving the capability-Rigidity paradox in new product innovation. *Journal of Marketing, 69*(4), 61–83.

Barab, S., & Dede, C. (2007). Games and immersive participatory simulations for science education: An emerging type of curricula. *Journal of Science Education and Technology, 16*(1), 1–3.

Barak, M., & Raz, E. (1998). Hot air balloons: Project centered study as a bridge between science and technology education. *Science Education, 84*(1), 27–42.

Barron, B. J., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., & Bransford, J. D. (1998). Doing with understanding: Lessons from research on problem-and project-based learning. *The Journal of the Learning Sciences, 7*(3–4), 271–311.

Beetham, H., & Sharpe, R. (Eds.). (2013). *Rethinking pedagogy for a digital age: Designing for 21st century learning*. London: Routledge.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.

California Department of Education. (2000). *Science content standards for California public schools: Kindergarten through grade twelve*. Sacramento, CA: California Department of Education.

Christiaans, H., & Venselaar, K. (2005). Creativity in design engineering and the role of knowledge: Modelling the expert. *International Journal of Technology and Design Education, 15*(3), 217–236.

Coble, J. (2006). Curricular constraints, high-stakes testing and the reality of reform in high school science classrooms (Doctoral dissertation). Available from ProQuest Dissertations & Theses Database (UMI No. 3207430).

Doppelt, Y. (2003). Implementing and assessing project-based learning in a flexible environment. *International Journal of Technology and Design Education, 13*(3), 255–272.

Doppelt, Y. (2009). Assessing creative thinking in design-based learning. *International Journal of Technology and Design Education, 19*(1), 55–65.

Doppelt, Y., Mehalik, M. M., Schunn, C. D., Silk, E., & Krysinski, D. (2008). Engagement and achievements: A case study of design-based learning in a science context. *Journal of Technology Education, 19*(2), 22–39.

Duran, M., Höft, M., Lawson, D. B., Medjahed, B., & Orady, E. A. (2014). Urban high school students' IT/STEM learning: Findings from a collaborative inquiry-and design-based afterschool program. *Journal of Science Education and Technology, 23*(1), 116–137.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*(1), 268–291.

Fortus, D., Dershimer, R. C., Krajcik, J., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-based science and student learning. *Journal of Research in Science Teaching, 41*(10), 1081–1110.

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education, 27*(7), 855–879.

Gómez Puente, S. M., van Eijck, M., & Jochems, W. (2013). Facilitating the learning process in design-based learning practices: an investigation of teachers' actions in supervising students. *Research in Science & Technological Education, 31*(3), 288–307.

Katzmann, J. M. (2007). The influences of implementing state-mandated science assessment on teacher practice. Available from ProQuest Dissertations & Theses Database (UMI No. 3280260).

Ketelhut, D. J., Nelson, B. C., Clarke, J., & Dede, C. (2010). A multi-user virtual environment for building and assessing higher order inquiry skills in science. *British Journal of Educational Technology, 41*(1), 56–68.

Kim, P., Miranda, T., & Olaciregui, C. (2008). Pocket school: Exploring mobile technology as a sustainable literacy education option for underserved indigenous children in Latin America. *International Journal of Educational Development, 28*(4), 435–445.

Laru, J., Järvelä, S., & Clariana, R. B. (2012). Supporting collaborative inquiry during a biology field trip with mobile peer-to-peer tools for learning: a case study with K-12 learners. *Interactive Learning Environments, 20*(2), 103–117.

Loh, B., Reiser, B. J., Radinsky, J., Edelson, D. C., Gomez, L. M., & Marshall, S. (2001). Developing reflective inquiry practices: A case study of software, the teacher, and students. In K. Crowley, C. Schunn, & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings* (pp. 279–324). Mahwah, NJ: Erlbaum.

Looi, C. K., Seow, P., Zhang, B., So, H. J., Chen, W., & Wong, L. H. (2010). Leveraging mobile technology for sustainable seamless learning: A research agenda. *British Journal of Educational Technology, 41*(2), 154–169.

Lyons, T. (2006). Different countries, same science classes: Students' experiences of school science in their own words. *International Journal of Science Education, 28*(6), 591–613.

Marshall, C., & Rossman, G. B. (1995). *Designing qualitative research*. London: Sage Publications.

Marulcu, I., & Barnett, M. (2013). Fifth graders' learning about simple machines through engineering design-based instruction using LEGO^{TM} materials. *Research in Science Education, 43*(5), 1825–1850.

Minner, D. D., Levy, A. J., & Century, J. (2010). Inquiry-based science instruction - what is it and does it matter? Results from a research synthesis years 1984–2002. *Journal of Research in Science Teaching, 47*(4), 474–496.

National Research Council (NRC). (1996). *National science education standards*. Washington, DC: National Academy Press.

Neber, H., & Schommer-Aikins, M. (2002). Self-regulated science learning with highly gifted students: The role of cognitive, motivational, epistemological, and environmental variables. *High Ability Studies, 13*(1), 59–74.

Nouri, J., Cerrato-Pargman, T., & Zetali, K. (2013). *Human-Computer Interaction. Applications and Services* (pp. 464–473)., Mobile inquiry-based learning Berlin: Springer.

Organisation for Economic Co-operation and Development (OECD). (2008). 21st century learning: Research, innovation and policy directions from recent OECD analyses. Retrieved May 1, 2014 from http://www.oecd.org/dataoecd/39/8/40554299.pdf.

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

Shen, J., Jing, L., Chang, H., & Namdar, B. (2014). Technology-enhanced, modeling-based instruction (TMBI) in science education. In J. M. Spector, M. D., Merrill, J. Elen, & M. J., Bishop (Eds.), *Handbook of research on educational communication and technology* (4th ed., Chap. 46). New York: Springer

Silk, E. M., Schunn, C. D., & Cary, M. S. (2009). The impact of an engineering design curriculum on science reasoning in an urban setting. *Journal of Science Education and Technology, 18*(3), 209–223.

Smith, L. K., & Southerland, S. A. (2007). Reforming practice or modifying reforms? Elementary teachers' response to the tools of reform. *Journal of Research in Science Teaching, 44*(3), 396–423.

Svihla, V., & Linn, M. C. (2012). A design-based approach to fostering understanding of global climate change. *International Journal of Science Education, 34*(5), 651–676.

Taylor, A. R., Jones, M. G., Broadwell, B., & Oppewal, T. (2008). Creativity, inquiry or accountability? Scientists' and teachers' perceptions of science education. *Science Education, 92*(6), 1058–1075.

Waks, S. (1995). *Curriculum design: From an art towards a science*. Hamburg: Tempus Publications.

Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development, 53*(4), 5–23.

Wissehr, C., Concannon, J., & Barrow, L. H. (2011). Looking back at the Sputnik era and its impact on science education. *School Science and Mathematics, 111*(7), 368–375.

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