

Wearable Learning: Multiplayer Embodied Games for Math

Ivon Arroyo

Worcester Polytechnic Institute
Worcester, MA
iarroyo@wpi.edu

Matthew Micciollo

Worcester Polytechnic Institute
Worcester, MA
mmicciolo@wpi.edu

Jonathan Casano

Ateneo de Manila University
Manila, Philippines
jonathancasano@gmail.com

Erin Ottmar

Worcester Polytechnic Institute
Worcester, MA
erottmar@wpi.edu

Taylyn Hulse

Worcester Polytechnic Institute
Worcester, MA
trhulse@wpi.edu

Ma. Mercedes Rodrigo

Ateneo de Manila University
Manila, Philippines
mrodrigo@ateneo.edu

ABSTRACT

We present a new technology-based paradigm to support embodied mathematics educational games, using wearable devices in the form of SmartPhones and SmartWatches for math learning, for full classes of students in formal in-school education settings. The Wearable Learning Games Engine is web based infrastructure that enables students to carry one mobile device per child, as they embark on math team-based activities that require physical engagement with the environment. These Wearable Tutors serve as guides and assistants while students manipulate, measure, estimate, discern, discard and find mathematical objects that satisfy specified constraints. Multi-player math games that use this infrastructure have yielded both cognitive and affective benefits. Beyond math game play, the Wearable Games Engine Authoring Tool enables students to create games themselves for other students to play; in this process, students engage in computational thinking and learn about finite-state machines. We present the infrastructure, games, and results for a series of experiments on both game play and game creation.

Author Keywords

Wearable learning; embodied cognition; educational games; mathematics; computational thinking; tutoring systems.

ACM Classification Keywords

Human Factors; Design

1. INTRODUCTION

This project is rich in the foundational constructs of learning sciences and technologies research with several

movable and exciting parts. From embodied active math learning experiences to collaborative game-based learning experiences, the project engages students with mobile technologies to support math learning, as well as game creation to promote computational thinking.

A growing body of research in math education and cognitive science describes the important role of embodiment, object manipulation and motion while learning mathematics [3-5, 22, 29]. Embodied learning involves the combination of movement and gestures with higher-order cognitive activities, such as analyzing and evaluating. By grounding students through physical movement and gesture, abstract concepts can become more concrete. We ground our research on Activity Theory, which poses that consciousness and activity, including the body and environment, are all interconnected within the same system [28]. This means that any artifacts used in activity, such as physical objects, tools, or technology, are also part of the same system. In learning environments, these tools mediate that activity system and can be used to enhance learning.

At the same time, recent technologies have become more tangible, sharable and even wearable. There is potential for these new technologies to redefine the way that teachers and students interact among themselves, the content, and technological artifacts, for a shared experience that improves learning through rich interactive discourse. The benefits of technology in education in particular are well known by now: Computers are good at instantly processing large amounts of data, providing students more agency and choice, allowing for self-paced trajectories through the content, providing just-in-time support and also helping teachers with assessment [7]. However, technologies that support embodied experiences are only now starting to emerge [23, 30-31, 34]. Embedding innovative, engaging, and effective high-quality embodied technologies in K-12 mathematics classrooms has the promise of improving support given to individual students, while motivating them in STEM, via rich experiences that blends technology into classroom culture. This research article introduces a new way of learning mathematics via wearable/mobile

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than the author(s) must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

Request permissions from Permissions@acm.org.

CHI PLAY '17, October 15–18, 2017, Amsterdam, Netherlands © 2017 Association for Computing Machinery. ACM ISBN 978-1-4503-4898-0/17/10...\$15.00

<https://doi.org/10.1145/3116595.3116637>

technologies that can integrate active physical play and math-rich experiences, facilitating shifts in both learning and affective outcomes. We present two series of studies that explore the feasibility of using wearable and mobile technologies for game playing and game creation, in the context of schools.

We first describe paper-based pilot studies that have iteratively driven the development of this technology. Second, we present the “Wearable Learning Games Engine” infrastructure. Third, we present results from research studies that investigated how these games, where players are supported by mobile devices, can yield gains in math achievement as well as affective gains (appreciation of math and comfort while solving math problems). Last, we present results of a recent study of students themselves creating their own embodied math games, switching their role from problem solvers to “problem posers”. This required students to think at a high level of abstraction, engage in computational thinking skills, and learn to specify the role of mobile devices as guides and helpers to the players, defining the behavior of the mobile devices at each step of the game, as finite-state machines.

1.1 Background Research

Educational games are at the forefront of learning technologies, and game-based curricula is implemented to foster engagement and motivation, provide communities of learning, and enhance performance [17, 20, 24]. Technology-based education games range in structure from individual practice to fully immersive, multi-player environments. Drill and practice games are more feasible to introduce into the classroom and integrate into a traditional curriculum [25]. Immersive adventure games such as Quest Atlantis [11] have a socially-responsive design and student-driven storyline played across individuals and entire classrooms.

Learning technologies for mathematics in particular have design features that benefit students more than traditional paper-based activities including immediate and adaptive feedback, dynamic interactions aligned with mathematical rules, as well as the potential for detailed formative assessment [7, 14, 25]. All together this makes for a richer, more interactive, and more informative learning environments for both teachers and students.

More recently, some have argued that mathematics learning environments should be more embodied [1, 5, 28]. The idea of embodied learning involves the creation, manipulation, and sharing of meaning through engaged interaction with artifacts [18]. Students may be guided to encounter, discover, rehearse, and ultimately investigate new perceptuo-motor schemas. A general objective of embodied learning is for learners to develop cognitive resources that presumably undergird specialized forms of human practice, such as solving mathematics problems by productively struggling with mathematical content during an activity with corresponding physical movement, rather than merely

repeating numbers or operations [1-2]. Embodied learning is also based on the constructivist tradition of promoting passages from non-symbolic interaction to symbolic representation [9, 12]. Further, this work builds on the Theory of Situated Learning first proposed by Lave and Wenger [26] as a model of learning in a community of practice. Situated learning argues that learning should not be viewed as simply the transmission of abstract and decontextualized knowledge from one individual to another, but a social process whereby knowledge is co-constructed, situated in a specific context and embedded within a particular social and physical environment. Still, we consider that the theory most aligned with this research is Activity Theory [28], which emphasizes the interaction between people, artifacts, and social groups. Activity Theory highlights the importance of leveraging life-relevant connections available within the physical space and considering policies and norms related to learners’ physical bodies, physical spaces and objects, and the importance of co-design with children and teachers. Activity Theory has already been used as a theoretical framework for other embodied technologies for science education, research that is co-occurring at the same time as ours [16].

Embedding mathematics in their everyday activities, games and lives encourages students to find mathematics everywhere –transmitting the idea that math can be reached and experienced with their hands and full bodies as much as their mind. One way this has been achieved has been through research using technology-based games in museums, especially scavenger hunts. For instance, Drake et al. [19] show two examples of how wearable devices can be appropriated for use in school settings. These examples focus on instances where students turned activity trackers into objects of inquiry using data from familiar activities. Similarly, Tsai & Sung [37] extend, preserve, and integrate the museum experience with visitors’ personal and social lives, via mobile apps can enhance visitors’ museum experiences via scavenger hunts. These scavenger hunts are based on individual experiences in informal settings, however, our work involves team-based and formal education settings and uses this ecological perspective to integrate students, teachers, physical objects and school spaces with learning math, playing math, creating math and growing together as a community of practice.

Regarding wearability, technological devices are becoming more portable and wearable (e.g. iWatch, Samsung’s SmartWatch, Google Glass). The outstanding benefits of mobile technologies are: light, easy to wear or carry, and the capability to track physical activity, location information and, thanks to Near Frequency Communication (NFC) also interact with objects. These characteristics make mobile technologies appealing for a variety of social purposes, such as education and health. For instance, Chiu & Liu [15] studied SmartWatches for older adults for fall detection and medication reminder applications. The Google Glass was used for simulation-based training to

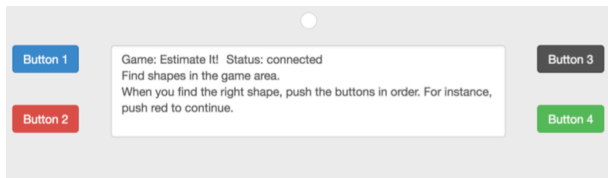


Figure 1. What students can see on their mobile device as they begin to play *EstimateIT!*

record actions and later analyze, showing that it can be integrated into simulation-based training and debriefing, not interfering with the simulation experience [40]. Some applications of mobile devices to education imply carrying one device. For instance, Google Expeditions enables students to take virtual field trips by hooking a cell phone in low-cost cardboard glasses.

2. THE WEARABLE LEARNING TECHNOLOGY

The technology explained next may be wearable or not --we have experimented with students wearing cell phones in armbands, and also created a client App for an Android-based SmartWatches. It is not conclusive yet what would be the best mode of carrying a device, and this might well depend on the characteristics of the game being played. Regardless of whether it is wearable (watch) or carried (cell phone), the assumption is that there is one easy-to-carry mobile device per student available, one per student-player.

2.1 The Wearable Learning Games Engine

The core of the software is a remote java-based web-server, which alternatively can run locally on the teacher's computer. The Wearable Games Engine plays the following roles: (1) communicates with the devices; (2) maintains the state of individual players and games; (3) aids the teacher in the general functioning of activities (start the game, verify progress, determine the winner); (4) allows management of classes and allows the teacher to specify teams of students; (5) keeps track of individual and team progress; (6) allows the creation of new games through an authoring tool.

It is important to note that a variety of games can be created with this infrastructure that make use of these same mechanisms. This goes beyond scavenger hunts, as will be shown later in Section 4.

When the Wearable Learning App in the SmartPhone or SmartWatch is launched and a student joins an active game, the device opens a web-socket communication and handshakes with the web-server, which returns the first "state" of the game. The Web Server connects to a database that keeps track of students, games, devices, and gathers a history (a log) of student events.

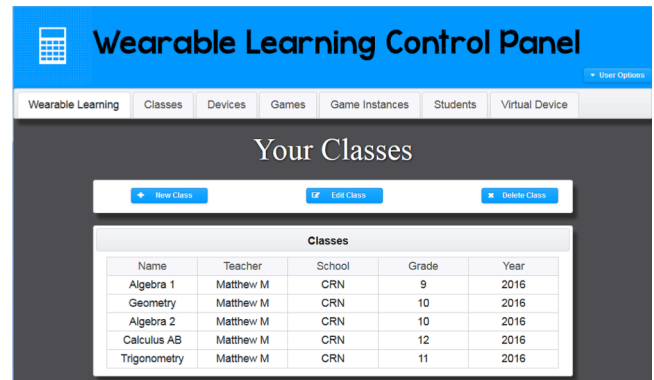


Figure 2. Control Panel for teachers to create, edit and delete classes, students, teams and start games (or create games).

Teachers have a web-based Control Panel available to them, the so-called *Wearable Learning Control Panel* (Figure 2), an HTML-based interface accessible from any web-browser. This tool allows teachers to log in to manage games, students and classes, as teachers might have more than one class of students working on the same games activity at different times. Teachers can create accounts, access and modify their own classes, students and devices. The data is persistent and remains stored in a remote location (database server). In the future, this control panel will also allow students to log in to create/enter their own games --for the time being, it is only teachers that can login.

2.2 The Games

Math Games involve multiple players and require players to have an Android-based SmartPhone or SmartWatch running an App. The first role of the mobile device is to maintain game flow --to give instructions to the player on what he/she should do, keep pace of the game; the second role is to provide feedback and support (e.g. 'that was incorrect; try again, or push the black button for a hint').

Behind the scenes, each game is specified as a finite-state machine (FSM), in that every output and text displayed on the device at any point of time is defined as a unique "game state". Figure 1 shows the first state of the *EstimateIT!* Game displayed on the phone, which all students see after joining that game. Note a FSM is an abstract machine defined as being in one of a finite number of states (an output state) and having transitions between states that correspond to events (input events, button presses, or NFC scans). The machine can be in only one state at a time, called the 'current state', which is the state the player is in at this time.



Figure 3. Everyday Geometric Objects tagged with Color Codes for EstimateIT! to be played

Transitions between states correspond to student inputs, such as colored button presses. The player's current state changes from one state to another after a specific event or condition is triggered, called a transition event. For instance, in the game described later called *EstimateIT!*, students push buttons for a few purposes: to “continue” to the next instruction (e.g. push any colored button to continue), to ask for help (“push the black button if you need a hint”), or to communicate that they have found a specific object (Each object in the game has been tagged with a 4-color “bar code” that needs to be entered by the student when the sought object is found, such as Red-Green-Blue-Red, see Figures 3-4). These tags identify and are attached to objects so that students can match and integrate the real world to the current state of the game -- from small geometric shapes to windows, sections of a playground/climber, depending on the game. Games may use NFC tags to identify objects, however, note this also makes the creation of new games (e.g., by teachers) somewhat harder than plain color sequences.

Within the game-creation authoring tool, states are represented as circles or boxes (Figures 5 and 6), and events connect states via directed arrows [27]. The authoring tool allows to specify games in graphical form (State Machine

view) or in pull down menu mode (Create Game States view). This is only accessible to teachers (and researchers) for the time being, but will be accessible to student accounts in the near future.

2.3 Collaboration and Cooperation

When students play, they may work individually or in teams. The game might have been set up to involve ‘collaboration’, implying that every member of the team gets exactly the same math question/challenge on each player’s device (everybody is given the same assignment or problem to solve) or ‘cooperation’ [36] implying that different people within the team get complementary roles and different assigned objects to find. In this case, the smartphones are semi-synchronized for people in the team so that individual players cannot move beyond certain states unless every person in the team has gotten there. We called this the “stall for team” condition of a game state, which implies that neither watch in the team can transition to the following game state until all students in the team have finished a specific task (i.e., the team cannot move on to the next stage until every person has solved the math challenge, opening up possibilities for peer help/support by team members). We consider this an innovative way to encourage peer support and collaboration.

3. GAME PLAYING

One of the major games developed for this infrastructure is *EstimateIT!*TM, a measurement estimation and number sense game for 4th–6th grade students [33]. The game is a Scavenger Hunt where students search for objects hidden around a physical space. Level 1 involves the search of geometric shapes and measurement estimation through team-based cooperation, where teams are given individual tasks to complete to help their team succeed; this may involve helping each other as more expert team players finish first. For example, the display could show the following message to a player: “Find a cube with a 6 inch side”. When pushing the hint button: “I am a volume with 6 equal faces: use your 12-inch dowel to estimate my height”. In level 1, one player in the team may look for a cube, while another looks for a cylinder. Game dynamics changes in Level 2, when every member on the team works together to find the same object. In the end, the team who



Figure 4. Students Playing EstimateIT! Left: a team discussing an object; Right: a student considering a triangular prism

finds all correct objects first wins the game.

3.1 *EstimateIt!* Scavenger Hunt Pilots

An initial usability study included students in grades 4-7 who played a few different variations of the *Estimate It Scavenger Hunt* game. The game was designed as a motivational tool for students to practice measurement/geometry and develop estimation skills outside the classroom in a real world environment.

We carried several usability studies that led to the creation of this technology. We summarize the major findings of these initial qualitative studies, with the first pilot study involving index cards, outdoors in a public park. Participants were given a stack of color-coded index cards with 25 clues, which corresponded to objects/shapes on the playground/climber on index cards, such as “*Find a rectangle 2’ wide by 14” long*”. Objects and parts of the climber were marked with stickers. Participants were given fixed time to find as many stickers as possible, using the index cards, and to place the stickers on the corresponding card. The total number of correctly placed stickers determined the winner. The second study involved students in a school gymnasium wearing an initial version of the technology-enhanced game, which used Arduino-lilypads devices sewn on sweatshirts and a flat LED display that showed text [8]. This electronic sweatshirt allowed students to move freely (this initial wearable technology did not use Wifi capabilities, and behavior was hard-coded in the Arduino mini-processor device). The objective of the game was to find shapes and volumes that satisfied measurement constraints on the playground or gym. Clues were given by the LED display on their sleeve instead of using index cards, like the first study. In these first studies, players had many tools available to support their problem solving: tape measure, carpenter’s square, calculator, pencil, paper.

Results from questionnaires, interviews and observations from this first iteration of active math game pilots indicated a benefit of wearable technology compared to paper stickers/index cards in a variety of aspects: (a) the wearable aspect affords freeing students’ hands to use measurement tools; (b) access to which measurement tools could help or hinder gameplay, especially for math estimations; (c) technology can scaffold/support students by providing hints/help at key moments, to guarantee individual progress and game flow; (d) a centralized “games engine” that delivers questions should allow easy creation of questions/hints and games via game authoring tools; (e) technology should provide flexibility to form student teams to collaborate, and possibility to synchronize watches/devices for team members; (f) assessing correctness automatically via RFID/NFC tags or similar input mechanism instead of matching stickers on cards manually would improve game accuracy and game

Measured Variable	Pretest Mean (SD)	Posttest Mean (SD)	% Increase
MCAS Standardized 7-item Test (min=0; max=1)	0.65 (0.22)	0.70 (0.23)	+5%
Self-confidence in ability to do math (min=1; max=5)	4.37 (0.50)	4.67 (0.41)**	+6%
Liking of Mathematics (min=1; max=5)	4.55 (0.89)	4.64 (1.15)	+2%

a. ** Significant paired-samples t-test difference, $p < 0.005$

Table 1. Cognitive and Affective Outcomes for thirteen (13) 9-10 year old students in the USA, Before and After Playing *Estimate It!*

flow; (g) technology allows for multiple solutions, as several tags/objects could be correct answers to the different questions; (h) possibility of “personalization” of question difficulty to a child’s ability level, at the edge of their knowledge, via adaptive problem/challenge selection, similar to intelligent tutoring systems; (i) possibility of logging students’ actions and mistakes for teacher assessment/progress reports for detection of gaps and challenging problems. These results helped to inform the “Wearable Learning Games Engine” creation, and set a precedent for the studies that followed.

3.2 *EstimateIt!* Study in the United States

We implemented the *Estimate It!* game within a group of thirteen fourth grade students during May 2015, using an initial version of the Wearable Learning Games Engine over Wi-Fi on a local server. The main goal of the study was to understand the feasibility of the game as an artifact that could engender mathematics learning.

As part of the activity, students wore cell phones strapped to their forearms via armbands, and because students were organized in teams, they had to both cooperate and collaborate in different levels of the game --watches were semi-synchronized so that students had to coordinate with each other and neither of the team members could succeed without the other members.

The study itself included a math pretest and posttest of geometry and measurement items from the Mathematics section of the Massachusetts Standardized Test for 4th grade (9-10 year olds), and an affective pretest and posttest survey to measure math appreciation and self-efficacy in doing math. Learning objectives included measurement and estimations, geometrical shapes and volumes. Students were given an unmarked 12” dowel as their only measurement tool. This imprecise tool gave students further opportunities to estimate, as they found the heights and widths of volumes around the space.

Measured Variable	Posttest Mean (SD)	N
Lecture-Only	8.06 (1.77)	17
Game-Only	8.44 (2.14)	18
Lecture + Game	9.93 (1.12)*	17

a. * Significant independent-samples t-test difference, $p < 0.05$

Table 2. Cognitive outcomes for fifty three (53) 9-10 year old students After playing *Estimate IT!* as part of math class, in schools in the Philippines.

Post-game survey results revealed that students enjoyed playing the game, though they found the questions and hints to be too simple and wanted more of a challenge, even though the material was supposed to match their grade level according to National Standards. This shows that an adaptive feature that could select more advanced math questions as students continue to succeed with no errors would give students the possibility to meet the edge of their ability level. Despite of this, scores on the mathematics post-test improved by 5% compared to the pre-test, after 20 minutes of play. There was also improvement in affective outcomes from pretest to posttest: mathematics liking, as well as mathematics self-concept increased after the intervention, with self-confidence in their ability to solve math problems improving significantly (see Table 2). These results are encouraging given the low number of students in the study and for an intervention lasting for about half of a regular math class session. The reasons for this boost in self-efficacy are still a matter of further study.

3.3 *EstimateIT!* in the Philippines

This study was carried out in two schools in the Naga province in the Philippines, using a new App that was child-friendly (it involved dragging the corresponding colors of the bar code instead of pushing buttons, which made it easier for children to keep track of what colors they had already entered as part of the sequence of colors; last, a gesture was required to indicate 'submit'). One major objective of this study was to analyze the feasibility of implementation to a much harder deployment target, by adjusting the technology to be feasibly implemented in the developing world, where the school's Internet connection may be slow or intermittent. The main idea was to establish a local server on the teacher's computer. Thus, the Games Engine was refactored to handle ad-hoc network connections, which allowed the client devices to connect to the teacher's computer directly. This computer acted as a hotspot, without the need of a continuous Internet Connection to a remote server [13], nor the use of a router. In addition, besides the technical feasibility of implementing the game in a classroom in the Philippines with about 20 elementary school students playing math games in teams against each other, the study attempted to understand the role of the math games themselves to either introduce or review mathematics concepts.

Participants were 53 students from two math classes in the Philippines (N=27 from School 1 and N=26 from School 2). Both groups were equally mixed in gender, male and female. Students in each school were assigned to one of three conditions with nine students each (one group had 8); groups were balanced in ability level according to school grades. All groups answered a demographics questionnaire before the start of the test and were randomly assigned to one of three conditions: a lecture-only group, a lecture-plus-game group, and a game-only group. The lecture-only group was given a lecture. The lecture-plus-game group was given the same lecture and then played *Estimate It!*. The game-only group played *EstimateIT!* but did not see the lecture. All groups were asked to answer a post-test after being exposed to their corresponding method of instruction. The post-test consisted of 14 math questions that measured their understanding of geometric shapes, math sense and estimation. Table 2 presents the means and standard deviation of the post-test scores for each group.

We used an independent t-test to measure significant differences in the scores of (1) the lecture-only group against the game-only group and (2) the lecture-only group against the lecture-plus-game group. Results suggest that there is no significant difference between the posttest scores of the lecture-only group versus the game-only group. However, the lecture-plus-game group did perform significantly better in the math posttest than the lecture-only group. The lecture-plus-game also did better than the game-only group. These results indicate that the game *EstimateIT!* seems to be a better teaching tool for practicing and reviewing mathematics material, than for introducing new material or preparation for learning. More importantly, given that the groups receiving *EstimateIT!* obtained the highest means in post-test scores, results show that the game and the technology in general are a *feasible* technology-based game to be implemented in schools, and that it is an activity conducive to student math learning, at least boosting the teaching/learning potential of a lecture covering the same material.

The students also responded to open-ended questions asking them about their experience of the game in general. We report the data in terms of varying percentages and frequencies, as there were some students who wrote answers that did not actually answer the questions given. Generally, the students seemed to really liked this active embodied math game. When asked if the game was fun, N=30 out of the 32 students who responded said yes (93%), citing reasons such as physicality (e.g. "the game not only makes me learn, it also makes me exercise"), and social interaction (e.g. "it's fun because I'm playing with my friends"). N=31 students (86% of those responding) said they would prefer playing the *EstimateIT!* game over usual classroom instruction. Fourteen (14) of the 24 students who responded (58%) answered "nothing" when asked what they liked the least about the game. Regarding the "wearability" aspect, twenty (20) students said they would like a

smartphone (cell phone) for this type of game and only 2 students said they would rather play it on a SmartWatch. Some students asked if the game is available for download in the app/play store. This suggests student experience in general was extremely positive.

3.4 Teacher Acceptance Study

After being presented with a demo of the framework, the Embodied Cognition game and the technology, as well as a video of students from the previous study playing *EstimateIT!*, eight (8) teachers in the Philippines were invited to answer a debriefing questionnaire that used a 5-point scale, with possible responses going from “Strongly Disagree” (1) to “Strongly Agree” (5). Questions were derived from the criteria described by Whitton [38] for effective educational design of game-based learning applications (see Table 3). Items relevant to the purpose of the experiment were re-constructed into questions. Table 3 shows the results of the expert evaluation. The specific questions in Whitton’s instrument are presented in Table 3. Follow-up questions asking what aspects the evaluators liked the most/least about the game, as well as their insights on its advantages/disadvantages over current teaching methods were also included.

Table 3 shows that teachers really liked the technology that supported game play. They generally strongly agree that the *EstimateIT!* game supports active learning, engenders engagement, is appropriate and aligned with the curriculum and is fit for classroom use.

We asked teachers to answer open-ended questions for a deeper understanding of the debriefing questionnaire scores. Overall, they think the idea of embodied math games supported by technology is promising. According to them, *EstimateIT!* seemed like a great way to compete with the smartphone apps and cellular phones that hinder students from paying attention, and actively participating in discussions. Although there are rules that prohibit bringing these gadgets inside the classroom, they reported they would often catch students secretly sending text messages and playing games in their phones. Some of the teachers reported they could foresee these cell-phone embodied games could bring their students to full and active participation. The teachers also said that they found the process of implementing games in the classroom seemed relatively easy. Some of them went on to say that if the game is found to be effective for student outcomes, they would want to use it in place of the lecture. Some teachers provided their contact numbers and asked to be contacted when the game becomes available for download. The results of this expert evaluation validates that the framework makes the system fit cultural expectation of Philippine teachers in terms of feasibility and ease of use.

4. GAME CREATION

The idea of co-designing games with teachers and students, for younger students to use, aligns with the community focus of our grounding Activity Theory. However, there are

added benefits to the generation of games. First, as a way for students to deepen their understanding of mathematics concepts, thinking about math questions from a “problem posing” perspective [6, 35] instead of a problem solving perspective; second, as a way to have students engage in the abstract and systematic thinking, also called computational thinking [39], which implies a high level of precision in the specification of a solution to a problem, a multiplayer math game in this case, which has contemplated all possible movable parts, such as temporal restrictions (what happens first and later), conditional restrictions (what happens only in specific situations, and what are the consequences of a condition), concurrency issues (e.g. states of players in the game might depend on the states of other players in the game, not only of the previous states of this same player).

This would imply having students conceive and specify multi-player math games, as well as define the behavior of the mobile devices as finite-state-machines, which act as supports to the players (both supporting game flow and support when gamers get stuck). We decided to allow student and teachers to define new games as finite state machines (FSMs), as these provide a simple way to explain computer behavior in the same way that we may think about world phenomena, as a series of actions and reactions. The behavior of FSMs can be observed in many devices that perform predetermined sequences of actions depending on external events e.g., vending machines that dispense products when coins are deposited; elevators and traffic lights that change state as cars or people are waiting.

We carried out a study to analyze the feasibility that students themselves might be able to create games for other students to play, and their ability to define games with a high level of precision. This was an exploratory study, attempting to answer the following question: “*Could high school students grasp the idea of designing a multiplayer math game (with mobile devices as supports for each player), using finite-state machines as a mechanism to specify the behavior of the mobile devices to individual players, at each step of the game?*”.

Some key aspects that make this game design endeavor challenging are: a) multiple perspective taking involved in a multi-player math game for a full class of students (i.e. different teams’ and players’ perspective); b) differentiating the game itself and its rules from the behaviors of the mobile devices that support/guide the players; c) addressing concurrency issues involved in the synchronization of the mobile devices of multiple players; d) the requirement of high precision in both the specification of the games, and the specification of the behavior of the mobile devices for each player, at different points of time, among others.

Fifty four (54) sixteen-year-old students from a high school in Massachusetts were involved in this “game design” study, three (3) classes of students with eighteen (18) students each. A survey was given to the students to take after they had played *EstimateIT!* and after they had

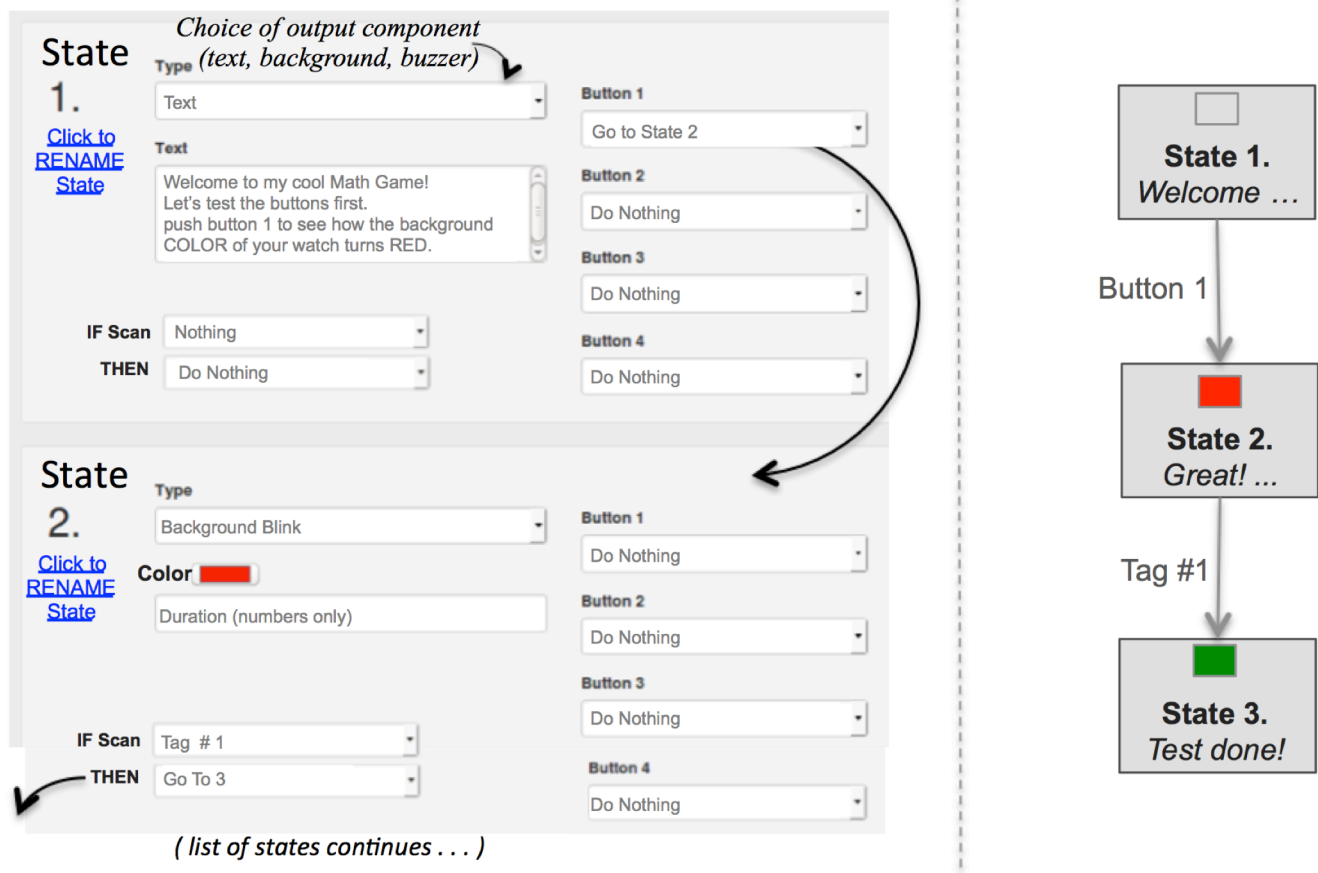


Figure 5. This interface design shows how we designed that game creators would alternate between two views: the “Create Game States” view (left) and the “Finite State Machine” view (right) as they create their own active math games; they program the behavior of mobile devices this way, so that they supports game flow, pace the game, assess success of challenges, as well as provide cognitive support when students need it.

redesigned their game to be state-based like *EstimateIT!* They were asked questions such as “was it hard to redesign your game?”, and “how much do you know about state machines?”. Students worked on a variety of activities during three one hour sessions, in three consecutive days in 2017. Students in each class were divided in two groups (red and blue). Students in the blue group (N=9) played *EstimateIT!* in a classroom, with the purpose of having students understand the role that mobile devices could play as guides and scaffolds in a math game. After this, a small presentation was given to the students explaining how the game they just played works as well the system behind it powering it. Lastly, they were given a small homework assignment to complete an online survey about their experience. During this same day, the so-called *red* group of each class (N=9), instead designed math games in another classroom. Students did the opposite activity on day 2, with some students playing first and some students creating math games first. The students were given the following constraints to follow when designing their math game: a) The game you design must be playable by 4-6th graders (9-12 year olds); b) The game has to teach students some math concept appropriate for their age; c) The game must be multiplayer, meaning that the game should work

for at least 6 simultaneous players; d) They should make sure the game is active by getting the students to move around, at least to some extent.

Student teams were given drawing pads and markers to plan out their design (3 teams of 3 students per red/blue team per class). At the end of the class period, teams presented their games to each other. After that they were then given a small homework assignment, which was to write a two-page explanation of how the game they created worked. They were allowed to include figures, pictures or diagrams and were asked “what was challenging” and “what did you like about it?”. During the second day, the activities of the subgroups were reversed: the students that played “Estimate It” the previous day would now be in the classroom designing games and vice versa. By the end of day 2, every team had both played *EstimateIT!* and designed some multiplayer active math game.

Day three was completely different than day one and two in that the main groups of eighteen were no longer split up in subgroups. Instead, the entire group redesigned the games they had created on either days one or two to include mobile devices, similarly to *EstimateIT!*. The first ten minutes of the session consisted of giving a 10-minute

presentation that summarized the idea of finite state machines, how the cell phone and server interacted, and how actually the *EstimateIT!* game was specified as a state-machine, from start to finish, with states as outputs and button presses as inputs and transitions between states.

Students proceeded to redesign their games to include cell phones, and specified the behavior of these as state-machines. After they were done redesigning their games, they presented their new games to each other. Similarly to the previous days, students were given another small homework assignment. This included writing a two-page explanation of how they adapted their game to be more like *EstimateIT!* what was challenging about it, what did you like about it, and a survey about their experience this day.

4.1 Results to the Game Design Survey

This section shows the results of the survey after students created the games and specified them as state machines. Because the survey was not clearly compulsory to students, and provided as homework, out of the 54 students that participated in the study, only 31 answered the survey of the last day. Still we consider the results are valuable and are a reasonable sample of what students thought. These results are summarized in Table 4.

Some of the questions shown in Table 4 evaluated the difficulty or ease of creating games to teach or practice mathematics. A high percent (87%) of the students who answered the survey found the task of designing a math game for others to play easy. Almost every person who answered the survey (94%) found the game created by their team during days 1-2 was not very similar (in terms of design and playability) as *EstimateIT!*, which was clear as their games targeted different math topics, and did not use technology to support the player.

Other questions regarded the challenge they might face in understanding and using finite-state machines as a language to specify the behavior of player devices. In a question regarding how hard it was to determine the underlying state-based definition of the mobile devices for *EstimateIT!*, a majority of students (87%) found it easy to determine the underlying state-based design of that game they played. When asked how similar the game they designed the first or second day was to *EstimateIT!* by the end of the third day, after redesigning their game to include the technology, a large majority (84%) found it easy to redesign their game to include mobile devices for player support by the end of the third day, and most students (84%) found it straightforward to adapt their game to the demonstrated state-based design. This is encouraging, as this specification in the form of a state-transition diagram is the method that the authoring tool would require to input as a next step in the Wearable Learning Games Engine web site, for them to program the mobile devices to behave as the game creators wanted, to support the players of their games.

Last, some questions asked the student about previous knowledge of finite-state machines, in case they already

		Strongly Agree	Agree
Active Learning Support			
1	The game encourages exploration, problem-solving,	78%	22%
2	The game provides opportunities for collaboration.	100%	0%
3	The game provides opportunities to test ideas and gain	90%	10%
4	The game provides opportunities for practice and	100%	0%
5	Game goals are aligned with the subject's learning	90%	10%
Engenders Engagement			
1	Goals of the game are clear and achievable.	72%	28%
2	The game supports a high level of interactivity.	79%	21%
3	The game stimulates curiosity and puzzlement.	100%	0%
4	The game establishes the application of estimation in	90%	10%
5	Game levels are appropriate and challenging.	90%	10%
Appropriateness			
1	Game goals are aligned with the curriculum.	39%	61%
2	Game goals are aligned with the subject's learning	39%	61%
3	A game-based approach is applicable for teaching	78%	22%
4	The game could be played within the allotted class	78%	22%
Classroom Use			
1	I think the game will help students learn estimation.	100%	0%
2	I think my students will find this game fun.	100%	0%
3	I think I would use this game in my classes.	100%	0%
4	I would recommend this game to my colleagues.	100%	0%

Table 3. Expert Evaluation: Responses of eight (8) teachers. Neutral, disagree and strongly disagree not shown (=0%)

knew about them. Most students (84%) said they did not know anything about state machines before the study. This knowledge apparently grew during the study, as most students (77%) perceived they knew more and felt they understood the concept of state machines after the study.

A detailed analysis of students' games finite-state machines, including errors and difficulties they might have faced, is still pending. However, after an initial analysis and design of a coding scheme for such qualitative productions, we can say that students managed to generate an extremely large variety of games, targeting not only geometry but also expressions, number lines, equations, and several other concepts using a myriad of playground games. Some of those games included Capture The Flag, Relay Races, Walking Number Lines, Multiplication Grids to be Traversed, and many others going beyond scavenger hunts. These young game authors managed to provide flexibility in games design that the researchers had not been able to achieve, requiring minor functionality beyond what the Wearable Games Engine already provides. The games designed by students involved a large variety of student interactions also: teams against other teams, individuals against the teacher, and individuals against each other, and combinations of the above. Rich data was collected in the form of videos that capture their group discussions that still remains to be analyzed.

5. DISCUSSION AND CONCLUSIONS

It seems reasonable that students would acquire more positive attitudes and perceptions of math due to the

Survey Question (min=1; max=4)	Mean (SD)	MODE
How much did you know about state machines BEFORE you started? (1=Nothing; 4=A lot)	1.65 (0.91)	1 (Nothing)
How much do you feel you know about state machines NOW? (1=Nothing; 4=A lot)	2.94 (0.81)	3 (Do know)
After looking at Estimate It, how difficult was it to determine its underlying state based design? (1=Easy; 4=Hard)	1.71 (0.78)	1 (Easy)
How difficult was it to adapt your game to a state based design? (1=Easy; 4=Hard)	1.74 (0.82)	1 (Easy)
How difficult was it for you to design a math game given the set of constraints during day 1? (1=Easy; 4=Hard)	1.84 (0.73)	2 (Sort of Easy)
How similar was the game you designed to Estimate It, by the end of the FIRST day you created the math game? (1=Not Similar; 4=Very Similar)	1.35 (0.71)	1 (Not Similar)
How similar was the math game you designed to Estimate It, by the end of TODAY, after redesigning the game? (1=Not Very Similar; 4=Very Similar)	1.94 (0.73)	2 (A bit similar)

Table 4. Means, Standard deviations and Modes of High School Students' Survey Responses about Creating Mathematics Games as Finite State-Machines

physical engagement and game components of the activities, because of its game-like nature. The interesting finding is that this excitement is paralleled with knowledge gains, especially when preceded by a short lecture. Future research should regard the analysis of the learning mechanisms and the contribution of motion and physical involvement using *EstimateIT!* as a testbed game. A variety of cognitive factors might be attributable to learning gains, for instance (1) visual imagery as students read the math description of the object to search for; (2) manual measurement procedures that involve comparisons between candidate physical objects and measurement tools (e.g. partitioning and unitizing) while using the 12" dowel in this case; (3) mental computations simultaneously performed with the manual measuring procedures while analyzing the object; (4) rounding procedures, as the measurements are inexact, students are forced to estimate up or down; (5) general problem solving, planning solutions and strategizing on how to proceed with the search; (6) right on time scaffolding via hint requests when the challenge is high; (6) right on time feedback when the incorrect object is scanned/input, allowing for revision of their work or seeking help; (7) team-based discussion and argumentation with peers, especially upon conflict or disagreement. We are ready to start using these mobile devices to collect a myriad of detailed data about students actions, including videos of students solving problems as they play and detailed logs of students actions to understand the mechanisms (both physical and mental) that mediate performance and learning within these technology-facilitated embodied games.

This research has also shown that it is feasible, at least for students of a technical high school, to create and define a diverse set of physically active math games, engage in computational thinking, perceive they learn about finite-state machines, and reach a design level where their multi-player games can be entered into the Wearable Learning platform. While this stage would require another step in which students may encounter challenges, students' state-machine diagrams closely resembled the actual diagrams we created ourselves when defining *EstimateIT!*. Given that the authoring tool is now ready for student use, our future work will go the extra step of having students enter their state-machines into the authoring tool and then playing their each others' games on mobile devices.

This work is a contribution to the field of educational games and embodied learning technologies, demonstrating the feasibility of the creation of smart contexts for education [10], wearable technologies that take an ecological perspective to formal learning environments. It is one of the first feasible learning technologies created that incorporate full classrooms of collaborating students, multiplayer games, active learning, mobile devices, and an alignment to the actual curriculum in mathematics education in formal school settings. As many have stated [21], implementing novel mobile technologies activities in real schools is not easy. We have come up with infrastructure that makes it feasible, and engenders learning and engagement. Students enjoy playing embodied math games aided by mobile devices; they learn target math skills addressed in the process; they are able to create games that combine physical play with mathematical concepts, and they develop a deeper understanding of mathematics and computational thinking. All of this while embedded within current curricula, classrooms and teaching practices.

Acknowledgements

This research was funded by NSF awards #1647023 and #1652579. Any opinions, findings, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NSF.

REFERENCES

1. Abrahamson, D. (2009). Embodied design: constructing means for constructing meaning. *Educational Studies in Mathematics*, 70(1), 27-47.
2. Abrahamson, D., Howison, M. (2010) Embodied artifacts: coordinated action as an object-to-think-with. Annual meeting of the American Educational Research Association (AERA), Denver, CO.
3. Abrahamson, D., Sánchez-García, R. (2016). Learning is moving in new ways: The ecological dynamics of mathematics education. *Journal of the Learning Sciences*, 25(2), 203-239.
4. Alibali, M.W., & Nathan, M.J. (2012). Embodiment in Mathematics Teaching and Learning: Evidence From

- Learners' and Teachers' Gestures. *Journal of the Learning Sciences*, 21(2), 247-286.
5. Antle, A. N., Corness, G., & Droumeva, M. (2009). What the body knows: Exploring the benefits of embodied metaphors in hybrid physical digital environments. *Interacting with Computers*, 21(1), 66-75.
 6. Arroyo, I, Schapira, A., Woolf, B.P. (2001). Authoring and sharing word problems with AWE . Proceedings of the International Conference on Artificial Intelligence in Education. IOS Press.
 7. Arroyo, I., Woolf, B. P., Bureson, W., Muldner, K., Rai, D., & Tai, M. (2014). A multimedia adaptive tutoring system for mathematics that addresses cognition, metacognition and affect. *International Journal of Artificial Intelligence in Education*, 24(4), 387-426.
 8. Arroyo, I., Zualkernan, I.A., & Woolf , B.P. (2011). *Hoodies and Barrels: Using a Hide-and-seek Ubiquitous Game to Teach Mathematics*. 11th IEEE International Conference on Advanced Learning Technologies (ICALT), Athens, Georgia.
 9. Bamberger, J., & Disessa, A. (2003). Music as embodied mathematics: A study of a mutually informing affinity. *International Journal of Computers for Mathematical Learning*, 8(2), 123-160.
 10. Barab, S. A., & Plucker, J. A. (2002). Smart people or smart contexts? Cognition, ability, and talent development in an age of situated approaches to knowing and learning. *Educational psychologist*, 37(3), 165-182.
 11. Barab, S., Thomas, M., Dodge, T., Carteaux, R., & Tuzun, H. (2005). Making learning fun: Quest Atlantis, a game without guns. *Educational technology research and development*, 53(1), 86-107
 12. Bruner, J. S. (1966). *Toward a theory of instruction* (Vol. 59). Harvard University Press.
 13. Casano, J., Tee, H., Agapito, J.L., Arroyo, I., Rodrigo, M.T (2016) *Migration and Evaluation of a Framework for Developing Embodied Cognition Learning Games*. The 15th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry (VRCAI 2016).
 14. Cayton-Hodges, G. A., Feng, G., & Pan, X. (2015). Tablet-based math assessment: what can we learn from math apps?. *Educational Technology & Society*, 18(2), 3-20.
 15. Chiu, C., & Liu, M. (2014). An innovative teaching model research affect the elder smart watch usage efficacy. *Gerontechnology*, 13(2).
 16. Clegg, T., Norooz, L., Kang, S., Byrne, V., Katzen, M., Velez, R., Plane, A., Oguamanam, V., Outing, T., Yip, J., Bonsignore, E., Froehlich, J. (2017) *Live Physiological Sensing and Visualization Ecosystems: An Activity Theory Analysis*. Computer Human Interaction Conference (CHI 2017).
 17. Devlin, K. (2011). Mathematics education for a new era: Video games as a medium for learning. CRC Press.
 18. Dourish, P. (2001). Where the action is: The foundations of embodied interaction. Cambridge, MA: MIT Press.
 19. Drake, J., Cain, R., & Lee, V. R. (2017). From wearing to wondering: Treating wearable activity trackers as tools for inquiry. In I. Levin & D. Tsybulsky (Eds.), *Optimizing STEM Education With Advanced ICTs and Simulations*. Hershey, PA: IGI Global.
 20. Gee, J. P. (2003). What video games have to teach us about learning and literacy. *Computers in Entertainment (CIE)*, 1(1), 20-20.
 21. Grotto, Lozano, Muldner, Burleson, Walker (2016). Lessons Learned from In-School Use of rTAG: A Robo-Tangible Learning Environment. CHI 2016, San Jose, CA.
 22. Howison, M., Trninic, D., Reinholz, D., Abrahamson, D., (2011) The mathematical imagery trainer: from embodied interaction to conceptual learning, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, pp. 1989-1998 , New York, NY.
 23. Johnson, K., Pavleas, J., & Chang, J. (2013). *Kinecting to mathematics through embodied interactions*. Computer, 46(10), 101-104.
 24. Kafai, Y. B., & Kafai, Y. B. (1995). Minds in play: Computer game design as a context for children's learning. Routledge.
 25. Ke, F. (2008) . A case study of computer gaming for math: Engaged learning from gameplay?
 26. Lave, J., Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.
 27. Micciollo, M. (2017) *Physical Games for Learning II*. Major Qualifying Project. Worcester Polytechnic Institute.
 28. Nardi, B. A. (1996). Context and consciousness: Activity theory and human-computer interaction. Cambridge, MA: MIT Press.
 29. Nemirovsky, R., Tierney, C., & Wright, T. (1998). Body motion and graphing. *Cognition and Instruction*, 16(2), 119-172.
 30. Ottmar, E., Landy, D., & Goldstone, R. L. (2012). Teaching the perceptual structure of algebraic expressions: Preliminary findings from the pushing symbols intervention. In Miyake, N., Peebles, D., & Cooper, R.P. (Eds). *Proceedings of the Thirty-Fourth Annual Conference of the Cognitive Science Society*,

- Sapporo, Japan (pp. 2156-2161). Pasadena, CA: Cognitive Science Society.
31. Ottmar, E., Landy, D., Weitnauer, E., & Goldstone, R. (2015) Graspable mathematics: Using perceptual learning technology to discover algebraic notation. In M. Meletiou-Mavrotheris, K. Mavrou, & E. Paparistodemou (Eds.), *Integrating Touch-Enabled and Mobile Devices into Contemporary Mathematics Education* (pp. 24-48). Hershey, PA: IGI Global.
 32. Reinholz, D., Trninic, D., Howison, M., & Abrahamson, D. (2010). It's not easy being green: embodied artifacts and the guided emergence of mathematical meaning. In *Proceedings of the thirty-second annual meeting of the North-American chapter of the international group for the psychology of mathematics education (PME-NA 32)* (Vol. 6, pp. 1488-1496). Columbus, OH: PME-NA.
 33. Rountree, W. L. (2015). *Redesigning Traditional Children's Games to Teach Number Sense and Reinforce Measurement Estimation Skills Using Wearable Technology*. Masters Thesis in Interactive Media and Game Development. Worcester Polytechnic Institute.
 34. Silva, M. J., Ferreira, E., Andrade, V., Nunes, O., & da Luz Carvalho, M. (2015, November). Embodied education: Senses, emotions, and technology. In *Computers in Education (SIIE), 2015 International Symposium on* (pp. 32-37). IEEE.
 35. Silver (1994) On Mathematical Problem Posing. For the Learning Mathematics. FLM Publishing Association.
 36. Slavin, R. E. (1980). Cooperative learning. *Review of Educational Research*, 50(2), 315-342.
 37. Tsai, H.; Sing, K. (2012) Mobile Applications and Museum Visitation. *Computer*. 45 (4), pp. 95-98.
 38. Whitton, N. (2009). *Learning and teaching with computer games in higher education. Game-based Learning Advancements for Multi-Sensory Human Computer Interfaces: Techniques and Effective Practices*. Thomas Connally, Mark Stansfield and Liz Boyle Eds. Information Science Reference, Hershey-New York.
 39. Wing, J.M., Computational thinking. *Communications of the ACM*, 2006. 49(3): 33-35.
 40. Wu, T., Dameff, C., & Tully, J. (2014). Integrating Google Glass into simulation-based training: experiences and future directions. *Journal of Biomedical Graphics and Computing*, 4(2).