Learning from Mixed-Reality Games: Is Shaking a Tablet as Effective as Physical Observation?

Nesra Yannier **Kenneth R. Koedinger** **Scott E. Hudson**
Human-Computer Interaction Institute
Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh PA 15213
{nyannier, krk, scott.hudson}@cs.cmu.edu

ABSTRACT

The possibility of leveraging technology to support children's learning in the real world is both appealing and technically challenging. We have been exploring factors in tangible games that may contribute to both learning and enjoyment with an eye toward technological feasibility and scalability. Previous research found that young children learned early physics principles better when interactively predicting and observing experimental comparisons on a physical earthquake table than when seeing a video of the same. Immersing children in the real world with computer vision-based feedback appears to evoke embodied cognition that enhances learning. In the current experiment, we replicated this intriguing result of the mere difference between observing the real world versus a flat-screen. Further, we explored whether a simple and scalable addition of physical control (such as shaking a tablet) would yield an increase in learning and enjoyment. Our 2x2 experiment found no evidence that adding simple forms of hands-on control enhances learning, while demonstrating a large impact of physical observation. A general implication for educational game design is that affording physical observation in the real world accompanied by real-time interactive feedback may be more important than affording simple hands-on control on a tablet.

Author Keywords

Tangible interfaces, Learning technologies, Educational games, Mixed-Reality environments.

ACM Classification Keywords

Human Factors

INTRODUCTION

As screen-based technologies such as tablets, computer games, and online videos are becoming increasingly more appealing for children, it is worth asking whether real world interaction is really needed to enhance learning or enjoyment. There is little research investigating the potential advantages of real world interaction or what features may cause them [32].

Figure 1. Students interacting with EarthShake (on the left is the mixed-reality version where children observe physical towers on the earthquake table with interactive feedback; on the right is the tablet version where they shake the tablet to shake the earthquake table on the screen)

Tangible interfaces and mixed-reality environments have the potential to bring together the advantages of physical and virtual worlds to enhance learning and enjoyment. Utilizing computer-vision technology to provide well-designed interactive feedback to children while they interact with physical objects in their everyday environment may be an engaging and powerful way to learn [30,17]. However one can question whether real world interaction is necessary, especially given that interactive responsiveness and feedback to real world actions is more difficult to implement. Since creating such affordances in the real world is technically challenging, it is tempting to hope that integrating easier-to-develop physical controls into a screen-based environment may improve enjoyment and learning just as well.

It is important to isolate the factors that are important for learning in mixed-reality environments. Is physical observation and experimentation with real physical objects critical to enhance learning or enjoyment? Or would it be sufficient to add simple forms of physical controls to a tablet game, such as shaking the tablet as an input? What kinds of features make tangible interfaces more enjoyable for children? What are the features that lead to more learning? We set out to address these questions and, more generally, to explore what role physical observation versus

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physical interaction/control plays in the learning process, especially for younger children.

Does Physical Interaction Aid Learning?

There is related research that has explored whether simple physical interaction has benefits for learning. In Montessori schools children are encouraged to play with physical items such as building blocks, shape puzzles and jigsaws in order to learn different skills. One review [15] claims that, young children have a strong attraction to sensory development apparatus and that they use physical materials with deep concentration for extended periods of time, as a result of which they advance in their critical thinking and ability to work collaboratively [15].

Piaget and Bruner showed that children had an easier time while solving problems when given concrete materials to work [5]. Locomotion can also aid children while categorizing and recalling in tasks of spatial imagery [22]. An experiment demonstrated that children were able to solve fraction problems by moving physical materials even though they were not able to solve the same problems on paper [14].

Theories of embodied cognition and situated learning have suggested that mind and body are deeply integrated in the process of producing learning and reasoning. Thought does not only happen in the mind; bodily activity can support cognition [11,18].

Nevertheless, research comparing learning from the virtual versus physical environment (without interactive feedback) has produced mixed results. 24 and 30 month olds were able to imitate the actions of an adult better after watching a live demonstration than after watching the same demonstration on TV immediately and after a 24 hour delay [10]. On the other hand, in a science learning task with fourth and fifth grade children, Klahr et al. [13] found no difference in learning from interacting with virtual objects versus physical objects. In an experiment with university students in the context of light and color, Olympiou and Zacharias also found no difference in learning from physical versus virtual interaction. However, a third condition, where students interacted with both physical and virtual materials sequentially, led to better learning from both the physical only and virtual only conditions [16]. This result suggests that physical and virtual interaction may have complementary benefits that may be combined in and further enhanced through the interactive support of a mixed-reality interface.

Mixed Reality Environments for Learning

Mixed-reality environments, including tangible interfaces, bring together the physical and virtual worlds by sensing physical interaction and providing interactive feedback [28]. They have the potential to aid learning by providing the benefits of interacting with the physical environment while leveraging computational power to give students personalized feedback and interactive instructional support.

There have been attempts to create tangible interfaces for learning. Some examples include a book with audio embedded on different pages [3], a constructive assembly system embedded with kinetic memory to record and play back physical motion [20]; a ball that displays information about acceleration [21] and a play-mat that captures stories [26]. However, most of these tangible interfaces were used for mere exploration in qualitative studies; they were not compared to a control to investigate the role of physicality.

There is some research that shows benefits for tangibles -- mostly immediate performance benefits rather than learning outcomes. Children solved puzzles more successfully when they used tangible puzzle pieces compared to a mouse [2]. A set of tangible objects provided children with a physical handle to reason about abstract sound concepts [4]. Problem solving and collaboration advantages were shown for a paper-based tangible user interface for educational simulations over mouse interaction [27]. Enhanced task performance, collaborative interactions, and sense of playfulness were demonstrated while using a tangible interface compared to a multi-touch interface [26]. Students remembered cause and effect relations in geography and climate better when they used a haptics-augmented environment compared to a solely virtual environment [29]. Rogers et al. came up with a conceptual framework for mixed reality environments, suggesting that novel mixes of physical and digital transforms facilitate exploration and reflection [24].

While these studies provide some evidence for the benefits of tangible interfaces and mixed-reality environments, there aren't enough controlled experiments that a) test whether these environments produce sustained learning benefits that yield better performance on later assessment and b) do so in comparison to simpler-to-develop and deploy flat-screen alternatives. Furthermore, these studies do not identify what it is that provides benefits for learning in these mixed-reality environments: Does observing physical phenomena play an important role for learning in an interactive setting or is it having physical/hands-on control that is critical to enhancing learning?

Factoring out the potential contributions to learning of physical observation versus physical control is not only of scientific interest (e.g., when can embodied cognition be evoked -- with or without physical activity), but is also of practical importance. Creating a system that supports one versus the other can involve substantial trade-offs in the cost of development.

Let us illustrate this factoring of physical observation versus interaction with some existing systems. In ListenReader [3], an electronically augmented paper-based book, does the hands-on action of turning pages provide any benefit? Or for BitBall [21], does the action of throwing the ball provide any learning benefits? Or is it more beneficial to observe a physical ball rather than a virtual ball on a flat-screen in order to learn the underlying principles of acceleration? To isolate the effects of each, we need randomized controlled experiments that factor out and control for these variables.

In a recent study, Yannier et al. showed that children observing physical towers in a mixed-reality game learned physics principles better and showed higher levels of enjoyment compared to students interacting with a solely virtual game on a laptop [30]. This result suggests that observing physical phenomena (along with mixed reality feedback on whether child predictions and physical results match) may enhance learning and enjoyment. But, is real world interaction necessary? Might adding simple forms of physical interaction to an easier-to-produce tablet game also increase learning and enjoyment? After all, it is intuitive to attribute potential benefits of tangible computing to physical interaction rather than physical observation.

Some argue that hands-on control and bodily movement may enhance engagement and learning [17]. These days we see a lot of games and applications on tablets for children where they move or shake the tablet to control the game. We present an experiment to investigate if adding such physical control would increase the enjoyment or learning or if observing physical phenomena is critical to enhance children's learning.

THEORETICAL BACKGROUND

The potential benefits of integrating physicality into an interactive game can be factored into the potential benefits of *observing physical phenomena* and *physical control/interaction*. Considering prior theoretical work, there are several explanations for the potential benefits of physicality. Below we discuss some possible explanations.

Benefits of experiencing physical phenomena

When children and adults learn or reason with abstract concepts, they often utilize mental simulations based on concrete motor-perceptual experiences [1]. During a physical interaction, neural patterns of brain activity are formed across modalities, integrated into a multimodal representation in memory. When such an experience is recalled from memory, the same neural patterns are reactivated with the multimodal representation [23]. For example, patterns of physically balancing the body give rise to neural patterns that are stored as a multimodal representation. This representation is activated when thinking about balance in abstract domains such as mathematics [1].

Experiencing physical phenomena in real life may help people perceive and mentally visualize the physical objects in 3D in their minds, make connections with objects they are familiar with, and as a result remember the concepts better. Yannier et al. showed that children used more meaningful gestures while explaining their predictions when they observed physical blocks in a mixed-reality game, compared to a screen-only version of the same game. This result suggests that children may be having more meaningful mental visualizations (demonstrated by the gestures they use) when they interact with 3D objects [30].

Having physical objects may trigger affordance for action, which in turn facilitates retrieval from memory. Research on embodiment has revealed that memory for actions (e.g. performing a command such as "open the book") is better than memory for the verbal description of the commands [8], suggesting that memory focuses on embodied information [9].

Research on baby media has shown that children learn vocabulary better from interacting with parents than watching matched videos, suggesting that very young children have difficulty understanding the relation between what they see on a screen and the real world [7]. In another line of research, Kahn et al. have found that in terms of heart-rate recovery from low-level stress, a glass window that afforded a view of a natural scene was more restorative than a plasma window that afforded a real-time HDTV view of essentially the same scene [12]. These studies provide evidence of cognitive benefits of observing scenes in the real world, compared to an on-screen counterpart.

Benefits of physical control/interaction

Physical interaction may further engage embodied cognition and enhance memory and learning beyond that achieved through mere physical observation [9]. In addition, having a physical control (such as shaking a tablet) in an interactive game may be inherently more engaging and enjoyable than interacting with the virtual game, which may in consequence enhance learning. This claim is supported by Montessori's theory that young children are highly engaged by sensory development apparatus [15]. There is also evidence that high engagement and enjoyment is linked positively with desirable learning outcomes such as critical thinking and grades [6].

Below we present an experiment where we have controlled for physical observation and a simple physical control in the context of an interactive game, to investigate the effect of each in turn for learning and enjoyment. We wanted to see if having a simple physical control would improve learning by producing higher enjoyment or if experiencing physical phenomena is more critical to develop deeper understanding.

EXPERIMENTAL METHOD

We conducted a 2x2 experiment, crossing mixed-reality vs. screen-only with the presence vs. absence of a simple hands-on/physical control. As outcomes, we measured enjoyment of the game and pretest to posttest learning gains, both on paper and through a hands-on task. This experiment examined EarthShake, a mixed reality game that helps children learn basic physics principles of stability and balance. In EarthShake, students make predictions about which tower will fall first when the earthquake table is shaken and then observe physical block towers with real time interactive feedback from the game [31]. The screen-only version of the game is displayed on a laptop, and includes matched videos of the physical towers shaking on the table. To investigate the effect of a physical control, we added a physical control to the mixed-reality game (children press a physical switch to shake the table) and implemented the screen-based game on a tablet with a physical control (children shake the tablet to shake the virtual table). We chose shaking the tablet and the physical switch conditions as alternatives to the screen and mixed-reality conditions in order to test if adding a potentially enjoyable experience via a physical/hands-on control would increase learning by increasing enjoyment. Observing that children loved pressing the physical switch during our pilots, we thought that giving them the physical switch might increase enjoyment (similar to how shaking a tablet might be enjoyable through a physical input experience) and in turn allow us to test if physical interaction improves learning by increasing enjoyment.

All participants interacted with the game in pairs, since no difference for learning or enjoyment was found for solo and pair conditions in a previous experiment [30].

Participants

Ninety-two 6-8 year old children (43 pairs and two groups of 3) participated. There were 22, 40, and 30 from Grades K to 2, respectively. Children were recruited from two different schools with students from mixed backgrounds with a high percentage from low-income communities. The teachers in the classroom randomly selected the pairs.

Materials

To conduct the experiment, we developed the materials and technologies to be used in the 4 different conditions: 1) mixed-reality version of EarthShake with mouse control; 2) mixed-reality version of EarthShake with physical control (pressing a physical button as input); 3) Screen-only laptop version of EarthShake with mouse control; 4) Screen-only tablet version of EarthShake with physical control (shaking the tablet as input). We discuss each in turn below.

1) Mixed-reality version of EarthShake with Mouse Control

EarthShake consists of an earthquake table, physical towers and a projected game synchronized with the real world via Kinect depth camera sensing and a specialized computer vision algorithm [31] (Figure 2). EarthShake teaches with a predict/observe/explain cycle. The game starts with the gorilla character asking students to make a prediction about which of two physical towers will fall first when he shakes the table under them [31]. The users can see the physical towers on the real earthquake table and the virtual representation (detected by our vision algorithm) of the towers in the projected interface of the game behind the table at the same time (Figure 1 left). To make a prediction, they can click on the tower (in the projected game) that they think will fall first using the mouse. The gorilla then tells the users to discuss with their partner why they think this tower will fall first. When they are done discussing, they can then click the shake button in the projected game using their mouse to shake the physical earthquake table (when they click the shake button on the screen, the experimenter activates the earthquake table with a switch). Once one of the towers falls down, the Kinect camera and computer vision algorithm determines the fall giving audio and visual feedback to the users. If the tower they had predicted falls first, the gorilla says: "Good job! Your hypothesis was right. Why do you think this tower fell first?" If they were wrong, he says: "Oh oh you were wrong! Why do you think this tower fell first?" This time they have to explain why this tower fell first by choosing one of the six multiple choice answers projected on the screen. The multiple menu consists of the following choices: "Because it is smaller", "Because it is taller", "Because it has more weight on top than bottom", "Because it has a wider base", "Because it is not symmetrical", "Because it has a thinner base" (Figure 5). This scenario is repeated for different contrasting cases targeting height, wide base, symmetry and center of mass principles (Figure 3).

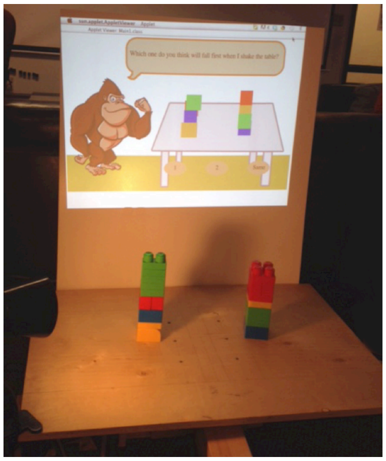


Figure 2. Mixed reality version of EarthShake. The projected game behind the towers is synchronized with the physical world via Kinect depth camera sensing.

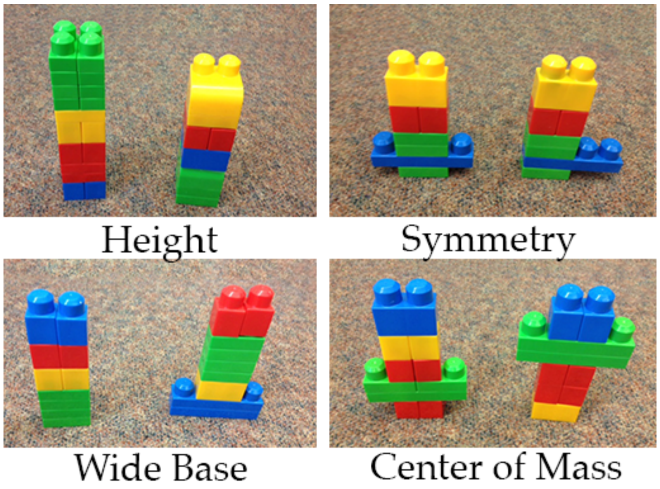


Figure 3. Contrasting cases used during the game.

During the experiment, children are asked to take turns using the mouse to select the towers and shake the table.

2) Mixed-reality version of EarthShake with Physical Control

For the second condition (mixed-reality & physical control) the same scenario as in the first condition was used. The only difference was that, children were given the physical control (a physical switch connected wirelessly to the earthquake table) to shake the table (See Figure 4).

Figure 4. Students interacting with the mixed-reality version of EarthShake with physical-control. They use a physical switch to shake the table.

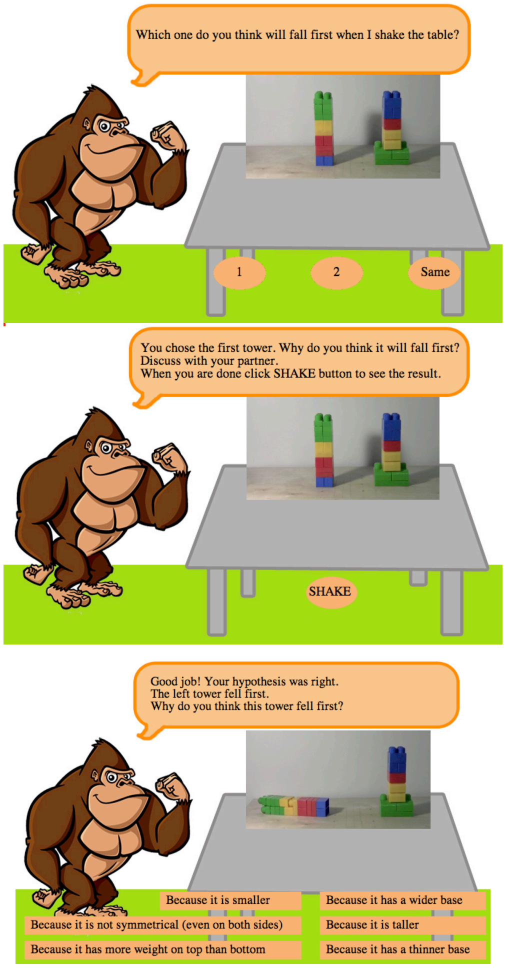
In this condition, one of the children participating in the study was asked to have the physical switch to shake the table, while the other one was asked to have the mouse to control the game. They were asked to take turns to use the physical switch and the mouse. Everything else other than the control with the physical switch was kept the same as the first condition.

The switch was connected wirelessly to the motor that was used in the mechanism to drive the motion of the earthquake table. Two wireless switches (one for the participants, one for the experimenter) were connected in series, so that if one of the switches was turned off the motor would stop working. The experimenter wirelessly disabled the children's switch when it was not time to shake the table.

3) Screen-only version of EarthShake with Mouse Control

In the Laptop version of EarthShake, the same interface of the game that was projected on the screen in the mixed-reality game was used. Instead of having the live projections of the real towers, a video of the towers shaking was integrated into the interface (Figure 6). The characters, the scenario and the button controls were all kept the same as in the projected game in Condition 1 & 2. All of the game interactions were kept the same, except that pressing the "shake button" on the screen (as in Condition 1) would start the video of the table shaking instead of having the students observe the physical earthquake table.

The participants used a mouse connected to the laptop to control the game on the screen. The partners were asked to take turns using the mouse to select and shake the table during the game.



Which one do you think will fall first when I shake the table?

You chose the first tower. Why do you think it will fall first?
Discuss with your partner.
When you are done click SHAKE button to see the result.

Good job! Your hypothesis was right.
The left tower fell first.
Why do you think this tower fell first?

Figure 5. The scenario of the game utilizing a predict/observe/explain cycle. The video of the physical towers shaking on the earthquake table is integrated into the game interface for the screen-only conditions.

Figure 6. Laptop version of EarthShake

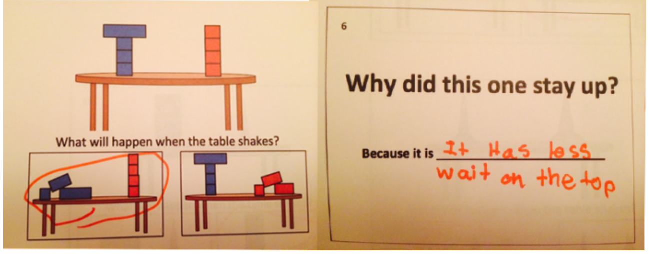
4) Screen-only tablet version of EarthShake with Physical Control

The tablet version of EarthShake used the same game interface as the mixed-reality and the laptop versions. Again, as in Condition 3, a video of the towers was integrated into the interface. The characters, the scenario and the button controls were all kept the same as in the projected game in Condition 1, 2 & 3. The only difference was that this time in order to shake the table, they had to shake the tablet with their hands instead of pressing the shake button as in Condition 2. Shaking the tablet would start the video of the towers shaking on the table (Figure 1 right).

In the tablet version, the partners were asked to sit on the floor next to each other in a position where both of them would be able to see the screen of the tablet. They were asked to take turns shaking the tablet and clicking the selection choices on the screen.

Measures

We measure learning with paper-based assessments and a tower construction task, using isometric pre- and post-tests. These tests were based on the NRC Framework & Asset Science Curriculum [19]. There were two different types of items included in the tests: prediction items and explanation items. First, the students were given a picture of a table with two towers on top of it and were asked to predict which tower would fall first when the table shakes by circling one of the options (Figure 7 left). Next, they were asked to explain why they chose this answer (Figure 7 right) by writing their explanation (the experimenter helped them if they had a hard time writing).


What will happen when the table shakes?

6

Why did this one stay up?

Because it is It Has less wait on the top

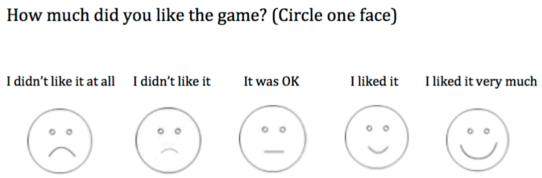
Figure 7. Examples of prediction (left) and explanation (right) items used in the paper pre/posttests.

We also used a tower pre/post test, where students built a tower given a limited number of blocks and a certain block as the base (See Figure 8). This task was the same for all the conditions, and was used as a transfer measure, to see how much their towers improved after interacting with the game.

After interacting with the game students were also given a survey to measure enjoyment. In this survey they were asked three questions as a measure of how much they enjoyed the game: “How much did you like the game?”, “Would you like to play it again?” and “Would you recommend it to a friend?” For each of these questions they had to choose an answer of a 1-5 scale demonstrated with smileys (See Figure 9).

Figure 8. Children building their own towers before and after interacting with the game.

A fourth question asked “How much did you like building your tower and testing it on the earthquake table?”, which was a measure of how much they enjoyed building their own towers during the tower pre/post tests.


How much did you like the game? (Circle one face)

I didn't like it at all	I didn't like it	It was OK	I liked it	I liked it very much

Figure 9. Example survey question measuring enjoyment.

Procedure

During the experiment, students were first given a paper pretest to see how much they already knew about the stability and balance principles introduced in the game. Then they were given a tower pretest, where they were asked by the experimenter to build a tower that would not fall down when the table shakes, using all the blocks in the provided set of blocks, and a certain block (2 by 2 square block) as the base of the tower. Then they shook the table to see if their tower would stay up. After that, they interacted with the EarthShake activity (mixed-reality or screen-only version depending on the condition they were in), which included 10 contrasting cases (Figure 3). After interacting with EarthShake, they were given the tower posttest where they were asked to build a tower again using the same rules as before. This tower was used as a measure to see if/how their towers had improved after interacting with the game. After the tower posttest, they were given a paper posttest to see how much they had learned on paper. At the end, they were given a survey as a measure of enjoyment from the game and the building activity (Figure 9). The experimenter also did a brief interview with them at the end to see what they liked/disliked about the activities and if they had any suggestions to improve the game. The same procedure was used for all 4 conditions: mixed-reality vs. screen-only crossed with physical vs. mouse control. The role of the experimenter was the same for all conditions.

RESULTS

We analyzed our paper pre and posttests, tower pre and posttests as well as the surveys that were given at the end of the game, in order to see the effects of observing physical phenomena in a mixed-reality game setting and physical control on learning and engagement.

Paper pre/post tests

A 2-way ANOVA analysis with overall pre-test score as the outcome variable confirmed no differences between the conditions at pretest (F's < .46 and p's > 0.50). To check for learning benefits, a 2-way ANCOVA was conducted with between-participant factors of control-type (mouse-control or physical control) and media-type (mixed-reality or screen-only), with pre-test score as a covariate and post-test as the outcome variable. The overall results (including both the prediction and explanation items) indicated that there was a significant effect of media-type (F(1,91)=8.2, p<0.01, d=0.37). The overall improvement from pre to post was 11.3 % in the mixed-reality conditions and 2.4 % in the virtual conditions. Thus, the mixed-reality game improved learning by 4.8 times compared to the screen-only alternatives. The average score on the posttests (both the prediction and explanation items) was 45% across the mixed-reality conditions and 39% across the virtual conditions. There was no effect of control type and no interaction effects. These results show that mixed-reality led to more learning than screen only, for both the mouse-control and physical-control conditions (Figure 10).

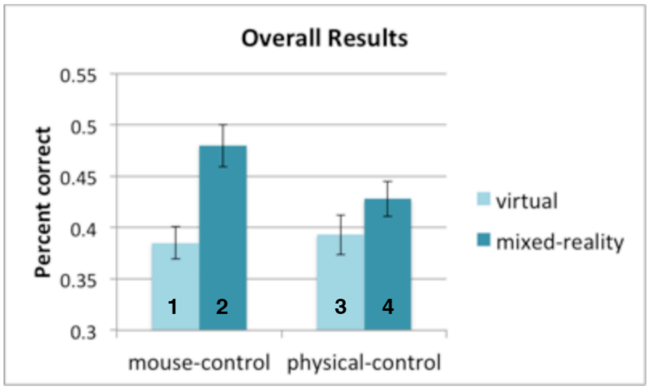


Figure 10. Overall results.

We can consider what choice improves learning most over a typical virtual, mouse-control game (#1 in Figure 10). The mixed-reality, mouse-control condition (#2) is significantly better (p<0.05), but the virtual, physical-control condition (#3) is not. In other words, facilitating physical observation was more powerful than facilitating physical control through shaking the tablet.

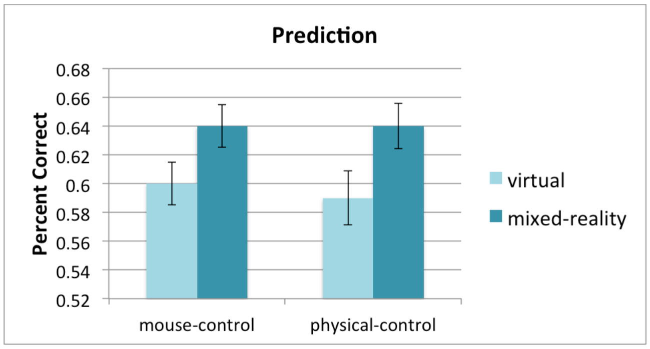


Figure 11. Percent correct for Prediction Items

Considering only the prediction items, there were again significant positive effects of the mixed-reality interface. The average of the mixed-reality condition for posttests was 64% while the average of the virtual condition was 60%. The improvement from pre to post for the prediction items was 7% in the mixed-reality conditions, whereas it was 1% in the virtual conditions (F(1,91)=4.2, p<0.05, d=0.41). There was no effect of control-type and no interaction effect of media-type and control-type (Figure 11).

The results were similar for the explanation items. Again a 2-way ANCOVA test showed that for the explanation items, the mixed-reality condition was learning significantly better than the virtual condition (27% vs. 18% for posttest items, F(1,91)=4.7, p<0.05, d=0.44). The improvement from pre to post for the explanation items was 15.5% in the mixed-reality condition, where as it was 3.7% in the virtual condition. Again there was no effect of control-type and no interaction effect (p=0.20) of media-type and control-type (Figure 12). However, there is an apparent trend: those in the mixed-reality with mouse-control condition seemed to be doing slightly better than those in the mixed-reality with physical-control condition. Analyzing only the mixed-reality condition on its own, we did not see a significant effect of control-type (p=0.20). Nevertheless, this trend makes some sense give our observation that kids having the physical switch in their hands were quite excited about pressing the button. As consequence, they may not have paid as much attention to providing explanations in the game.

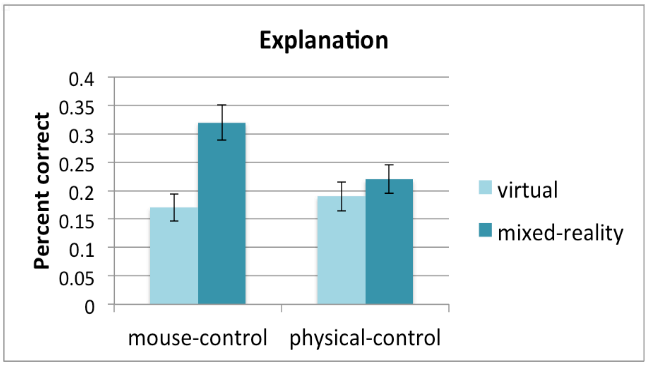


Figure 12. Percent correct for Explanation Items

Tower pre/post tests

The towers were analyzed to see if there was a difference for how much the towers had improved from pre to post in different conditions. The coding scheme, shown in Figure 13, was used to analyze the towers. Each pair of towers (pre and post) was coded according to three different principles: height, symmetry and center of mass. The fourth principle, wide base, was not used, since the base was kept the same as a constraint in the given task. If the tower pair had improved from pre to post on a certain principle, i.e. if the post tower was shorter than the pre tower, we gave them a 1. If the post tower was taller than the pre tower, we gave them a -1. If the pre and post towers had the same height we gave them a 0 for this principle. We repeated the same procedure for different principles, i.e. they got a 1 on symmetry if the post tower was more symmetrical; they got a 1 on Center of Mass if the post tower had a lower center of mass than the pre tower. After giving a score for each principle, we added up the scores to get a total score the tower pair (Figure 13). Then the total score data was analyzed to see if there was any difference for the scores between different conditions.

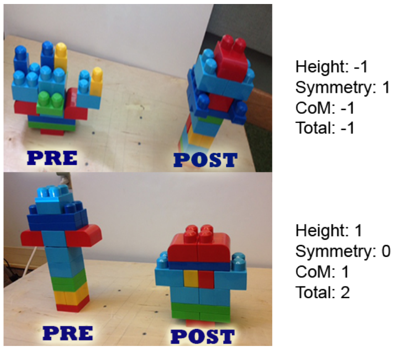


Figure 13. Coding scheme for Tower pre/post tests

The results of a 2 way ANCOVA show that there was a significant effect of media-type for the tower scores (F(1,91)=6.9, p=0.01, d=0.64). There was no significant effect for control-type and no interaction effect of media-type and control-type. Thus, the kids in the tangible condition were improving more on building stable towers than those in the virtual condition, for both the mouse-control and physical-control conditions (Figure 14). This result is particularly interesting as it demonstrates better transfer of instruction involving mere physical observing (over flat screen observing) to actual physical interaction with the blocks.

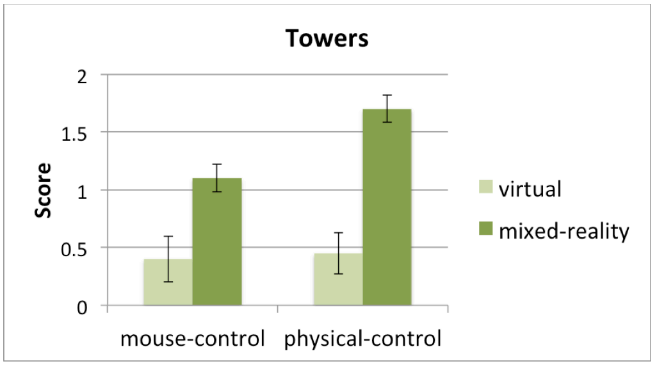


Figure 14. Tower scores

Engagement and Enjoyment

As a measure for enjoyment, the survey data was used, where the students were asked three questions (Figure 15). Comparing the scores of the children in different conditions, we saw that the students who were in the mixed-reality condition said they liked the game significantly more than those in the virtual condition (F(1,92)=6.7, p=0.01, d=0.55). There was no significant difference between the mouse-control and physical-control groups for enjoyment (Figure 15). There was also no interaction effect of media-type and control-type. However analyzing only those who interacted with the mixed-reality game (either with mouse-control or physical-control), we saw that there was a marginal effect of control-type (p=0.08, n=45). Thus the physical switch in the mixed-reality game was increasing enjoyment slightly. On the other hand, looking at only those interacting with the virtual game, control-type did not have any effect.

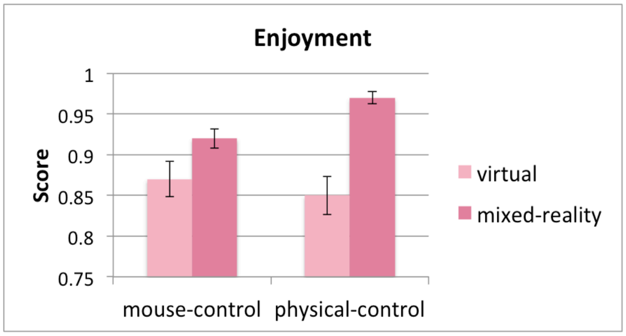


Figure 15. Enjoyment scores based on the survey

OTHER OBSERVATIONS/COMMENTS

Children seemed to be very much engaged during the game. One of the kids in the tangible condition asked if she could trade some of her toys to get an EarthShake at home. Another student said: "Can I steal your computer and set this up at home?" Some others mentioned that they would want to use this game in the circles that they do in their classrooms. Another girl said: "I never thought something we do at school could be so much fun", while another stated: "I wish all our science classes were fun like this." Another student cited that she thought this was like the next version of smart boards.

Many kids made comments indicating that the experience of seeing what actually happens in real life was better than having a computer tell them what is going to happen, which suggests that observing physical phenomena in the real world might be more believable, leading to more learning.

While kids were interacting with the game, it appeared that the explanation menu particularly helped them learn. After making a wrong prediction and observing the towers fall, many kids had an a-ha moment when they saw the menu appear behind the towers and recognized one of the items as being the reason why their prediction was wrong. The menu provided a basis for them to understand the physics principles of balance and stability (symmetry, wide base, height and center of mass). Also during our pilots we saw that children who interacted with the physical setup on its own (earthquake table and physical blocks) without any virtual component did not learn much.

Many kids mentioned that they liked building their own towers and wished there were more building activities during the game. Also, looking at the fourth question in the survey, we saw that children scored 98% on average, expressing that they liked building their own towers very much. Thus, integrating more hands-on building activities into the game may make it even more engaging.

In addition, children mentioned that they liked the gorilla character in the game, telling their friends about their *gorilla friend*. This suggests that having a character in the game made it more engaging and memorable for children.

DISCUSSION

Our experimental results provide evidence that observing physical phenomena in the context of an interactive mixed-reality game plays an important role for learning and enjoyment, while adding simple physical controls such as having the kids shake the tablet in a screen-only game or press the physical switch in a mixed-reality game does not have an effect on learning or enjoyment.

We wanted to test the claim that the learning benefit of physical observation is not just an effect of enjoyment or the novelty of the physical earthquake table, but seems to result from changes in how children better think about the physical phenomenon when they observe it in the real world. To do so, we selected out the subset children in both virtual and mixed reality groups who experienced the highest level of enjoyment (those who all scored more than 90% in the enjoyment survey). The results revealed that even for this subset there was still a significant effect of mixed reality (over virtual) on learning ($p<0.01$). Also, a 2-way ANCOVA with the enjoyment score and pre-test as covariates and post-test as the outcome variable showed that there was no significant effect of enjoyment on learning. These results suggest that enjoyment was probably not a critical mediating factor for learning (albeit a desirable independent outcome).

Comparing the mixed-reality physical switch and mouse conditions also revealed an interesting result: having the kids use the physical switch compared to the mouse increased the enjoyment marginally. However, the physical switch condition did not learn any better than the mouse condition; in contrast there was a trend in the opposite direction. Thus increasing enjoyment did not always increase learning. That's a point worth highlighting for educational technology design – adding an enjoyable feature does not always increase learning and may even be distracting in some cases.

In contrast to enjoyment as mediator, it may be that observing physical phenomena is critical to develop understanding through embodied cognition. This explanation is supported by the greater number of meaningful gestures that children made in the mixed reality condition in our prior study [30]. A similar explanation is that having a physical view of the real world phenomenon produces a sense of reality and believability that engages deeper sense making and leads to better learning. More broadly, our results are consistent with a body of theory and research suggesting that young children often fail to use information communicated to them via symbolic media including pictures, models and video [7].

These results are important since laptops and tablets are the most common tools that children interact with these days. Thus, instead of trying to integrate physical controls into screen-only environments, such as shaking the tablet, it may be worth integrating interactive instructional feedback into the physical environment, without losing the benefits of experimenting with physical objects in the real world.

CONCLUSION AND FUTURE WORK

We provided evidence that experiencing physical phenomena accompanied by interactive feedback via depth camera sensing in the real world improves learning (by approximately 5 times compared to a solely screen-based environment), while also enhancing enjoyment significantly. On the other hand, integrating simple physical controls such as shaking the tablet has little effect. Thus, mixed-reality games that support physical observation in the real world have a great potential to enhance learning and enjoyment for young children.

Although we found that adding a simple form of physical control where the hands-on actions are not relevant to the learning objectives does not have a significant effect on learning or enjoyment, a related question still remains. Do more elaborate hands-on activities where children actually build with the blocks further increase learning and/or enjoyment? Children's comments and our survey data suggest that having more building activities integrated into the game can make it more enjoyable for children. In future work, we aim to explore the role of combining more hands-on activities while maintaining the vision-based interactive learning feedback.

We also aim to expand our mixed-reality game for different content areas in education (e.g., using a balance scale rather than earthquake table) to test the generalizability of our results. Our goal is to eventually create a scalable, mixed reality platform, connecting virtual and physical worlds via affordable depth camera sensing, that can be reused for different content areas in education to improve children's science learning and enjoyment.

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REFERENCES

1. Antle, A. N. Research opportunities: Embodied child–computer interaction. *International Journal of Child-Computer Interaction* 1, 1 (2013), 30-36.
2. Antle, A. N., Droumeva, M., & Ha, D. Hands on what?: comparing children's mouse based and tangible-based interaction. *In Proc. IDC 2009*, ACM Press (2009), 80-88.
3. Back, M, Cohen, J, Gold, R, Harrison, S and Minneman,S, Listen Reader: an electronically augmented paper-based book. *In Proc. CHI 2001,* ACM Press (2001), 23-29.
4. Bakker, S., van den Hoven, E., & Antle, A. N. MoSo tangibles: evaluating embodied learning. In *Proc.of Tangible, embedded, and embodied interaction* 2011, ACM Press (2011), 85-92.
5. Bruner, J. Toward a Theory of Instruction. Vol. 59. Harvard University Press (1966).
6. Carini, R. M., George D. K., and Stephen P. Klein. Student engagement and student learning: Testing the linkages*. *Research in Higher Education* 47.1 (2006), 1-32
7. DeLoache, J. S., et al. "Do babies learn from baby media?." *Psychological Science* (2010).
8. Englekamp, J. & Zimmer, H. D. Memory for action events: A new field of research. *Psychological Research* 51.4 (1989), 153–157.
9. Glenberg, Arthur M. What memory is for: Creating meaning in the service of action. *Behavioral and brain sciences* 20,01 (1997), 41-50.
10. Hayne, H., Herbert, J. & Simcock, G. Imitation from television by 24- and 30-month-olds. *Developmental Science*, 6, 3 (2003), 254-261.
11. Henning, P. (1998). Everyday Cognition and Situated Learning. In Jonassen, D. (Ed.), *Handbook of Research on Educational Communications and Technology*. (2004), 829-861.
12. Kahn, P. H., Severson, R. L., & Ruckert, J. H. The human relation with nature and technological nature. *Current Directions in Psychological Science*, *18*, 1 (2009), 37-42.
13. Klahr, D., Triona, L. M., and Williams, C. Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching* 44.1 (2007), 183-203.
14. Martin, T., & Schwartz, D. L. Physically distributed learning: Adapting and reinterpreting physical environments in the development of the fraction concept. *Cognitive Science*, 29 (2005), 587–625.
15. Montessori, M. *Montessori method*. Random House Digital, Inc., (1964).
16. Olympiou, G., and Zacharias C. Z. Blending physical and virtual manipulatives: An effort to improve students' conceptual understanding through science laboratory experimentation. *Science Education* 96, 1 (2012), 21-47.
17. O'Malley, C., Stanton-Fraser, D.: Literature review in learning with tangible technologies, Nesta FutureLab Series, report 12 (2004).
18. Pouw, W. T., Van Gog, T., & Paas, F. An embedded and embodied cognition review of instructional manipulatives. *Educational Psychology Review*, *26*, 1 (2014),, 51-72.
19. Quinn, H. et al., A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas, *The National Academies Press* (2012)
20. Raffle, Hayes Solos, Amanda J. Parkes, and Hiroshi Ishii. Topobo: a constructive assembly system with kinetic memory. *In Proc CHI 2004*, ACM Press (2004), 647-654.
21. Resnick, M., et al. Digital manipulatives: new toys to think with. *In Proc. CHI 1998,* ACM Press (1998), 281-287.
22. Rieser, J.J., Garing, A.E. and Young M.F. Imagery, action and young children's spatial orientation-it's not being there that counts, it's what one has in mind. *Child Development*, 65, 5 (1994), 1262-1278.
23. Rizzolatti, G., Craighero, L. The mirror-neuron system, *Annual Review of Neuroscience,* 27 (2004) 169–192.
24. Rogers, Y., et al. *A conceptual framework for mixed reality environments: designing novel learning activities for young children*. *Presence: Teleoperators and Virtual Environments* 11, 6 (2002), 677-686.
25. Ryokai, R. and Cassell, J. (1999). StoryMat: a play space for collaborative storytelling. *In Proc. CHI 1999*, ACM Press (1999), 272-273
26. Schneider, B., Jermann, P., Zufferey, G., & Dillenbourg, P. Benefits of a Tangible Interface for Collaborative Learning and Interaction. *IEEE Transactions on Learning Technologies*, 4 (2011), 222–232.
27. Shelley, T., Lyons, L., Zellner, M., & Minor, E. Evaluating the embodiment benefits of a paper-based tui for educational simulations. *Ext. Abstracts* CHI 2011, *ACM Press (2011),* 1375-1380.
28. Ullmer, B. and Ishii, H. Emerging frameworks for tangible user interfaces. *IBM Syst. J. (2000)* 915–931.
29. Yannier, N., Basdogan, C., Tasiran, S., Sen, O. L., Using Haptics to Convey Cause and Effect Relations in Climate Visualization, *IEEE Transactions on Haptics*, 1, 2 (2009), 130-141.
30. Yannier, N., Hudson. E. S, Wiese, E., Koedinger, K., Adding Physicality to an Interactive Game Improves Learning and Enjoyment: Evidence from EarthShake, *In Review*
31. Yannier, N., Koedinger, K. R. and Hudson, S. E. Tangible Collaborative Learning with a Mixed-Reality Game: EarthShake. *Artificial Intelligence in Education*. Springer Berlin Heidelberg (2013), 131-140.
32. Walker, E., & Burleson, W. Using Need Validation to Design an Intelligent Tangible Learning Environment, *Ext. Abstracts CHI 2012, ACM Press* (2012), 2123-2128.