# Evaluating Elementary Student Interaction with Ubiquitous Touch Projection Technology

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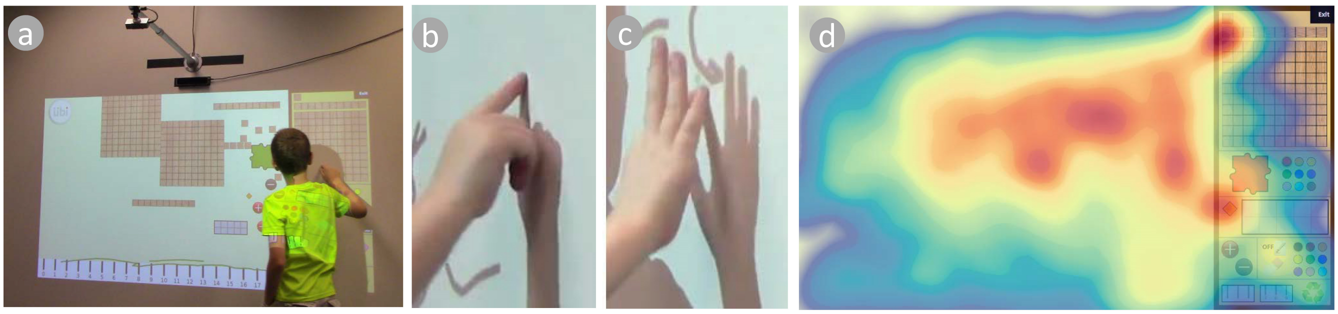


**Figure 1. Third-grade students interact with a touch-projection environment. (a) A student interacting with math manipulatives. (b) An example of observed hand-dragging behavior. (c) An example of observed hand splay behavior. (d) Manipulative application interface with a heatmap overlay of student touches over all experimental sessions (18 children).**

## ABSTRACT

Ubiquitous touch projection technology is entering the market and allows touch screens to be projected onto any smooth surface at a lower cost. We created a mathematics manipulative application for a low-cost, ubiquitous touch projection system, and we conducted an observational study with 18 third-grade elementary students. Through our analysis of both video and system data, we identify common student interaction problems, evaluate how those interaction problems affect usability, engagement, and pair-work, and we make practical suggestions to aid future developers, educators, and students in using such a platform.

### Author Keywords

manipulatives; multi-touch; ubiquitous; touch projection

### ACM Classification Keywords

• **Applied computing~Interactive learning environments**
• *Human-centered computing~Ubiquitous and mobile computing systems and tools* • Human-centered computing~Touch screens

## INTRODUCTION

We call technology that allows a touch screen to be projected on any smooth surface *ubiquitous touch projection* technology.



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This technology has been made possible and better through recent advances in low-cost camera and emitter hardware and software. These systems typically employ a combination of a camera, emitter(s), projector, and a commodity computer to convert large everyday spaces (i.e. walls, floors, and tabletops) into interactive spaces. Ubiquitous touch projection technology is attractive in that it is cheaper than a Smartboard or interactive whiteboard, can be retrofitted easily into most classrooms, allows the use of user-developed apps, and usually allows participants to interact natively without the use of a specialized pen or stylus. We have not found research evaluating the use of this technology with elementary-aged students. Such research may help educators and developers determine if this technology is suitable for a classroom environment. Our research uses a ubiquitous touch projection system [15] to project a custom mathematics manipulative application on a wall (Figure 1a). Manipulatives are often used in the classroom to help students learn mathematical concepts [2,4,7–9,13,14].

Our paper contributes an observational study of third-grade students interacting with a large-scale, multi-touch, projected display. We created a customized mathematics manipulatives application designed for large wall projection. Students were given a chance to explore the environment by playing with the projected objects and then were asked to solve a third-grade math problem using the manipulatives in multiple ways. We collected data by using video cameras and software to record both student and system interactions. We uncovered a series of common interaction problems, and we evaluated usability, level of engagement, and a pair-work session to help determine if a ubiquitous touch projection environment is suitable for a larger-scale pedagogical environment. Finally, we present practical suggestions to help mitigate the interaction problems.

## BACKGROUND AND RELATED WORK

### Touch Applications

Romeo et al. [12] investigated how children interacted with touchscreens. The research found that large icons were essential for the ease-of-use for children, as well as a simplistic, easy-to-understand interface. Touch screens had significant advantages in collaborative activities when compared to a mouse and keyboard, although the ability of one student to interfere with another's work must be considered. Peltonen et al. [10] found that users of large, wall-mounted, multi-touch surfaces tended to act independently by designating roles and taking turns rather than direct collaboration. Hornecker et al. [3] found that collaborative touch surfaces, while not directly enforcing collaboration, builds a strong awareness of other users.

Mental and physical limitations of children are important to consider when designing touch applications [12]. Aziz et al. [1] suggests using gestures that young children can consistently understand and perform accurately. The study found that a majority of children's applications implemented some form of both the 'Tap' and the 'Drag' gestures which could be fully understood. Gestures such as 'Free Rotation', 'Pinching', and 'Drag & Dropping' were more difficult for young children to understand. Gestures implemented should be consistent throughout the application developed and should resemble a similar gesture that would be used to interact with a physical form of the component in question.

Kammer et al. [5] observed interaction with kindergarten-aged children around an interactive tabletop and found children naturally performed various multitouch gestures with no significant problems using a child-oriented interface design and metaphors for the tasks. Rick et al. [11] performed an analysis of children working together on a multi-touch tabletop and found that children use the entire tabletop but focus especially on the areas closer to their positions. Khaled et al. [6] researched multi-touch play on an interactive tabletop using games. If children were initially hesitant to interact due to unfamiliarity with the technology or games, a demonstration of the interaction would be required before the child would begin to interact.

### Touch Projection Technology

Many elementary classrooms have an interactive white board (IWB). These technologies often also contain or utilize a combination of camera, emitter, and projector to display an interactive environment. IWBs such as the Smartboard [16] and Promethean boards [17,18] come pre-packaged with a large board, limiting their portability and installation, while costing thousands of dollars [19]. These systems often lock the educators into using the software ecosystem of the manufacturers and enforce the use of a pen or stylus in some or all scenarios. Finally, some boards also contain electronics in the frame that allow them to have a touch sensitive surface [20].

The eBeam Edge [21] and MimioTeach [22] are hybrid examples of technology that are more portable than an IWB. They are lower cost and attach to existing whiteboards to make them interactive through ultrasound and infrared technology. However, they both require a pen or stylus for touch interaction.

Ubiquitous touch projection technology allows a touch screen to be projected on any smooth surface such as a wall or tabletop. These systems are relatively new and lower cost, and the hardware and software are currently evolving. Ubi Interactive [15] combines software with a "touch kit" consisting of a proprietary camera and emitter to allow users to project a large touchscreen onto a flat surface. Touchless Touch [23] uses free software (for non-commercial use) along with one or more commodity emitters. Sony Xperia Touch [24] combines a short-throw projector, emitter, and embedded camera into a small appliance that can create up to a 23 inch touchscreen. TouchJet Pond [25] combines the functionality of a projector and an Android tablet to project a large interactive touchscreen using an interactive stylus or Airmouse.

We chose to evaluate student usability on the Ubi Interactive platform, as it is well-supported, works with commodity Windows computers with traditional projectors, and allows a large screen size to be projected on a variety of smooth surfaces. It also advertises multi-touch natural interaction with fingers, which we believe is a large selling point for interaction with children.

## EXPERIMENTAL DESIGN AND METHOD

### Framework

Our setup consists of a hardware/software package purchased from Ubi Interactive, a manipulatives application we built for evaluation purposes, and analysis software we built to record touches and interactions.

We used the enterprise version of the Ubi Interactive software which allows up to 20 simultaneous touches and a "touch kit" consisting of a wall-mounted camera and emitter. The emitter projects an emitter curtain slightly above the wall, and touches are recorded when observed by both camera and emitter. We projected our screen against a plain white wall and used a standard projector with a laptop to run the software. Students stand in front of the wall and interact with it. We placed video cameras facing the left, center, and right sides of the screen to record participants (see Figure 2).

Our mathematics manipulative application includes six manipulatives chosen to be relevant to a third-grade lesson plan including a pen mode to be controlled via fingers (see Figure 1d). The application consists of two main areas: a play area on the left, and a toy box area shown on the right. Participants may drag manipulatives from the toy box area into the play area.

We recruited 18 third-grade students to participate in our half hour study to interact with our system. All children were between the ages of 8-9 years old. Each session took approximately 30 minutes.

After consent/assent forms were signed and questions answered, we began the study. To encourage the children to become

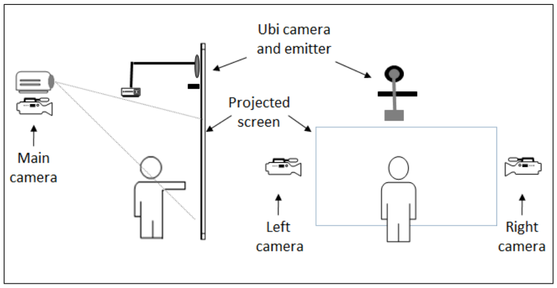


**Figure 2. Positioning of test environment.**

comfortable interacting with projected images, we started our ubiquitous touch system with a common touch-interface game (Angry Birds [26]). All student participants indicated they had encountered this game before. We allowed the student to play with this game until the student seemed comfortable interacting in this manner.

Next, we loaded our custom manipulatives application and briefly introduced each manipulative through verbal explanation and demonstration on the system. We then allowed the students to play with the manipulatives without any formal direction to give them a chance to acclimate with our manipulatives application. Next, we randomly asked the student to solve one of two third-grade level math questions three different times using different tools from the toy chest. Finally, we asked questions about their experience. On average, students spent 20 minutes using the system: around 5 minutes playing Angry Birds, 5 minutes playing with manipulatives, and 10 minutes solving math problems.

The two third-grade math questions were randomly chosen via coin flip and were evenly distributed: (A) *Marci has 67 marbles. Dan gives her 45 more. How many marbles does Marci have now?* (B) *Sunnyside Park has 67 oak trees and 38 pine trees. How many more oak trees are there than pine trees?*

The students could ask for the question to be repeated and could hold a sheet of paper with the printed question.

We recorded 16 students using the system by themselves and a pair of students using the system together. Eleven students indicated they had solved math problems like this using objects before when asked at the end of the study. These manipulative include physical, Smartboard and Promethean boards, MimioTeach, and iPads/Chromebooks.

## FINDINGS

### Usability

Although it is intuitive to approach the projected wall in the same way as a large touch screen, differences do exist. A touch screen is responsive to touches, yet our framework relies on the inputs from a camera and a projected emitter curtain to interpret touches. Even in perfect scenarios, we noticed the camera and emitter interpret touches in a less-precise way than a touch screen. This is largely due to the need to approximate locations of the touches based on the locations of the camera, emitter, and projected screen size. Thus, we designed our manipulatives to be large and manipulative actions to be simple.

Throughout this study, we observed common interaction problem behaviors that can cause the system to misinterpret touches or cause other unexpected behavior. The first two problems concern accidentally breaking the emitter curtain. The last two problems concern some form of occlusion.

***Hand-dragging*** occurs when the participant is pointing at the projected wall at a sharp angle and the knuckle, side of the hand, or the heel of the hand breaks the emitter plane. Figure 1b demonstrates an example of hand dragging where the participant's knuckle is breaking the emitter plane in addition to the intended index finger.

***Multi-finger splay*** occurs when students interacted with multiple fingers splayed, thereby breaking the emitter curtain. Figure 1c demonstrates an example of finger splay where the participant's fingers are splayed causing some fingers to unintentionally break the emitter plane.

***Camera occlusion*** occurs when the participant stands directly in front of the camera so that only the emitter detects the touch. In this scenario, the touch may be interpreted inaccurately or completely dropped.

***Shadow blocking*** occurs when the participant is casting a shadow on a part of the interface that he or she wishes to use in a way which causes interaction problems.

We observed that hand-dragging and multi-finger splay caused unique problems on this system that would not otherwise be caused on a regular touch screen. Since the system must rely on approximations on touch locations based on the camera and emitter inputs, extra fingers or parts of a hand accidentally breaking the emitter plane can cause the original touch point to reapproximate position, jump, or cause new approximations of multiple touch points. Translated into actions, this can cause extra lines, dots, and unanticipated line origins in pen mode. Using regular manipulatives, hand-dragging or multi-finger splay could cause the manipulative to be dropped prematurely or accidentally broken apart. In other scenarios, manipulatives not meant to be moved could be accidentally moved.

We identified that students may often employ hand-dragging or the multi-finger splay during informal testing. Therefore, during the Angry Birds step of our study, we instructed children to point with one finger keeping their finger and arm "straight like a stick". If students struggled heavily (got stuck) with any of the interaction problem behaviors during the rest of the study, we reminded them to use one finger or point with a straight arm. On average, we gave advice three times per session.

We analyzed the videos of each of the single sixteen students interacting with the manipulatives application (both in play time and solving the math question). We then coded each time any of the following behavior caused something unintended to happen: hand-dragging (HD), multi-finger splay (MFS), camera occlusion (CO), and shadow blocking (SB). See Figure 3a.

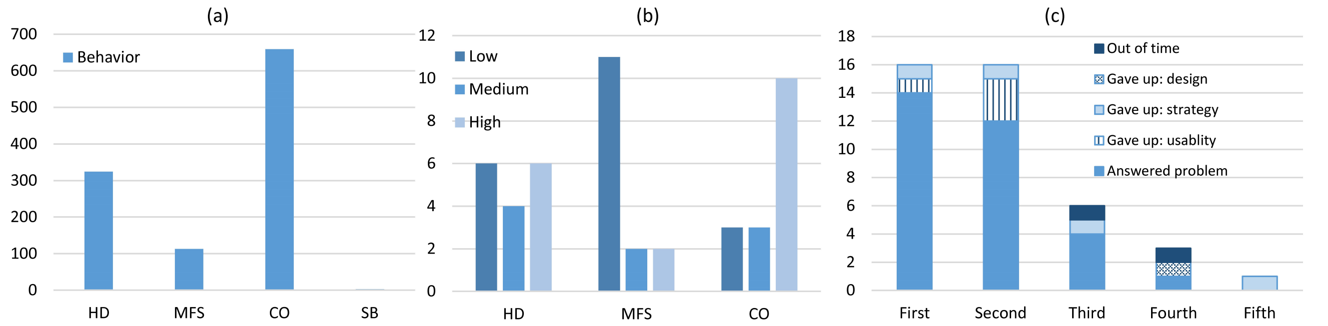


**Figure 3. Student usability and engagement graphs. (a) Recorded instances of behavior that affected usage of the interface in unintended ways. (b) Students categorized by rate of problem behaviors using manipulatives. (c) Math problem attempts by number of students.**

No student seemed to struggle with shadow blocking. Even though students would often block manipulatives with their shadows for a short period of time as they moved, they remembered where the manipulative was and could still use it successfully (see Figure 1a). In the three recorded times their shadow caused them to miss the manipulative, they quickly figured out what happened and stepped to the side so that they could again see that area of the wall.

On the other hand, problems with hand-dragging, multi-finger splay, and camera occlusion seemed to surprise students. Hand-dragging and multi-finger splay caused the system to drop the object the students were dragging, accidentally break apart a 10- or 100-block (these manipulatives will break into smaller manipulatives when touched at two points), or else "catch" and drag another unintended manipulative. However, camera occlusion provided no feedback to students other than the gesture not working. Many of the high camera occlusion numbers come from students trying the same occluded touch gesture 5-10 times rapidly before trying something different.

After gathering these totals, we noticed that the students that had little issue with the interaction problem behavior tended to have 0-10 recorded instances of the behavior, those with medium issues tended to have 11-20 instances of the behavior, and those with more than 20 instances had high levels of issue with the interaction problem behavior (Figure 3b). Students with little issues had few to no occurrences of the behavior in which it interfered with their actions. If the behavior did interfere, students quickly adapted. Students with medium issues were slowed but could continue. Students with high levels of issues had enough interference to cause frustration and require more guidance from the study administrators.

Problems with hand dragging varied almost equally among the students. Only two students struggled badly with multi-finger splay, and the rest only tended to exhibit this behavior when reaching very high for a manipulative. On the other hand, many students struggled with camera occlusion. Camera occlusion seemed to cause the largest problem with items in the lower-right quadrant of the screen when the students were standing just to the left of the toy box. We discovered this is unfortunately due to the central overhead camera perspective and angle to the student causing the camera occlusion to occur. Unfortunately, many commonly-used tools and buttons were placed in the lower-right quadrant, such as the pen slider, pen color selector, and the reset button. Students that had medium to low issue tended to naturally step to the side or else kneel when accessing these areas.

We evaluated pen mode separately from the rest of the manipulatives, as the severity of any unexpected interference mattered more than the frequency towards the overall user experience. Four students were able to use the pen with little to no extra lines/dots appearing with the drawing originating from their intended fingertip. Conversely, six students had a high amount of hand-dragging or finger splay, which caused many extra unintended lines/dots to appear with the origin of the drawing not necessarily originating from the intended finger. (For example, the system might pick up the heel of their hand instead of the finger.) Writing in this way was unreadable or bordering on unreadable. Finally, six students used the pen in a messy but readable way.

We also noted if the students improved their pen-writing by the end of the session. We saw that 50% of the messy-but-readable difficulty pen writers were able to improve, whereas only one student out of six improved in the higher-difficulty category. Some improvement is encouraging in the short time they were evaluated, and future work in a long-term classroom setting would need to be performed to see if students could improve further.

### Engagement

In this subsection, we ask the following question: Is the system engaging enough that children can use it to complete a pedagogically-relevant question three times using three different manipulative tools? All sixteen students attempted to solve the problem two ways, six students attempted three ways, three students attempted four ways, and one student attempted five ways for a total of 42 attempts (Figure 3c).

Even though some students had a high occurrence of some behavior (such as camera occlusion), it did not always cause them to give up. Instead, it often just slowed them down. Only six students had enough time to move onto solving the math problem a third way. We noticed problems with pen writing did not prevent students from finishing a task, but it did cause them to adapt: go slower, erase more often and start over, write very large, or in some instances leave numbers almost unreadable. No student quit the study early.

Specifically, we had four instances in which interaction problem behaviors caused students to give up solving the math problem in a certain way. One student had hand-dragging problems with both sliding the ruler and drawing precisely on the ruler. One student could not reach the single block of the 100-blocks without jumping, which caused the student to miss. When manipulating the 10-block, the student's hand dragging caused the block to unintentionally break. Another student's finger splays while reaching high to drag out 10-blocks caused the block to unintentionally break. One student attempted to use 10-frames and counters, but camera occlusion kept the student from being able to drag the counters out of the toy chest.

Four students had mathematical strategy errors that caused them to give up prematurely. Finally, one student used a combination of manipulatives in a way that made sense but did not work with our application design. Specifically, this student was disappointed that their pen markings did not scroll with the ruler at the bottom of the screen. We created a separate "Gave up: design" category for this in Figure 3c as it wasn't a faulty strategy and the reason for giving up was not due to an interaction problem behavior described in the usability subsection.

Excluding the two attempts in which the students did not have sufficient time to completely solve the problem, we found that students were engaged enough to come up with an answer to the problem the majority of the time at 77.5%. It is expected that some students would have strategy or logic problems that prevent them from solving the problem, and this occurred 10% of the time. Students had usability issues with interaction problem behaviors that caused them to give up answering the math problem another 10% of the time.

### Pair-Work Session

Our pair-work session consisted of two children. We followed the same study procedure as the single students. When using only the manipulatives, both children were able to drag out and use the manipulatives in their own space without interfering with each other. In pen mode, one child hit the erase button thinking only her marks would be erased, and she was surprised to see both participant's marks erased. One child tended to both splay her fingers and hand drag, while the other child did not.

Overall, we observed students needed to be aware of each other to coordinate access to the toybox. The large screen and right-located toybox caused the students to move quite a bit and made solving the math problem a nice physical activity. We were pleasantly surprised to see the amount of coordination between both students to both play the Angry Birds game and solve the math problem. We also observed the student with more interaction problem behaviors observing the other student's more-successful gestures and copying some of them to greater success, which may suggest that students can learn to correct their gestures by observing each other in a collaborative environment.

### Other Findings

At the application level, we were able to record touch location and duration values students made for each session. Figure 1d contains a heat map of all recorded touches. Many touches were recorded on the counter, base-10 blocks, and the middle play area. The high use of the 100-block and counter makes sense, as the majority of the students indicated they had used manipulatives in some way, and the base-10 blocks and 10-frames with counters are appropriate tools used in third-grade pedagogy to teach basic addition and subtraction.

Specifically, we noticed two types of unintended touches that we call *discontinuous touches* and *accidental touches*. A discontinuous touch is a dragged touch which is moving in the same direction and contains a drop (up + down event) with a duration of less than one second inside a distance of 10cm or less. An accidental touch captures a secondary touch near a primary touch (within 10cm) with a system touch duration of less than 250ms (touch + instantaneous release). In other words, this measures extra touches that were likely unintended due to their proximity and quick duration. On average, accidental touches occurred 3x more than discontinuous touches. Both distance and duration amounts for discontinuous and accidental touches were determined through empirically interacting with the system and reviewing the results.

Over each of the 16 individual student sessions, we found the percentage of unintended touches to total touches. On average, we found unintended touches made up 36.34% (± 4.41% calculated standard deviation error) of all recorded touches at the application level. Adding in the pair-work session did not significantly change the figure (35.9% ± 4.36%).

To further explore how these unintended touches might occur, we generated a heat map of only unintended touches over all student sessions (Figure 4). Two main hot spots appeared: one in the top right quadrant of the play area and one on the very bottom right quadrant of the play area. One small hot spot also appeared in the middle of the play area.

The top right hot spot is easily explained. We found that students spent the majority of their time standing directly to the left of that hot spot in order to comfortably reach the toy box area with their right hands. When dragging out a 10- or 100-block to that hot spot, many students' right arms formed a right angle, causing the knuckles, heel of the hand, or splayed fingers to come in closer contact to the play area. Many 100-blocks were accidently "broken up" in that region when the system then falsely recognized a second touch. The middle hot spot is less significant and occurred where some students released 100/10-blocks, broke them up, and manipulated the smaller pieces while hand-dragging or splaying fingers. The bottom right hot spot came more as a surprise. Unintended touches in this region came primarily from waist-level clothing brushing against that area of the wall. This behavior did not cause visible problems when manipulatives were not in that space.

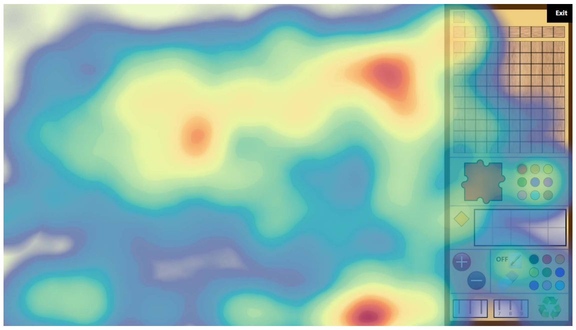


**Figure 4. Heat map of unintended touches over all sessions.**

## DISCUSSION AND RECOMMENDATIONS

Camera occlusion seemed to cause the largest problem with items in the lower-right quadrant of the screen when the students were standing just to the left of the toy box. Most third-graders did not realize they were blocking a camera and repeated the same motion until they gave up, stepped to the side, or used a different hand. We suggest the following to help mitigate the camera occlusion problem:

***1) Design common tools to be selected at shoulder height or higher.*** Camera occlusion typically did not occur at this height. With our application, we could redesign the toy box to reside at the top of the screen. It would be especially important in this case that the top of the screen should not be out of reach.

***2) Use more than one camera.*** If multiple cameras are used and placed strategically, one camera could see a touch gesture that another camera misses. Unfortunately, most ubiquitous touch projection kits only include one camera. In addition, extra cameras would likely cause more software processing, further slowing down the software reaction time. Finally, setting up multiple cameras could negatively affect portability.

***3) Mount the camera in front of the user.*** For example, mount a downward-facing camera beside the emitter. This may help eliminate camera blockage by body on the x plane, but blockage could still occur on the y plane with multiple arms in use.

Hand dragging and multi-finger splay broke the emitter curtain and caused problems during student interaction with the system. Most students were unaware of the emitter projecting a touch-sensitive curtain in front of the wall. Hand dragging tended to occur in two distinct scenarios: dragging items with the right hand out of the right-side toy box allowing the heel of the hand to break the plane, and writing in pen mode where the heel of the hand is directly below the index finger. We make the following suggestions to help mitigate hand dragging:

***1) Disable multi-touch on the system.*** If only a single touch is recorded, other confounding touches should be ignored until the original touch is released. Unfortunately, this suggestion would effectively make it a single-user system and disallow natural actions like using two fingers to “break apart” an object.

***2) Create a single touch threshold distance*** the size of a hand where only a primary touch is recorded and all other touches are ignored until the primary touch is released. We observed our system [15] did in fact instantiate such a non-configurable threshold, although its size seemed to vary at different points on the wall. The distance was often not wide enough to eliminate hand dragging problems. We also noticed unfortunate averaging behavior where two simultaneous touches within this threshold would cause it to register a single average touch in the middle (thereby releasing the object grabbed through the original touch).

***3) Educate the students to not drag their hand and to step back from the wall.*** Since the time interacting with the system was around 20 minutes in each session, future research is needed to see if elementary students can adapt to such directions over the long term in a classroom environment.

Finger splaying tended to occur most at head-height or higher, and it caused similar problems with the system as hand dragging. In addition to suggestions made to mitigate the hand dragging problem above, we also make the following additional suggestion to help mitigate the finger splay problem:

***1) Make sure students can easily reach the top of the screen without having to stretch***. We noticed the finger splay behavior especially occurred when students had to stretch to reach the upper level of the toy chest (for example, to drag out the one-block).

Finally, our application recorded unintended touches over the duration of each session. Many of these unintended touches can have no consequence (such as brushing near a non-used area of the wall with clothing). Designers should take careful consideration of where a participant is likely to stand to minimize unintended interactions with the application, and educators may want to periodically remind students to step back from the wall.

## CONCLUSION

Interaction problem behaviors were observed throughout the study with third-grade students that would not otherwise be a problem with a typical touch screen. Out of those behaviors, camera occlusion seemed to cause the most trouble. We discovered roughly one-third of the touches registered at the application level involved unintended touch actions. However, engagement levels in solving math problems were high. Two students successfully worked together, often using the system at the same time to reach a common goal. We also identified recommendations to system designers, application designers, and educators to cut down on the negative interference interaction problem behaviors can cause. We believe the use of ubiquitous touch projection technology shows promise in an educational setting, and future work includes studying the use of such a system in a live classroom environment.

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## SELECTION AND PARTICIPATION OF CHILDREN

We followed an informed consent process in accordance with US federal human subjects research requirements (45CFR46.102f). Our university's Institutional Review Board (IRB #17-0156) approved all processes and letters/forms. Third-grade student participants received a $25 gift card to a popular department store for participating in our study, even if they chose to withdraw. Signed informed consent forms were acquired from all parents/guardians of participants. We reviewed an assent letter with our student participants that they could choose to sign or not, regardless of parental consent. All study participants attended school in the US.

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