Designing a Tangible Learning Environment with a Teachable Agent

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Abstract. To date, the majority of learning technologies only afford virtual interactions on desktops or tablets, despite evidence that students learn through physical manipulation of their environment. We implemented a tangible system that allows students to solve coordinate geometry problems by interacting in a physical space with digitally augmented devices, using a teachable agent framing. We describe our system and the results from a pilot involving students using our system to teach a virtual agent. Students used a variety of strategies to solve problems that included embodied behaviors, and the majority did feel they were teaching their agent. We discuss the implications of our findings with respect to the design of adaptive tangible teachable systems.

Keywords: tangible learning environments, teachable agents, geometry.

1 Introduction

Research suggests that children construct much of their knowledge through active manipulation of the environment [1], which allows them to connect abstract concepts to something observable [2]. Despite these findings, most educational software, including Intelligent Tutoring Systems (ITSs), has been designed for personal computers [3]. These computers afford little physical interaction, in part because they involve the WIMP (window, icon, menu, pointing device) paradigm that creates an artificial separation between the input device, system output, and underlying real-world representation [4]. Consequently, little is known about how to design novel technologies that step outside of the virtual realm into the physical classroom or their impact on student learning, behaviors and/or perceptions. Our research aims to fill this gap.

As a first step, we implemented a tangible learning environment (TLE) that we call *Tangible Activities for Geometry* (TAG). Students interact with TAG in a physical space with digitally augmented devices to solve geometry problems. In contrast to other TLE work, TAG uses a teachable agent framing, for reasons we explain shortly.

One of the first TLEs was Papert's system, where students used LOGO primitives to control robots [5], for instance to solve geometry problems. Subsequently, other TLEs have been developed, for instance allowing students to interact with balls augmented with acceleration-triggered LEDs during physics activities [6], or using

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digitally-augmented, interactive table tops to support creativity [7] or to facilitate teachers' classroom organization [8]. In general, TLEs afford the manipulation of objects, or sometimes one's own body, that can be mapped to domain concepts students should acquire. For example, in Howison et al.'s TLE [9], students move their hands to different heights to demonstrate different fractions. Another example pertains to classrooms turned into observation centers of seismic activity or orbiting planets [10]. Phenomena occur as class is in session, and students investigate them over multiple sessions. TLEs have also been used in "programming by example" systems, allowing students to record the motion of tangible objects and then play that motion back [11].

Despite TLE's promise, there has been little investigation of their utility. Moreover, while some evaluations have yielded positive results [12], others have shown no difference between tangible and virtual environments [13]. However, TLE's have traditionally provided highly exploratory activities with little structure, despite evidence that explicit support may be needed for learning [14]. TAG aims to address this issue by providing students a set of problems to work on and by using a teachable agent framing. Peer tutoring research suggests that students can learn by teaching because they pay more attention to the material, reflect on misconceptions, and elaborate their knowledge when they construct explanations [15]. Following up on human-human results, computational systems have been developed, and the results are promising: teaching a computer agent can lead to more learning than being taught by an agent [16], and can be more effective than regular classroom instruction [17].

Our goals for the present research were as follows: (1) the design and implementation of a TLE for geometry that includes a teachable agent framing, and (2) evaluation of its impact on student behaviors and perceptions. While TAG relies on sophisticated sensing devices and algorithms to support tangible interactions, the system does not yet include any adaptive support, because we wanted to evaluate TAG before adding more functionalities. In this paper, we begin with a description of TAG and present results from a user study. We conclude with TLE design implications that highlight opportunities for introducing support tailored to students' needs.

2 Tangible Activities for Geometry (TAG)

The TAG system is comprised of three components (see Fig. 1). The *problem space* is a geometry application (Geogebra) that is projected on the ground using a short-throw projector to minimize obstruction by the user. The projection includes a Cartesian plane with zero or more points and the agent - a simulated robot called R2 that is represented by a circle intersected with a line to indicate where it is facing. The *mobile interface* is provided on an iPod touch that (1) displays problems for students to solve, (2) responds to events generated in the *problem space*, and (3) receives student input (provided by tapping and/or its virtual keyboard). The *tangible interface* includes a *hanging pointer*, which acts like a mouse, and which controls the position of the virtual cursor projected onto the ground as the student moves the hanging pointer over the plane; "clicking" is done by pulling the hanging pointer down to the ground to select a click location and then lifting it back up (equivalent to a mouse-up event).

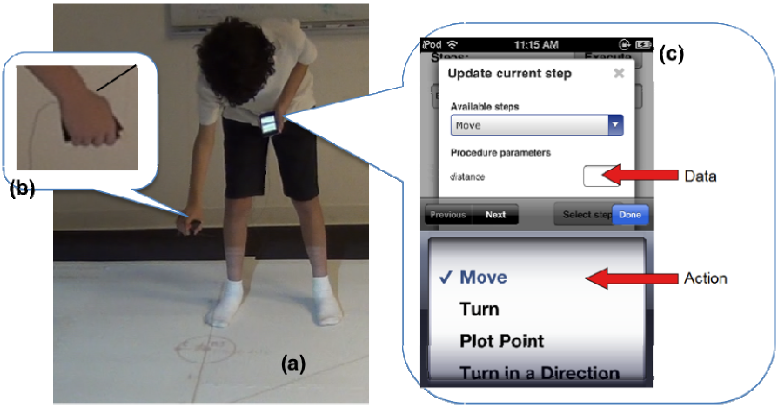

Fig. 1. A student walking in the TAG problem space (a), using the hanging pointer "mouse" to click on projected objects (b) and subsequently select from a menu of iPod actions (c)

When interacting with TAG, students can walk in the problem space and use the hanging pointer to click, which brings up a menu of available actions on the iPod. To illustrate, students can move R2 by positioning the hanging pointer over R2, pulling down on the hanging pointer to simulate a mouse click, and tapping *move* on the menu that appears on the iPod (Fig. 1c). Four actions are provided when a student clicks on R2, including *move* (to move R2 distance *d*), *turn* (to turn R2 *n* degrees), *turn in a direction* (to turn R2 N/S/E/W), and *plot point* (to plot a point in R2's current location). The remaining three actions are shown on the iPod if a student clicks on a point, including *move to a point* (R2 moves to that point), *turn to a point* (R2 turns to that point), and *draw line between points* (R2 draws a line between two user-specified points). For instance, if R2 is located at (0,0) and facing West, plotting the point (2,3) could involve the following sequence of commands (clicking R2 is required to show each command): *turn in a direction* East, *move* 2 units, *turn in a direction* North, *move* 3 units, *plot point*. All commands are automatically added to a list available on the iPod, so that students can watch R2 "execute" a series of commands at once, akin to running a program (commands can also be deleted).

We chose the current task domain because of its conceptual and graphical properties. In theory, as students move over the projected coordinate system and gesture towards particular aspects of the projection, they can physically encode concepts such as how positive and negative coordinates relate to graphical quadrants, and how the rise and run influences the slope of the line.

Figure 2 shows the TAG architecture. All applications communicate with one main computer. The *problem space* is realized by a Geogebra Java applet that includes a JavaScript API. Since the iPod needs to respond to events in the *problem space*, like a click on R2, and then subsequently sent data back to Geogebra (e.g., to plot a new point), a bidirectional communication mechanism is necessary, implemented in TAG with the WebSocket protocol.

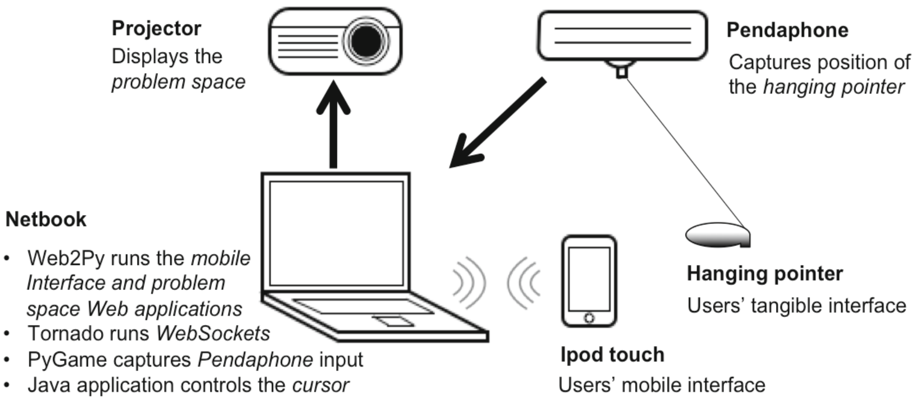

Fig. 2. TAG architecture

The hanging pointer, used to simulate a mouse in a physical space, is attached by wire to a device we call a pendaphone, a modified PS2 Gametrak controller that can detect the x-y-z coordinates of a retractable pointer. When the pendaphone is mounted on the ceiling, it detects the coordinates of students' hand in space as they move the hanging pointer. A Python script is used to send messages between the pendaphone and main computer to indicate when a click event occurs. Prior to use, the hanging pointer must be calibrated, by moving it to three pre-defined points on the projected problem space. This calibration provides information about the projected plane's size relative to (1) the origin of the hanging pointer, using the two vectors made by the three points, and (2) the projected computer screen size, by mapping the physical location of the three points to their known digital locations. This allows TAG to compute the projection onto the coordinate plane of the vector from the pendaphone origin to the physical pointer's endpoint. As students manipulate the hanging pointer, TAG uses the java.awt.Robot library to hijack the mouse cursor and set its location to be the projection of the physical pointer. If a user moves the pointer below a pre-defined threshold, a mousePressed event is generated, followed by a mouseRelease when the pointer is moved above the threshold. The threshold is manually set – in the future we plan to set it automatically during the calibration process.

3 Students' Behaviors in TAG and Perceptions of TAG

We piloted TAG with four participants (S1-S4; one from 6^{th} grade, two from 7^{th} grade, and one from 9^{th} grade). Our key research questions were as follows:

(Q1) What strategies do students use to solve problems in TAG?
(Q2) How does TAG impact students' embodied behaviors and perceptions?
(Q3) How does the teaching framing in TAG influence student perceptions?

All students (1) signed an assent form; (2) filled in a brief background survey; (3) were introduced to TAG (*Training Phase*, ~30 minutes); (4) showed R2 how to solve geometry problems (*Teaching Phase,* 45 minutes); (5) discussed their experience

(*Interview Phase,* ~20 minutes); (6) were compensated ($20). We used the talk aloud protocol for the teaching phase by asking students to verbalize their thoughts and feelings as they worked with TAG. Sessions were conducted individually and were videotaped; two experimenters were present during each session.

To train students on how to use TAG, we asked them to read aloud from a booklet describing the system and also perform the corresponding TAG actions (e.g., plot a point); an experimenter answered any questions that students had. During the teaching phase, we told students to "*tutor R2 about how to solve geometry problems […] The goal is for R2 to learn enough so that it can solve all kinds of geometry problems. So when you are telling it how to solve a geometry problem, think about what would be most useful"*. Students then taught R2 by working through a series of geometry problems related to (1) plotting points in various quadrants; (2) drawing the rise and run for various lines and specifying the slope of those lines; (3) drawing lines with a specified rise and run (only the 9th grader reached these in the time provided). If students got stuck on how to use the system they could refer to the instructions and/or ask the experimenter. Feedback for correctness was provided through a Wizard of Oz technique: When students indicated they were finished with a problem, they heard a sound (one for correct answers and one for incorrect). Students could try a problem as many times as they wished, and if stuck, could ask for help (but only after trying the problem at least once on their own). The help was provided by the experimenter, who used the standard scaffolding technique of starting out with general prompts that became more specific if students required further help. Once 45 minutes elapsed, students participated in a semi-structured interview between the participant and two experimenters. The interview questions were designed to obtain information on students' experience with TAG, the tangible interaction and the teaching framing.

3.1 Analysis and Results

We analyzed the video data from the teaching and interview phases using qualitative description [18], by iteratively deriving codes from the data, organizing these according to emergent themes, and refining these as needed. Our goal with this coding was to provide a qualitative summary of students' experiences and perceptions. In general, subjects found the system easy to use (S1-S4; e.g., "*I can't think of how to make it better, it was pretty easy*" (S4)). We were concerned students might find obstructing the projector distracting, but none of the students mentioned this when asked "what did you find difficult about using TAG?". When asked to compare TAG to other contexts (paper and pencil, and computer), S2 mentioned he preferred TAG over a computer because "*it was more fun*". S3 and S4 chose TAG as their preferred activity due to its embodied and fun nature. For instance, S3 stated that "*you get to walk around and do crazy things*". S3 also mentioned, however, that "*it's a little harder to concentrate on the problem because you have to use all the equipment*" – this may have been a start up problem, since he subsequently said this overload was reduced as time went on.

We now present our results: each section first provides results coming from the *teaching phase*, followed by students' perceptions collected in the *interview phase*.

Problem-Solving Strategies in TAG. Students used a variety of strategies to solve problems in TAG. When plotting points, all students but one first moved along the X-axis first and then the Y-axis. S1 instead was more opportunistic, in that if R2 was already pointing in the necessary direction he would move it that way first; otherwise, he went along the Y-axis first, because he "*preferred to think of rise over run*". Some students chose to minimize the number of actions they had to perform: S2 moved R2 backwards with negative distances, instead of turning R2 and moving it forward. Other strategies to facilitate solution construction included using the cardinal directions (N/E/S/W) instead of numeric angles (all did this except S3, who used the numeric approach for the first 3 problems). Common mistakes on plotting points included moving in the wrong X or Y direction, which students corrected on their own after obtaining the audio feedback for correctness.

In one of the problems, students were provided with two points and asked to draw the rise and the run of the line that included those points. All participants started by drawing a line between the two points (even though it was not necessary), using the closest point to them and R2 as a first reference, by clicking on it (S2 and S3) or by using R2 steps to get to it (S1 and S4). This problem was more challenging for the younger participants (grade 6 and 7) and students did ask for domain hints.

As far as students' perceptions related to strategies they chose, S3 proposed that TAG's scaffolding, which encouraged breaking solutions into small steps, was beneficial: "*it can help you learn why you are doing what you doing, because instead of just looking for the point you are going over and up instead of just diagonal*". S4 echoed these sentiments: "*I'm not very good at geometry but I think breaking it down into little steps has helped me*". In contrast, S1 suggested it would be helpful to combine instructions (e.g., "*I think in the same instructions you should be able to turn and the go again – it should be like on the same page*"). This participant had the highest domain expertise (he was the only grade 9 participant and solved the most problems) and so it is not surprising that he wanted to be able to "chunk" steps [19].

Embodiment: Behaviors and Perceptions. Instead of staying still, students used a range of embodied actions (shown in brackets is the *total number of actions* across all students and *the range of actions* executed by individuals), including *walking around the problem space* in between actions (489; 83-166), *pointing* with some part of the body towards elements in the problem space (169; 24-91) and *sliding/twisting motions* (59; 4-27). These embodied actions appeared to help participants find and physically visualize the strategy to solve the problem before they started to select steps for the agent. For instance, to plot a point, participants would *walk around the problem space,* using their foot *to point* to the places where the point could be plotted, and/or use their foot to outline the path that R2 could take (e.g., moving parallel to the X-axis to the X coordinate). To draw lines corresponding to the rise (or run) of a line *L*, they sometimes would align themselves on the point where the rise and L intercepted and *twisted their body* to orient themselves and so identify the rise line that would be drawn from that point. To specify the slope of a line, they counted the rise and run units by actually stepping while pointing with their hand.

In order to get more insight on the embodied behaviors, we also classified them according to when they occurred, namely during *reading* of the problem, *strategizing* before actually selecting a step for R2, or *action selection* when students moved to click on R2 or a point. Since participants had to approach R2 or a point to perform actions, we expected the majority of embodied behaviors would be in the *action selection* phase and that these would correspond to *walking around the problem space*. While this was true (49%-72%), there was a great deal of variability between subjects in terms of where the embodied actions took place: 12%-39% of total embodied actions took place in the *strategizing phase* and 1%-10% in the *reading phase*.

As far as students' perceptions of the embodied aspect, two explicitly commented on liking the embodied nature of the system (S2, S3). S2 likened it to a game: "*it is kind of like a Wii that is on the floor and you can walk around on a big computer screen that is on the floor and you are the mouse*". This comment highlights that by "becoming the mouse", this student imagined himself to actually be a part of the system. He later added that he liked the projection on the floor because "*you can actually visualize graphing on a line and I think it just fun to walk on it*". While S3 also explicitly mentioned liking "*moving around*", he went on to caution that embodiment might not always be appropriate. Specifically, he believed that when one is first learning the domain, more traditional activities might be better as the technology might be a distraction. S3 also described how he felt TAG's tangible nature influenced his actions, by encouraging him to perform fine grained steps when plotting points, instead of a more direct approach (i.e., "*because you are actually walking you'd use an angle to turn*" and on paper you would "*usually go diagonal*").

Teaching Framing: Behaviors and Perceptions. Although R2 was a projection, participants appeared to connect with it at some level. They followed R2 with their eyes, faced in a similar direction as R2, and even walked around R2 to avoid stepping on the projected circle. Another relevant behavior pertains to students executing the list of actions taught to R2, something referred to as a *testing phase* in other teachable frameworks [16]. S2 did this after finishing a problem, possibly to watch what R2 learned. S3, however, used this for a different purpose: he made a mistake during the solution of one problem, and upon realizing it deleted steps from the iPod list of actions right up to the mistake, essentially allowing him a convenient "restart". S3 was the only participant that did not feel that he was teaching the R2 (see below). It is interesting to note, therefore, that S3 favored the trial and error strategy instead of rethinking the process and so executed the most commands and had less correct responses (60%) than the other students (77%-100%).

When asked if they felt like they were teaching the agent R2, the majority of students responded affirmatively (S1, S2, S4). S4 said this was because he had to "*make the robot do all the actions*" and that without this instruction R2 "*would not know how to do that*". S1 suggested that it was his mistakes that made an impact on R2, i.e., "*I made a mistake so it knows - I forgot to plot a point*". He later suggested R2 might be able to avoid making that mistake. S4 stated R2 was "real", i.e., "*its not fake even though it is not completely real it stills seems like it because it has all the aspects*". However, students felt there were limitations to the "teaching" activity. While all students felt that R2 learned how to plot points and lines (S1-S4), several felt this was due to the R2's "memory". S3 also stated that the agent was not capable of transfer to new problems. Participants went on to say they were telling R2 exactly what to do - e.g., S3 stated that he was "*controlling the robot*", and that R2 had "*no reason to know why I was doing what I was*", while when he was teaching someone, he provided explanations. S2 cited the lack of direct interaction as hindering his "teaching": "*you're not looking at somebody you are looking at a computer screen on the floor*". Another student whose data was lost due to technical issues mirrored this sentiment, indicating that if the agent had a face, then he might feel like he was teaching more.

4 Discussion, Design Implications and Future Work

In this paper, we presented TAG, a tangible teachable agent system for learning concepts related to coordinate geometry. Our pilot study with four users provided promising indications that the embodied aspects of TAG and its teachable agent framework influenced student behaviors and perceptions in ways that could potentially deliver enhanced learning outcomes. When using TAG, student problem-solving process became physical: They would "twist" and "slide" around the environment to identify the distances and orientations needed to solve a problem. These embodied actions encouraged by TAG are consistent with the proposed advantages of TLEs in the literature, where students learn by making abstract concepts physical [2]. Our preliminary results suggest that TAG was successful in achieving a tangible interaction with the problem space. However, in contrast to other TLEs, students in our environment interacted with a teachable agent to solve problems. This agent became an external and physical representation of their problem-solving process, as students encoded their strategies in terms of distances travelled, angles turned, and steps taken by the agent. By merging the teachable agent and the tangible learning environment, students were able to create a physical external representation of their thinking that could move within the environment.

Overall, we saw both advantages and disadvantages to the embodied tangible interactions. Students enjoyed the embodied nature of our system (e.g., using expressions like "*it's awesome*"). However, S3 suggested that tangible nature and its corresponding technologies could interfere with learning new concepts. Research indicates that the degree of cognitive load induced from certain features depends on expertise and that for novices load is reduced once cognitive elements became automated [20]. Although these guidelines are intended for multimedia environments and not TLEs, it is conceivable that some would apply. For instance, there may be an ideal trajectory for learning geometry that involves various contexts, where for learners of a certain expertise, paper and pencil activities may be best, while for others, tangible activities would be preferable. Where exactly in that trajectory TLEs best fit to support learning and foster motivation, and for which learners, is an open question for future work.

Our pilot highlights that to provide ITS-style support in a tangible environment, it is important that the system models physical aspects of students' interaction. Using a ceiling-mounted camera system combined with a depth camera, the TLE may be able to recognize a student by, for instance, a special hat s/he would be asked to wear, and then detect student movements. We plan on improving TAG to adaptively scaffold students in linking their movements to the target concepts they are trying to master. TAG can also demonstrate to students that there are multiple physical strategies that map to the same conceptual outcome. For instance, as described above, only one student realized he could move a negative distance instead of turning the agent 180 degrees before moving it a positive distance. Representing these multiple strategies for navigating around the coordinate space and adaptively drawing student attention to the fact that various actions have the same outcome may give students a better intuitive understanding of graphical concepts and their relationships to each other. Prior work has shown that multiple representations in virtual ITS benefit learning [21]. TLEs could extend representations beyond the symbolic and graphical to the physical.

Another way we plan to introduce artificial intelligence into the system is by extending the agent's support in cognitive and social ways. A current limitation of TAG, as identified by students, is that the agent could only do what it was told. We plan on extending the agent's design by adding inferential ability. For instance, a student could ask R2 to perform two fine-grained steps: *turn an angle / move*, which could be chunked by R2 into one (as suggested by S1). This chunking then would be reflected in the commands on the iPod interface, to highlight that R2 learned. Students could also teach the agent by signaling when it should mimic their behaviors, and having R2 follow the student as s/he moves around in the problem space. This scenario encourages students to take embodied action and to observe the agent actions.

Yet another opportunity for enhancing the design of the agent in a TLE pertains to the affective dimension, by adding behaviors that would build a rapport with the student. We observed students express satisfaction after getting a problem correct by smiling and/or verbal utterances (e.g., "yes!"). Since non-verbal mirroring in virtual environments has been shown to increase motivation, this functionality could be extended to TLEs by having the agent mirror student affect, for instance by twirling around rapidly. This ability requires not only knowing where the student is, but also what he or she is feeling. Incorporating student models of affect and learning is especially critical for TLEs, given that these types of environments inherently encourage exploration. Thus, the TLE needs to rely on a model to understand when to intervene as to not interrupt students at points that might be disruptive to moments of motivation or moments of learning. How to devise such models for physical spaces that involve embodied behaviors, or to orchestrate social interactions between the student and the robot are open questions for future work.

In general, a tangible teachable learning environment that provides cognitive and social support to the learner could potentially be highly effective at engaging students and helping them map their concrete physical understanding to abstract concepts. To conclude, we believe situating a teachable agent within the context of a tangible environment serves as a promising foundation for future exploration.

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