On the Effectiveness of Tangible Interfaces in Collaborative Learning Environments

Lori L. Scarlatos, Shalva S. Landy, Julia Breban, Robin Horowitz, Chanie Sandberg
Brooklyn College, CUNY
2900 Bedford Ave.
Brooklyn, NY 11210 USA
+1 718 677 6170
lori@sci.brooklyn.cuny.edu

ABSTRACT
The advent of tangible interfaces has greatly expanded the many possible ways that one may interact with a computer. TICLE (Tangible Interfaces for Collaborative Learning Environments) is a project that explores new ways that a computer can enhance learning by responding to students' actions in a physical environment. We have developed a prototype system that watches children as they play with a Tangram puzzle on a physical tabletop, and acts as a guide on the side by offering help at appropriate times. This system is currently installed at the Goudreau Museum of Mathematics in Art and Science.

This paper describes the results of two usability tests conducted at the museum. Our study suggests that the TICLE interface helps children to stay focused, think about the problem in new ways, and complete the problem at hand. It also suggests that TICLE may help children to develop problem-solving skills that transfer to similar problems. This demonstrates that a computer "guide on the side" working in conjunction with a tangible interface can be effective in an educational setting.

Keywords
Tangible interface, education applications, K-12 math and science education, ubiquitous computing, multimedia user interface, intelligent multimodal interaction, guide on the side, usability study

INTRODUCTION
Over the years, educators and governments have searched for ways to improve learning in our schools, particularly in the areas of math and science. As educators come to recognize the importance of collaborative activities, learning through play, and teacher guidance, shrinking school budgets are making it harder to support these approaches to learning. Tangible Interfaces for Collaborative Learning Environments (TICLE) was conceived in response to this need [15].

TICLE embodies a different notion of support for collaborative learning, combining the advantages of physical learning activities with those of computer tutors that ask relevant questions when the students get stuck. With TICLE, a group of children is given a set of physical puzzle pieces and a specific goal (such as put these shapes together to make a square) which is designed to teach some math or science concept. As the children work with the puzzle, a computer system observes their actions. This system encourages the group as they make progress, and offers to give them hints when they don t. The hints take a scaffolding approach, asking the children to consider smaller related problems.

The advantage of TICLE is that students are allowed to focus on solving the puzzle without having to worry about how to give instructions to a machine or whose turn it is to use the mouse. Yet they may also turn to the computer for help and further information if and when they feel that they need it. TICLE is unique in that it

- makes the computer take on the role of guide on the side without dominating the educational activity,
- allows the students to work in groups on physical learning activities, without having to learn a computer interface, and
- prescribes a method for uniquely representing the state of a puzzle or model, enabling the system to rapidly check for solutions or partial solutions.

This paper describes a prototype TICLE system that we developed and installed at the Goudreau Museum of Mathematics in Art and Science (Figure 1). We conducted a usability study of this system at the museum, which is the focus of this paper. Although our prototype uses a very specific mathematical puzzle, the interface techniques that we are exploring can apply to a wide variety of educational experiences. These include anatomical models that students dissect in a biology lab; physics experiments that involve an arrangement of levers and pulleys; or molecular models constructed in a chemistry class. A TICLE interface may also be used to check the assembly of models, furniture, even equipment.

The results of our usability study have several implications. We've seen that the computer can be a useful guide even when the "users" are not directly using the computer. We've also observed that this type of help can keep students focused and get them to think about a problem in new ways. This opens up a wide range of possibilities for creators of intelligent tutors, educators, and interface designers.

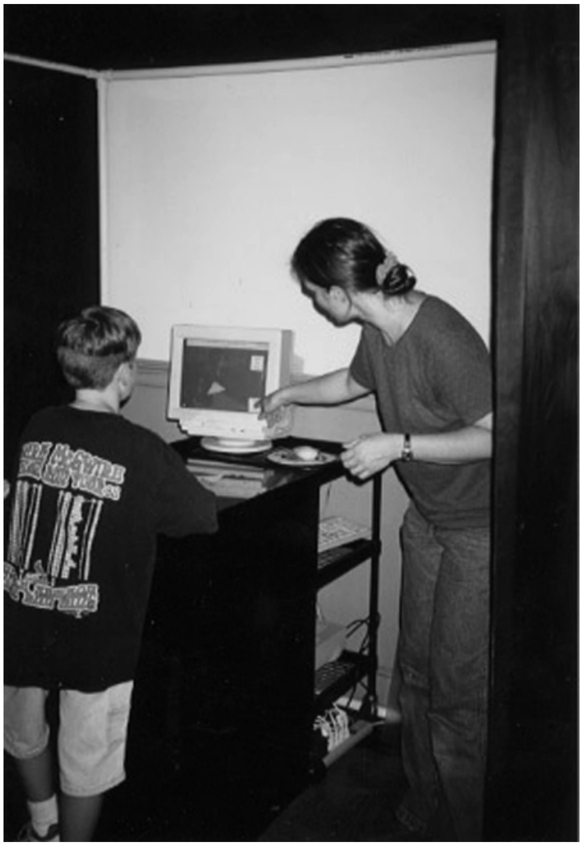

Figure 1. TICLE at the Goudreau Museum

BACKGROUND

Educators and researchers have been struggling for years to uncover the best ways to help students to learn better. In this quest, several approaches have been taken. TICLE combines attributes of many of them.

Many educators and researchers recognize the benefits of having a knowledgeable instructor standing by. As Polya pointed out, the expert guidance of an instructor can help to ensure that students engage in the metacognitive processes that lead to understanding a problem [10]. By asking appropriate questions, teachers can help students to think about the problem in appropriate ways and thereby bolster their problem solving skills. When teachers are not available to provide this help, computer programs may be developed to temporarily fill in the gaps. Numerous researchers are studying various approaches to intelligent tutoring, such as [3, 6, 14]. In all of these cases, the goal is to provide the sort of help that a good teacher would. Many are quite successful, and are able to show an increase in learning. Yet their reliance on traditional computer interfaces, making the computer the focus of the activity, limits their applicability.

Other educators and researchers have discovered that fun, engaging learning activities help students to retain lessons learned, and to later apply them to related problems. Many of them incorporate puzzles into interactive learning activities on the computer. At the University of British Columbia, the E-GEMS (Electronic-Games for Education in Math and Science) group is researching and developing strategies and materials to integrate game-like computer activities with other forms of classroom learning. For example, they have experimented with different manipulative computer interfaces for the Tangram puzzle [13].

The trouble with many computer games is that children must play with them alone. Children who work in groups are able to build on one another's insights and understanding. At the University of Michigan, work is being done on scaffolded integrated tool environments that help students to pose the questions and engage in activities needed for scientific inquiry [11]. The E-GEMS group has demonstrated that collaborative teamwork motivates girls to try harder, and helps them to achieve more than they could individually [7]. Recognizing the disadvantages of collaborating on traditional computer systems, this group has also experimented with using two mice simultaneously so no one student retains exclusive control [9].

Traditional computer interfaces using a mouse and a keyboard for input also pose problems. First, they restrict the number of students that can participate: after all, only one student can control the mouse at a time. Second, direct manipulation is not always that direct. Actions that are simple in the real world like rotating and translating a puzzle piece at the same time are complicated by the need to use intermediate devices and techniques that must be learned. On the other hand, manipulating physical objects is a very natural way to solve, think about, and learn about spatial problems. For example, one study shows how manipulating objects aids the design process for engineers [2]. This suggests the need for tangible interfaces in collaborative learning environments.

The idea of using tangible interfaces to help people learn is already being explored. The Tangible Interface group at the MIT Media Lab has created the Illuminating Light project [18] which illustrates how optics equipment (represented by a set of physical objects) operates together. Although this information could be depicted in a two-dimensional image, being able to test different configurations and freely rotate the pieces helps users to better understand optical concepts. Another example, used by even younger children, is the curlybot [5]. The curlybot is a half sphere with two wheels on the bottom and a record/play button on top. Children learn about geometry, by experimenting how different shapes can be made with repetitive patterns. For example, to make a circle, only a small arc must be recorded.

Meanwhile, the Epistemology and Learning group has developed "crickets", devices that make use of programmable integrated circuits and infrared sensors to communicate with one another. This group has developed a variety of construction kits that enable children to build things that move, react to stimuli, and communicate with one another [12]. The group also sponsors a Computer Clubhouse where children can work on their own projects using this technology.

In fact, tangible interfaces have a wide range of possible applications [8, 17]. Some examples are "Urp", a tangible interface for urban planners, and self-sensing devices [19]. Yet most of the learning activities that use tangible interfaces still tend to focus the learning activity on the technology. Although this provides excellent learning opportunities for some students, it is not appropriate for all. Different children tend to learn differently [4], and so for those children who are not being reached by these efforts, an alternative approach to learning and a novel application of technology to teaching are needed. TICLE is one such alternative.

A TICLE PROTOTYPE

For our first prototype system, we chose to use the Tangram, an old Chinese geometry puzzle. The Tangram is popular in both elementary school math lessons and standardized tests because it achieves several objectives. For the very young, it helps them to learn the names of some standard polygons. It also helps children to develop a basic understanding of what "area" and "congruence" are without having to resort to formulas. Finally, it helps children to develop a geometric intuition that should help them to better grasp more complex geometric concepts later in their school careers.

The Tangram puzzle consists of five triangles (two large, one medium-sized, and two small), one square, and one parallelogram, all precisely cut from a large square as shown in Figure 2. Although one may choose to reconstruct literally hundreds of different shapes with the Tangram pieces, the first and most important challenge is to reconstruct the square from the pieces. This seemingly simple task is also one of the trickiest.

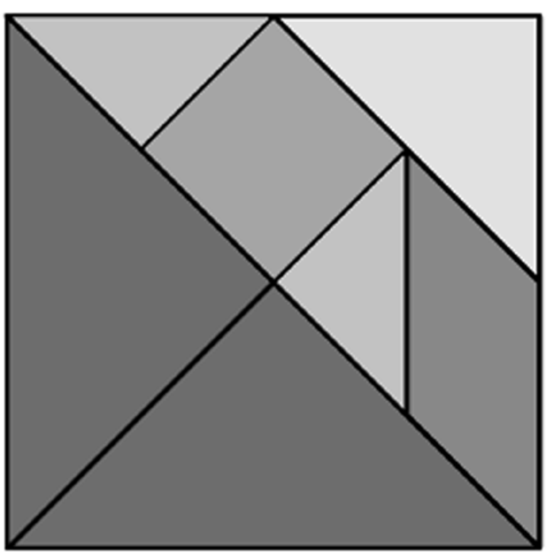

Figure 2. The Tangram

Tracking Puzzle Pieces

Computer vision techniques help us to track the puzzle pieces as they are moved about. We have adopted Underkoffler s approach [18], tagging the pieces with reflective markings and tracking them with a videocam mounted next to a light source.

Each puzzle piece is marked with three colored spots. Yellow indicates the precise center of the piece. The other two spots, placed adjacent to one another along a straight line, help the system to determine the orientation of the piece. The colors of the other two spots help to identify which piece it is. Thus by merely identifying patterns of spots, the system can quickly determine both the positions and orientations of the puzzle pieces.

The videocam and lights are all located under a Plexiglas tabletop that is used as a playing surface. Using reflective markings and a light source next to the videocam greatly simplifies the computer vision problem by causing the relevant markings to stand out. Placing the camera beneath the playing surface virtually eliminates the problem of accidental obscuration.

Uniquely Expressing Topological Relations

Once the system knows where the puzzle pieces are, it must do some reasoning about the state of the puzzle. Has a solution been found? If not, has a partial solution been found? Compared to the previous puzzle state, is the group making progress or losing ground?

To help answer these questions, we developed a shorthand notation for expressing a puzzle’s current state in terms of how pairs of puzzle pieces meet [15]. These meet relations have the advantage of being translation and rotation invariant, so that students working with the puzzle need not be concerned about the position or orientation of the finished puzzle. Each meet relation can be expressed as a short sub-string; these sub-strings are then sorted and concatenated in a string to produce a unique representation of the state of the puzzle.

Our system reads in a solution string upon startup. Then, for each video frame that is processed, the system updates the positions and orientations of the puzzle pieces. For each pair of pieces that might meet (determined by checking positions of the centers), our system uses an internal geometric representation to determine whether the pieces meet and, if so, how. If a meet relation is detected, the system generates the appropriate sub-string and adds it to a list. When all relations have been found, a string representing the current state is generated. Our system can quickly check to see if a solution was found, simply by comparing the current state string to the solution string. Partial solutions may be detected by searching for sub-strings from the current configuration in the solution string.

The Interface

In considering the design of our user interface, we needed to make sure that it could be seen, heard, understood, and used by elementary school children from up to three feet away. We placed a computer display next to the table where the puzzle pieces are in play. A touch screen on that display allows children to select options without having to manipulate a mouse. We tried to keep the graphics bold and simple, and the audio short and sweet. For the hints, the audio is supplemented with text: just a few words on the screen, shown in a very large typeface. Two large buttons on the side allow children to review the objective of the puzzle or ask for a hint.

While the puzzle is in play, the computer monitor shows the current puzzle configuration as seen by the computer vision system. Meanwhile, the system continually updates a sorted list of sub-strings representing the current state of the puzzle. The system uses this current state to initiate a variety of responses. For example, if the children are making progress (i.e. the number of current state sub-strings found in the solution string increases), a female voice offers encouragement. If, however, they do not make progress after a measured period of time, the voice invites them to ask for a hint. And when the solution is found, of course, the voice offers congratulations.

The current state of the puzzle is also used to select an appropriate hint. We ensured that there is at least one hint appropriate to every possible (incomplete) state of the puzzle. We even included a hint to be given when one or more puzzle pieces disappeared from view for an extended period of time. Furthermore, most states of the puzzle correspond to several possible hints, so that the children don't have to see the same one over and over.

The hints themselves are prepared as short interactive animations with a similarly simple look and feel. Rather than telling the children what to do, the hints pose questions about related sub-problems. After asking the question, the animation pauses to give the children time to ponder their answer, and then shows them the solution to the sub-problem when they touch the screen.

TICLE CASE STUDY

With our TICLE-Tangram system installed in the Goudreau Museum, we conducted a case study using local girl scouts and boy scouts. In our study, we were particularly interested in testing the following assumptions:

1. A "guide on the side" providing hints, encouragement, and reminders about the objectives will help to motivate students and keep them from getting distracted or giving up too soon.
2. Context-sensitive hints will get students to think about the problem in new ways, leading to more metacognitive activities (e.g. discussing why a particular approach will work).
3. Because they are focused and thinking more deeply about the problem, groups using TICLE will be more likely to solve the puzzle.
4. Working with a TICLE system will help children to develop problem-solving skills that will transfer to similar problems.

We had conducted an earlier case study at the museum [16] which primarily revealed the need for improvements to the initial version of our program, and a need for more rigorous testing methods. This new case study addresses all of those earlier problems, yielding much more substantial results.

Case Study Logistics

We ran two separate test sessions at the Goudreau Museum: one with a group of girl scouts finishing third grade, and the other with a group of boy scouts finishing second grade. In each session, we divided the students into six groups of two (pairs). Groups were assigned based on where the students were sitting: we assumed that children who sat next to each other would work well enough together as a team. Children wore labels marked with consecutive numbers, which were used to identify them in our observations.

The test itself was conducted in three parts. First, each team was asked to make a square using all of the Tangram pieces. Half of the teams got to use the TICLE system for this part. The other half used the museum's regular Tangram puzzle, with no computer or teacher aid. Video cameras were stationed at both the TICLE table and the regular table, to record students actions. The children were told that they had up to ten minutes in which to solve the problem; they were able to quit sooner if they wanted. In the second part of the test, the teams were asked to make a rectangle using regular Tangram pieces at a separate set of tables. Video cameras were also stationed at these tables to record student actions. Once again, they had up to ten minutes time to solve the problem. In the third part of the test, students were interviewed individually. They were asked a fixed set of questions regarding their team (and how they felt about collaboration), the Tangram (and what they thought they learned from it), and the TICLE interface (including pros, cons, and suggestions for improvement). The interviews were recorded on audio tapes.

Evaluation Methodology

For evaluation purposes, we adopted Artzt and Armour-Thomas' cognitive-metacognitive framework for protocol analysis [1]. This framework was designed to "differentiate explicitly between cognitive and metacognitive problem-solving behaviors observed within the different episodes of problem solving". Metacognition, which is basically "cognition about cognition", includes understanding, analysis, planning, and verification: essential steps in mathematical problem-solving, according to Polya [10]. Alternatively, cognition may be observed in behaviors such as watching, listening, exploring, and implementing a plan.

Like Artzt and Armour-Thomas, we used our videotapes of the tests to classify the observable behaviors of the teams. We produced a table with rows representing the behaviors: understanding, analyzing, exploring, planning, implementing, verifying, watching/listening, and distracted/fooling-around. We added this last category (essentially a non-cognitive behavior) to the framework because it was something that seemed to happen a lot. Columns in our table represented time slices of thirty seconds. With a separate table for each team, we marked all of the observed behaviors for each time slice, using the children's labels (numbers) to indicate who was doing what. Because we couldn't know what the children were thinking, we only recorded metacognitive behaviors when the children's comments suggested that they were thinking about the problem in a particular way. We also marked the tables with other significant events such as children's comments and discussions, getting hints, and stealing a teammate's hat.

Table 1 shows a sample table for a team of girl scouts that worked particularly well together. They frequently stood back to analyze the situation. For them, the hints caused them to think about the problem in new ways that ultimately led to the solution. The top row in this table labels the time slices in which the behaviors were observed. The numbers beneath the table correspond to observable events that are described in greater detail below. For convenience, we have used letters instead of numbers to indicate individual team members in this table.

Table 1. Observed behaviors for team G1

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
under-stand																		
analyze				B						A					A			
explore	A B	A B	A B	A B		B	A B	A B	A	A B	A B	A B	B	B	A B			
plan	A B					A			B				A		A			
imple-ment	A B					A			B				A	A		A B	A B	A B
verify																		
watch/ listen					A B			A B										
fooling around																		
	1			2	3	4		5	6	7			8		9			10

1. Start by making a triangle (half of the square) using the 2 large triangles: a great start.
2. B: "That's going to pop out"
3. Watch hint
4. A: "Try to form a triangle" using the remaining pieces
5. Watch hint
6. B: "Let me try something…I got it!". Start building the other triangle on top of the triangle created in (1).
7. A: "But what about that space?"
8. A: "I got an idea."
9. Finish building 2nd half of the square on top of the 1st half.
   A: "Now we have to transport that there."
10. Puzzle solved.

Observations

Our observations strongly suggest that the TICLE system does indeed keep students focused and help them to solve the puzzle. Figure 3 shows that four out of six teams using TICLE were able to make a square from the pieces; only one out of six teams using a conventional Tangram were able to do that.

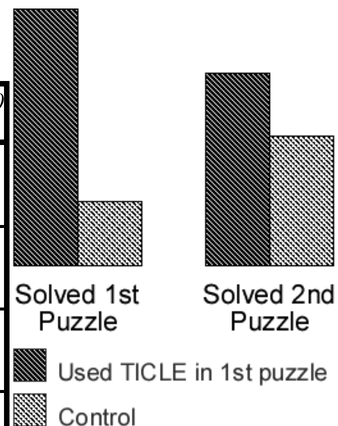

Figure 3. Number of teams that solved the 1st puzzle (with and without TICLE), and number of teams that solved the 2nd puzzle (conventional puzzle only)

Perhaps even more encouraging, our observations suggest that the lessons learned from using TICLE may transfer to similar problems. Figure 3 also shows how many teams were able to construct the rectangle using a conventional Tangram. Three of the six teams that had used TICLE earlier were able to solve the problem. All three had also managed to make a square. The one team that had solved the first problem, but not the second, had solved it very quickly with no discussion and without looking at any hints. Perhaps one of them had seen the puzzle before, and simply remembered the solution. On the other hand, only two of the teams that had used a conventional Tangram earlier were able to construct the rectangle. One of those teams had also successfully constructed the square. We have no explanation for why the other team was able to solve the second problem.

Table 2 shows a summary of our observations of the first part of the test. This table shows, for each team, in what percentage of the time slices were metacognitive behaviors (understanding, analyzing, planning, verifying), cognitive behaviors (exploring, implementing, watching and listening), and non-cognitive behaviors (fooling around or distracted) observed. Because several different behaviors may have been observed within a single time slice, the sum of the percentages often exceeds 100%. This table also shows which teams solved the first problem (making a square using TICLE or a conventional Tangram) and the second problem (making a rectangle using a conventional Tangram). Teams labeled with a "G" are comprised of girl scouts; teams labeled with a "B" are comprised of boy scouts.

Table 2. Summary of observations of the 1st part of the usability test

	team	*meta-cognitive*	*cognitive*	*fooling around*	*solve #1*	*solve #2*
	G1	56%	100%	0%	Y	Y
	G3	0%	100%	0%	Y	N
With	G5	17%	100%	0%	Y	Y
Computer	B1	29%	100%	0%	Y	Y
	B3	0%	100%	5%	N	N
	B5	10%	100%	30%	N	N
	G2	0%	100%	67%	Y	Y
	G4	6%	100%	31%	N	Y
No	G6	0%	77%	92%	N	N
Computer	B2	20%	100%	0%	N	N
	B4	20%	100%	55%	N	N
	B6	11%	100%	72%	N	N

As shown in this table, teams using TICLE tended to have more metacognitive interchanges. Many times when the children would get a hint, we would hear "Oh, yeah " and see a flurry of activity indicating that the hint had caused them to think about the problem in a new way. Sometimes the hints helped in unexpected ways. For example, when one group was told that pieces shouldn't be stacked on top of one another (because the system had lost track of a piece), they got the idea of building the second half of the square on top of the first half of the square, and then moving it into place. For them, this was the key to the solution (which they did ultimately find).

The table also shows that TICLE users spent a lot less time fooling around. We noticed that in several of the teams, the children would take turns working on the puzzle. For those teams using TICLE, the child who was not exploring with the puzzle would often be looking at the hints. For the control teams, other goings-on in the museum proved far too tempting for the idle teammate. We also observed a few of the control teams making comments such as "Can you help us?", "This is impossible!", and "Can we use the computer now?". No one using TICLE made such comments.

However, the interviews at the end of the study did show that our system could be improved. Several children who used the TICLE system said that the voice offering encouragement was "annoying" and "distracting". In addition, a few of the children thought that we needed to create more hints.

CONCLUSIONS

The results of our case study are encouraging: children using our TICLE system are far more likely to solve the presented problem than those using a conventional puzzle with no assistance. Furthermore, our observations suggest that children that use TICLE may be better able to solve related problems, even when they are given no other assistance.

Our observations also seem to confirm our other assumptions. First, it is now evident that a computer "guide on the side" can help to motivate students and keep them from getting distracted or giving up too soon. Second, context-sensitive hints do seem to get students to think about the problem in new ways. We've seen that they do lead to more fruitful discussions and actions, suggesting that they trigger more metacognitive activities.

The implications are clear. Tangible interfaces do indeed provide a new way for us to enhance our children's education without forcing them to sit in front of a computer. Instead of being the focus of educational activities, the computer can now take on a new role: guide on the side. The possibilities are endless.

Future Work

Although we already have some encouraging results, we would like to continue with our testing. After making the suggested improvements noted in the observations, we plan to test the system further. In particular, we would like to involve children from more diverse backgrounds. We may also want to see how individuals do on puzzles after working with TICLE (instead of just teams). It would also be useful to have follow-up interviews with the children, perhaps even asking them to comment on the video tapes of them (i.e. tell us what they were thinking).

We are also in the process of developing a system for specifying new puzzles, hints, and the states that should trigger those hints. This information will be stored in an initialization file which, along with the multimedia hints, will form the basis of a new 2D game. This will allow us to generate a range of different activities relatively quickly. It will also serve as the foundation of a system which we hope, some day, to distribute to educators so that they can design their own TICLE puzzles.

In addition, we are experimenting with alternative technologies that will allow us to extend TICLE to the third dimension, where 3D objects will be tracked within a closed environment. This will greatly expand the number of possible TICLE applications, and will more clearly demonstrate the benefit of this technology.

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