

Beyond One-Size-Fits-All: How Interactive Tabletops Support Collaborative Learning

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ABSTRACT

Previous research has demonstrated the capacity of interactive tabletops to support co-located collaborative learning; however, these analyses have been at a coarse scale—focusing on general trends across conditions. In this paper, we offer a complimentary perspective by focusing on specific group dynamics. We detail three cases of dyads using the DigiTile application to work on fraction challenges. While all pairs perform well, their group dynamics are distinctive; as a consequence, the benefits of working together and the benefits of using an interactive tabletop are different for each pair. Thus, we demonstrate that one size does not fit all when characterizing how interactive tabletops support collaborative learning.

Categories and Subject Descriptors

H.5.2 [Information Interfaces and Presentation]: User Interfaces—*user-centered design*

General Terms

Design, Human Factors

Keywords

Interactive tabletops, collaborative learning, case study

1. INTERACTIVE TABLETOPS

With the advent of commercially available systems such as the Microsoft Surface and the SMART Table, user studies of multi-touch tabletop interaction are progressing apace. Previous research finds that interactive tabletops are enjoyable to use [7], promote playfulness [19, 20, 26], support awareness [13], encourage equity of participation [9], and can promote learning [10, 17, 25, 27, 30, 34]. These studies have tended to be controlled comparative studies. Tabletop interfaces are compared to other interaction mechanisms, such as with desktop computers [7], vertical displays [31], non-digital materials [25], or a different tabletop interface [9, 28, 30]. The goal here is to hold other factors constant between conditions to test potential statistical regularities in behaviour related

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ICD 2011, June 20–23, 2011, Ann Arbor, USA.

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to using the tabletop system. Thus, the factors to be compared are decided upon *a priori*.

A second strategy has been to apply qualitative analytic approaches such as video interaction analysis [14] and ethnography to study, in detail, interactions between people and with the material environment when using tabletop systems. The goal here has been to draw regularities from a corpus of specific instances [36]. Work has focused on how people approach, share, and come to understand how to use tabletop systems in real-world contexts and some of the problems that can result [3, 11, 12, 23, 24], on the physical mechanisms used to mediate conflicts at the table [21], and on the general mechanisms for learning at the tabletop [8, 27].

Individual differences between groups working in the same situation are often underemphasized. For controlled experiments, this is to highlight differences between conditions. In video-analytic or ethnographic studies, specific episodes are selected from a large sample and regularities are drawn out in how people use this technology. To summarize, previous research has been carried out using a largely *nomothetic approach*—constructing a generalized understanding based on a large sample set (although not necessarily generalized beyond a specific context of use). In this paper, while we rely on detailed video analysis of interactions between users of an interactive tabletop, we take an *idiographic approach*—constructing specific understanding of compelling cases. Our interest is in children’s collaborative learning with tabletop interfaces. We purposefully select three dissimilar cases to emphasize how different group dynamics influence how children collaborate using interactive tabletops. Through this analysis we demonstrate diversity in the ways that interactive tabletops can support collaborative learning.

2. DIGITILE

DigiTile is an adaptation of DigiQuilt [18] to the DiamondTouch [5] interactive tabletop [29]. Like DigiQuilt, it is a construction kit for learning about math and art by designing colorful mosaic tiles. In addition to being aesthetically pleasing, these tiles lend themselves to mathematical analysis. The designs embody fraction concepts and can be symmetrical. For instance, the design in Figure 1 is half red and half yellow; it also has horizontal and vertical lines of symmetry. While DigiQuilt was designed for a single user, DigiTile was designed for two concurrent users positioned side-by-side in front of the interactive tabletop.

DigiTile’s interface is split into four main areas (Figure 1). The central tile (a) is a square grid (2-by-2, 3-by-3, 4-by-4, or 5-by-5)

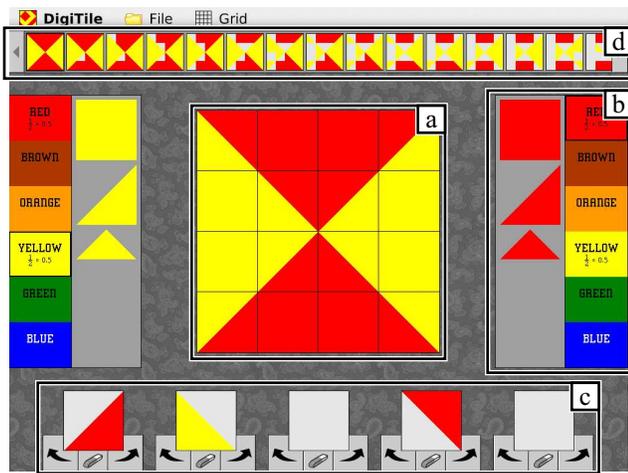


Figure 1: Screenshot of DigiTile, with main areas marked

of snaps. Pieces can be dragged into these snaps to create a colorful tile. Both users are provided with their own palette area (b) on the left and right side to choose pieces of different colors and shapes. Pressing on a color button changes the color of the pieces on that palette. For this study, each palette contained three different shapes: a snap-sized square, a half triangle, and a quarter triangle. To provide feedback on fraction tasks, each color button displays the portion of the central tile corresponding to that color in three representations separated by equal signs: 1) as a fraction with a lowest common denominator, 2) as a reduced fraction, and 3) as a decimal. In the case where the first two are identical, only one fraction is shown (e.g., in Figure 1, the red and yellow buttons display $\frac{1}{2} = 0.5$). Users can drag pieces to one of the five work snaps (c). There, multiple pieces can be assembled and rotated. When pieces are dragged out of a work snap, a copy is automatically created; thus, the assembly and rotation work does not have to be repeated. To clear a work snap, the user presses the eraser button below that snap. A scrollable bar contains a graphical history (d) of how the tile was created. By clicking on a thumbnail, users can revert to an older version of the tile.

3. PARTICIPANTS AND PROCEDURE

Participants, age 8 to 9, were selected from the same classroom. DigiTile sessions were conducted in the back of that classroom during normal class time. The sessions occurred during a “Maths Week,” where more emphasis was given to Mathematics; as such, the learning goals of fraction understanding fit in well with the standard curriculum. All sessions were video taped from two angles: one on the learners and one on the display. These were edited together for analysis. The three sessions analyzed in this paper were purposefully chosen using the following criteria: good audio and video quality, success on completing the tasks, and to showcase various styles of working together. Two researchers iteratively analyzed the video. The cases are a synthesis of their interpretations.

At the beginning of each session, the researcher demonstrated how to move and rotate pieces, change their color, and use the graphical history. Participants briefly tried out these features. After this introduction, each pair attempted the same three tasks (i.e., challenges that they needed to complete by working together). For each task, the children were given a printout stating the task; the researcher also read the task description aloud. Once students completed a

task, the researcher set them to work on the next task. After 30 minutes, the researcher ended the session, even if it meant that the third task went unfinished. While they observed sessions, both the classroom teacher and researcher took a hands-off approach, only intervening a few times.

4. THE THREE TASKS

The first task was to replicate the pattern in Figure 1. The children were provided with a printout of the pattern, including grid lines, to guide their work. The purpose of the task was mainly to serve as an introductory exercise to familiarize students with the interface and working together on the DiamondTouch. While this task was completed by all, matching the pattern was not trivial; all pairs made errors placing pieces. Most participants found it difficult to orient a triangle to fill a gap. The interaction pattern of orienting a piece, dragging it to the intended location, realizing that it did not fit, and dragging it back for further rotation was common.

At the end of the first task, the researcher asked, “What fraction of the square is red and what fraction is yellow?” Most pairs were able to come up with the correct answer on the first try; if not, the researcher helped them to realize it was one half. As a follow up, the researcher asked, “What percentage of the square is red and what percentage is yellow?” These questions were asked to draw the participants’ attention to the different representation of the fractions on the color buttons. This was important as the next two tasks focused on fraction understanding.

For the second task, the researcher asked the participants to “make the square three eighths orange and three eighths brown. Some of the square can be left blank. That means you don’t have to fill it all in if you don’t want to.” This was a relatively easy fraction challenge for several reasons: 1) it only required figuring out one fraction ($\frac{3}{8}$); 2) as it makes use of empty space, the likelihood of children interfering with each other’s work was minimized; 3) the task could be completed using only square pieces (6 out of 16 snaps).

For the third task, the researcher asked the participants to “make the square one tenth red, four tenths green, two tenths blue, and three tenths yellow. Now, this one is a bit different to the last one. In this one, none of the squares should be left blank.” The third task is significantly more challenging than the second for several reasons: 1) it uses a larger grid (5-by-5 versus 4-by-4 for the previous tasks); 2) it requires four different fractions; 3) participants had to use triangular pieces (e.g., $\frac{1}{10}$ is most easily composed of two squares and one half triangle); 4) it requires using unreduced fractions (e.g., $\frac{4}{10}$ for green); 5) as the whole tile must be filled in, the chances for clashes between users or accidental destruction of previous progress is increased, particularly towards completion of the task when the tile fills up.

Common fraction misconceptions were observed. First, students often fail to realize that a larger denominator indicates a smaller fraction (e.g., $\frac{3}{16} < \frac{3}{8}$). In such cases, students mistakenly try to take away pieces to achieve the larger fraction. Second, students sometimes fail to realize that the position of pieces does not affect the fraction. Third, students do not realize that they can multiplying a pattern of pieces to multiply the numerator of the fraction. For instance, on the second task, a student might find that two square pieces equals $\frac{1}{8}$ but not realize that therefore six square pieces equals $\frac{3}{8}$. Fourth, students do not realize that two fractions can be equivalent. This is particularly problematic in the third task where teams observe $\frac{1}{5}$ blue and fail to realize that they have ac-

Table 1: Descriptive Statistics of the Pairs

Pair	Amy & Ben	Chris & Dave	Emily & Ford
<i>% of time with matching colors</i>			
Task 1	0%	69%	27%
Task 2	0%	97%	12%
Task 3	0%	93%	6%
<i>verbal declarations / exchanges per minute</i>			
Task 1	0.8 / 0.5	2.4 / 3.1	0.8 / 0.8
Task 2	3.3 / 1.4	2.8 / 4.4	0.3 / 0.9
Task 3	4.7 / 1.7	2.2 / 2.4	1.0 / 1.2

completed the goal of $\frac{2}{10}$ blue. As these cases demonstrate, students engage these misconceptions by working with DigiTile on these tasks.

5. THREE DIFFERENT CASES

A previous article reported the quantitative results of this field study: It detailed the learning gains in fraction understanding made by DigiTile users over a comparison group, using standardized pre- and post-tests [30]. Here, we report on the qualitative findings based on video analysis. We present three cases as a *case study* [38] of how individual group dynamics affect children’s collaboration on interactive tabletops. The children are given corresponding-gender pseudonyms in alphabetical order based on case order and position at the tabletop (left to right in the figures). To further protect participants and aid comprehensibility, figures based on the video are presented as sketches.

Before detailing the cases, we preview the major differences between pairs. While these differences are qualitative, they are corroborated by simple quantitative analysis of the interaction. Table 1 shows what percentage of time the colors of the two palettes matched and the rate at which pairs engaged in verbal declarations (the partner does not respond) and exchanges (the partner responds).

Amy & Ben All three tasks were designed to be split up by color. Amy and Ben choose to strictly divide the task, never using the same color. While they work on different parts of the task, they use *narration* (a running commentary on their actions) to communicate; this manifests as a high rate of verbal declarations.

Chris & Dave They choose to work together on the same part of the task. Whenever they move on to a new part, Dave switches both palettes to that color. Because of their joint focus, they are able to discuss strategies before executing them; this manifests as a high rate of verbal exchanges.

Emily & Ford Like Amy and Ben, they choose to split up the task by color; however, their verbal communication is minimal. It is so noticeably lacking that the teacher prompts them to communicate to solve the challenge in the first and third task. While this prompting sparked bursts of verbal communication, their overall rate was still relatively low.

While the collaboration styles diverged, all three pairs were successful, demonstrating increasing competency throughout the session and succeeding on the tasks. All three accomplished the first

two tasks and made significant progress on the third. Chris and Dave were the only pair to finish the third task. Amy and Ben briefly completed the challenge, but failed to realize it as they had problems understanding the equivalence of unreduced fractions. While Emily understood how to complete the third task, Ford’s contributions accidentally stopped her from finishing the task in the allotted time frame; at several points, at least three out of the four parts were solved.

Each case begins with an introduction to the pair’s dynamic. Then, one episode of collaborative learning is detailed for each of the fraction tasks. These episodes were chosen to exemplify the differences between the pairs.

5.1 Amy & Ben: Dividing the Task

Amy and Ben strictly divide each task by color. While all three tasks were explicitly designed to allow for parallel work, the researcher never gives any indication that they need to divide the task. Amy and Ben chose that strategy for themselves from the beginning. Although they work on different parts of the task, they communicate well, speaking often and regularly checking in on what the partner is doing. They do not get frustrated with each other, even when the task seems difficult or a technology malfunction makes their actions interfere with each other. Occasionally, they will even share a laugh about it.

One remarkable feature is that they tend to mirror each other: making eye contact, replicating the same tile pattern, or expressing the same body language. When the researcher asks them what percentage of the tile is red, they have to think about it. Ben guesses “twenty percent.” Amy doubts it, “Is it? No. Uh. I don’t know.” They make eye contact and simultaneously answer “fifty percent.”

That mirroring is most evident in the second task, where they frequently place the same tile pattern (when reflected across a vertical line of symmetry). In all, such physical mirroring occurs ten times; in contrast, there is not one instance of mirroring for the other pairs. At one such occasion, Ben states, “One eighth. . . I’ve got an eighth.” Amy giggles and replies, “so do I.” Neither knows where to go from there. They simultaneously scratch their heads. After some more experimenting and narration, Amy discovers three eighths with orange. She announces, “Oh [surprised], I’ve done mine.” Five seconds later, Ben has mirrored hers to accomplish three eighths brown (Figure 2).

The third task proves to be more difficult with initial progress being slow. Finally, Amy stumbles onto $\frac{1}{10}$ working in green; she uses two squares and a half triangle. She announces, “I’ve got one tenth.” Ben replies, “What? How did you get a tenth?” He examines her side of the board. She admits, “I don’t know. I think that’s one tenth [points]. Isn’t it?” Ben points to her green button, which displays $\frac{1}{10}$, and replies, “It says so.” Amy proceeds to replace the green pattern with a red one. Meanwhile, Ben narrates, “We need three of those.” He replicates her pattern three times in yellow (Figure 3). Successful, he announces, “Three tenths.” “Is that what you needed,” Amy enquires. “Yeah.” Here Ben demonstrates competence in the multiplication principle, which he was unable to use during the second task.

While they choose to work on independent parts of the task, they communicate well through both physical (as exemplified by the mirroring) and verbal (as exemplified in the exchanges from the third task) means. So, while they do not share a joint task focus

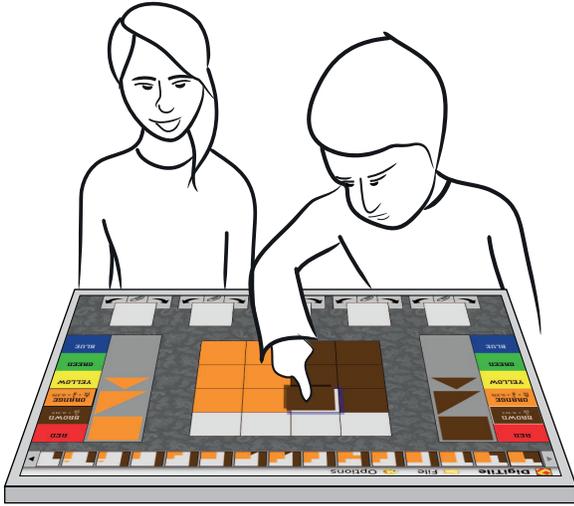


Figure 2: Ben mirrors Amy to complete Task 2

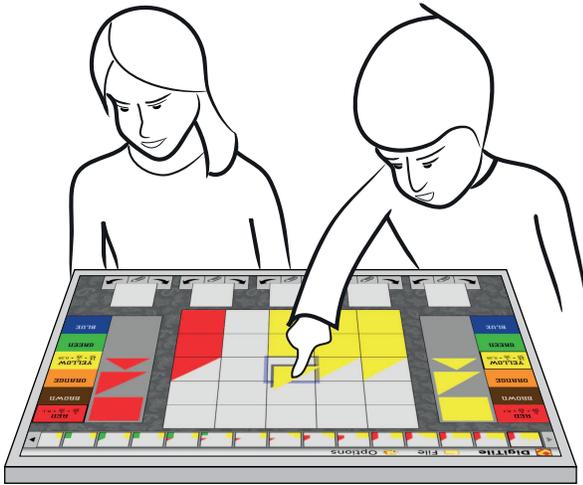


Figure 3: Amy checks the fraction as Ben completes $\frac{3}{10}$

(something often considered essential to collaboration [6]), they manage to communicate and learn together. Furthermore, the physical mirroring they exhibit is an indicator of *group flow*, a state where the group is performing at the peak of its abilities [1].

5.2 Chris & Dave: Sharing the Task

Chris and Dave work well together, but both contribute different properties to their group dynamic. Chris is intense in both his verbal and body language. His emotions, ranging from excitement to doubt and frustration, are readily apparent. Dave is more relaxed. While Chris talks significantly more, Dave usually takes the leadership in physically placing pieces. Unlike Amy and Ben, Chris and Dave choose to share the task. They work together on one color at a time.

As evident in the second task, Chris and Dave often take turns actively moving pieces and observing / commenting. Dave starts by adding four triangular pieces to the second row. Chris comments, “That’s one eighth.” Dave narrates, “[I’ll] do it again underneath

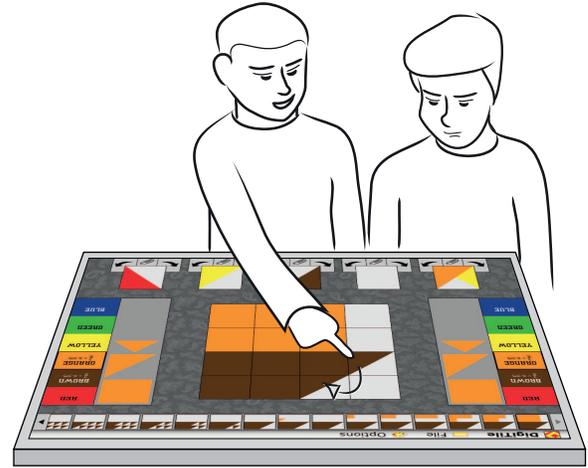


Figure 4: Chris explains Task 2 solution to Dave

here,” as he places triangular pieces in the row below it. Chris wants to reserve the lower rows for orange pieces and starts moving the pieces up one row. Dave agrees and they end up with the top two rows containing half triangles. Chris announces, “That’s one fourth. It’s got to be three eighths. . . I think the squares [indicating the central tile] need to be bigger.” Chris wants to keep the brown pieces confined to the top half, but wants another row to place more pieces. He comes up with a solution, rotating a brown piece around to fill in the gaps left by the existing triangles: “No, but we could still do this.” Dave agrees. Both place brown pieces into the gaps rapidly. At one point, Chris notices that the interface shows $\frac{3}{8}$. Dave does not notice and places another piece, thereby changing it. Chris exclaims, “Three eighths. Take that [pointing to a triangle] off.” He removes the piece himself and they have the brown part of the challenge. Dave changes both palettes to orange. Dave claims, “Now, we just need to do the same. . .” as he is about to place orange triangles. Chris counters, “Hold on. Wait, wait, wait, wait. Hold on, hold on, ‘cause you can do squares [moving an orange square onto the board].” Dave agrees, “Oh yeah. Let’s do squares then. It’s easier.” After they have placed six orange squares, Chris notices that they are done. He is surprised that the orange pattern is not the same as the brown pattern. He steps back and shrugs while looking around. After twelve seconds, he realizes why both patterns represent the same fraction. He explains it to Dave, “Oh yeah. Look! ‘Cause when you switch that round [Figure 4], it’s three eighths.”

The third task proves more difficult. After several failed attempts to accomplish $\frac{1}{10}$ red, Chris claims, “Oh! I know how to do it.” He starts over and fills in one column with red half triangles. He explains that he’ll fill another column, but Dave notices that the current arrangement is one tenth. Proudly Dave proclaims, “We’ve done it.” Surprised, Chris accepts it: “That is one tenth.” Both are noticeably excited. Encouraged verbally by Chris, Dave quickly adds two columns of blue triangles. They are thrilled to discover that it is two tenths as expected. With broad smiles, both exclaim, “Yes!” Dave switches both palettes to yellow. As in the previous task, Chris is worried that they will run out of space for yellow, given that there are only two empty columns. Dave understands his concern and comes up with a solution. He rotates a yellow half triangle to fill in the gap made by the red and blue triangles. Once he realizes what Dave is doing, Chris gives his approval: “Yeah.

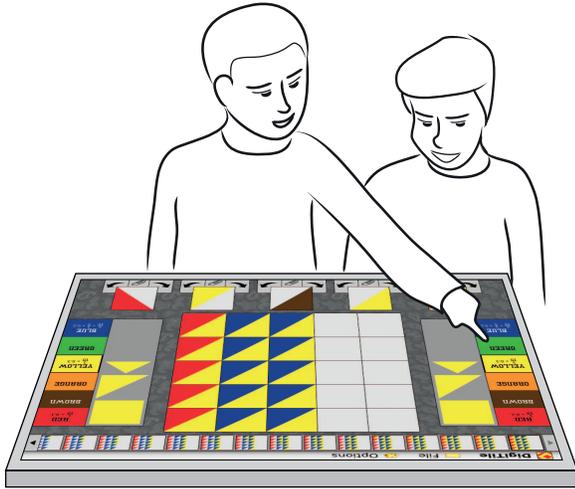


Figure 5: Chris and Dave accomplish $\frac{3}{10}$ on Task 3

You've got it." Dave fills in the gaps in the center column with yellow triangles. Dave is planning to continue in the empty columns, but Chris motions him to the remaining gaps in the blue and red columns: "That means, just do it over there [gesturing to the triangular gaps]." They fill in the empty spaces together. Reading the display, Chris announces, "Boom! Three tenths" (Figure 5).

Chris and Dave's interaction is a textbook example of collaboration: they share a joint task focus, are able to smoothly alternate between engaging the task and reflecting on it, and are invested in a successful outcome. Because of the joint focus, each is able to halt the physical activity to verbally negotiate the next step (something that Amy and Ben do not do). They often also take different roles: actor and observer. This role division is particularly well suited to DigiTile as one can manipulate the tile representation while another observes the fraction representation. As the examples above demonstrate, the observer is able to notice unexpected progress, leading to quicker task progress and gains in domain understanding.

5.3 Emily & Ford: Working in the Same Space

Emily and Ford are generally cordial, but not particularly friendly with one another. Unlike the other pairs, they seldom communicate, either verbally or physically. Another marked difference is that Emily is noticeably ahead of Ford in fraction understanding. By a strict definition, their interaction is not collaboration. Instead, we characterize it as working in the same space on the same task.

When they start working on the second task. Both work independently with a different color on their respective halves. Emily picks brown; Ford picks orange. They work independently. He gets stuck using quarter triangles. After some experimenting, Emily figures out that six squares solve $\frac{3}{8}$ brown. She stops working. Soon after she stops working, Ford notices. He inquires, "[Are] you done?" Emily nods. Ford continues to work on orange with the small triangles as Emily looks on. Ford fails to understand that he could just replicate her pattern. At one point, she squints with concentration. A few seconds later, she approaches him. "Hey Ford. You see how I used six pieces to do my part (Figure 6). You could use the same thing." He accepts, "Oh, yeah." As he quickly places blocks to mirror her, she continues, "but you don't need to put it in the same

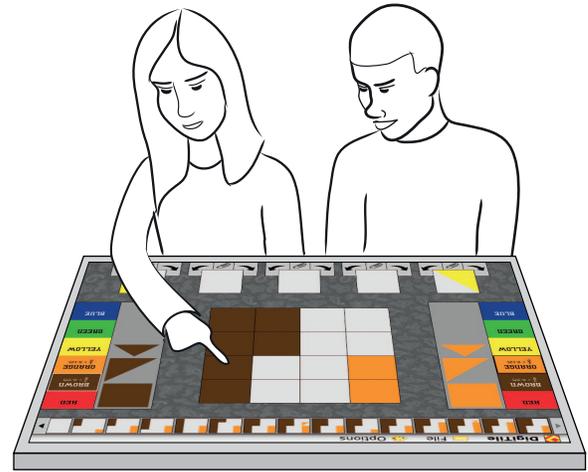


Figure 6: Emily explains Task 2 solution to Ford

pattern, so you could put it over there [motions]." Ford accepts and creates a different pattern to complete the task. Thus, she coaches him to understand the shape and location independence principle.

Before task three, the researcher encourages them to talk. Again, both of them work independently and mostly in silence. They seem to quite systematically try out different combinations of shapes. Emily works on yellow; Ford works on red. Then, Ford discovers that $\frac{1}{10}$ can be made with two wholes and a half triangle. He pauses. Emily glances at Ford's side of the board, noticing that Ford has completed red (top of Figure 7). She proceeds to immediately duplicate his pattern three times to achieve $\frac{3}{10}$ (bottom of Figure 7), thereby demonstrating her mastery of the multiplication principle. While this example is similar to that of Amy and Ben's (i.e., Amy and Ford discover $\frac{1}{10}$; Ben and Emily use it to achieve $\frac{3}{10}$), there is, remarkably, no verbal communication. Ford has no awareness that Emily has appropriated his finding or that she understands a principle that will be useful for solving the rest of the challenge.

Given the limited communication, it is even more difficult to characterize this pair's work as collaboration than for Amy and Ben; however, their interaction is still a successful example of collaborative learning: Both learners benefit from working together. As evidenced by the former example, Ford benefits by working with a more knowledgeable peer who can, at times, act as a tutor. As evidenced by the latter example, it is not a one way street: Emily is able to appropriate a discovery made by Ford.

6. BEYOND ONE-SIZE-FITS-ALL

As these three cases demonstrate, collaborative learning using an interactive tabletop takes different forms, even for children from the same classroom working on the same task with the same application. When trying to characterize how interactive tabletops support collaborative learning, *one size does not fit all*. Table 2 summarizes the differences between the pairs

6.1 Benefits of Working Together

One oft-cited model of how two people engage in learning is Vygotsky's [37] *zone of proximal development* (ZPD). The range between tasks that a person can accomplish by themselves and those

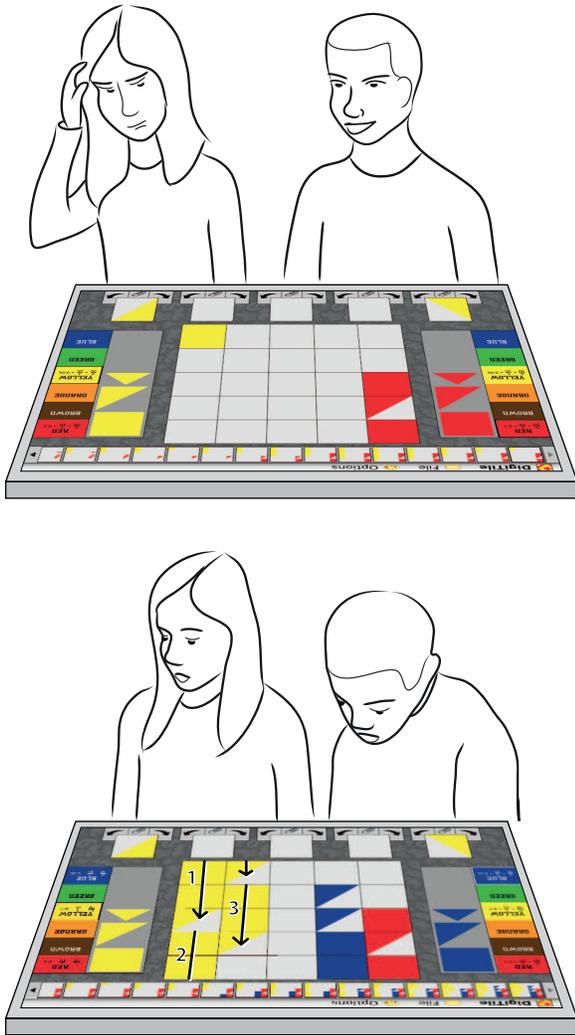


Figure 7: Emily uses Ford's solution to $\frac{1}{10}$ red for $\frac{3}{10}$ yellow

that they can accomplish with the other's help is the ZPD. Vygotsky based this model of learning on observations of how mothers play with their young children. Inherent to this model is an inequity between participants as Vygotsky is concerned with the learning and ZPD of the child, rather than that of the mother. Of the three cases, this model only applies to Ford and Emily. Emily is noticeably more proficient in all three tasks. For the first two tasks, her actions provide Ford with a model of how to accomplish his part. Occasionally, she provides explicit verbal guidance. In these exchanges, Emily acts as the tutor to Ford's pupil. Ford benefits by working with a more capable peer. Emily benefits by articulating her understanding, a valuable meta-cognitive skill [4].

While Emily is ahead of Ford, it is not by that much; hence, she cannot always articulate her understanding. Her mental effort in assisting Ford is particularly visible towards the end of the second task. In the third task, the tutor / pupil relationship breaks down. Emily ignores Ford's confusion and seems annoyed when his work on blue interferes with her progress on green. When prompted by the teacher to assist Ford, Emily does try to explain fraction equivalence to Ford, but her explanation is not well formed and ineffec-

tive. Even though he fails to understand, she makes no effort to follow up, perhaps because her own understanding is still tenuous. For such a challenging task, the ZPD created by Emily working with Ford is insufficient to allow Ford to accomplish the task. We should also remember that Emily is not a trained tutor; she mainly chooses to help Ford when it directly benefits her (e.g., avoiding inactivity at the end of the second task).

A different model of collaboration is Roschelle's [32] *convergent conceptual change*: as two learners work with a tool that embodies the domain concepts, their conceptual understanding tends to converge with each other and the domain concepts. Unlike the zone of proximal development, this theory allows for the learners to be comparable in skills and content understanding. The criterion for useful collaboration is that both learners are able to generate ideas and evaluate them. As the tool allows them to test their theories, correct concepts are more likely to endure than misconceptions. In his characterization, Roschelle places emphasis on learners having to work together (i.e., a joint task focus) to choose which ideas they want to evaluate. This is a fitting description of how Chris and Dave work. They discuss their conflicts and negotiate which ideas they will test. They fluidly transition between the roles of suggesting ideas and evaluating them.

Roschelle based his theory on observations of pairs using desktop software with only one entry point—a shared mouse. Furthermore, his software ran one simulation at a time. In contrast, interactive tabletops allow users to interact concurrently and DigiTile allows users to work on different parts (i.e., colors) of the task concurrently. The pairs from the first and last case chose to divide the task and work in parallel. For Ford and Emily, this allowed them to work independently. Do-Lenh et al. [7] report on a study comparing the same jigsaw task being performed on an interactive tabletop and a desktop machine. As groups in the tabletop condition worked independently, they had little need to share their individual understanding. As a result, groups using a desktop machine learned more, even though the tabletop interface was preferred. While interactive tabletops can fail to support collaborative learning because there is less impetus to interact and compromise, Amy and Ben demonstrate that this is not inherently the case. While they worked in parallel, they consistently shared ideas and converged on correct concepts.

6.2 Benefits of Using an Interactive Tabletop

Two oft-cited benefits of interactive tabletops are their ability to support the *awareness of other's actions* and the ability to support *concurrent input*. While other studies have demonstrated these benefits in general, we further show how individual group dynamics impact how these benefits support collaborative learning.

Interactive tabletops are large horizontal displays that users engage through direct manipulation. As the surface is large, actions tend to be large enough that fellow users are able to be aware of them even if they occur in their peripheral vision. In contrast, staying aware of another's mouse cursor in *single display groupware* [35] requires more direct attention. As the objects are directly manipulated, it is easy for a user to transition between interacting with the application and gesturing to communicate with others at the table. Thus, tabletop interfaces improve indirect and direct communication respectively. In a study that compared mouse and touch input for collaborating on a planning task, awareness of others' activity was increased in the touch condition [13]. The touch condition also led to an increase in *awareness work*, defined by Schmidt [33] as

Table 2: Summary of Learning and Interaction by Pair

Pair	Amy & Ben	Chris & Dave	Emily & Ford
<i>benefits of working together</i>			
<i>Learning Theory</i>	[no established theory]	Convergent Conceptual Change	Zone of Proximal Development
<i>Advantages</i>	They can work independently, but still share their findings with each other.	By running experiments and reflecting verbally on the results, they are able to converge on a better domain understanding.	The more advanced student acts as a model to help scaffold her partner through tasks that would have been too difficult for him.
<i>benefits of using an interactive tabletop</i>			
<i>Awareness</i>	While they divide the task, communication channels remain open through narration and being visually able to check the other's progress.	Learners switch smoothly between acting and observing, thereby enabling verbal exchanges centered on the shared task goal.	The less advanced student is aware of the progress of his partner. Thus, these actions can model the domain skills.
<i>Concurrent Input</i>	They are able to smoothly split up the task to explore their solutions to the problem separately.	They smoothly transition between actor and observer. At times, they simultaneously place pieces.	The more advanced student is unable to dominate the interaction, allowing the partner to make contributions.

reciprocal practices of monitoring others and designing actions so as to render visible certain aspects of activity.

For Ford and Emily, there was little explicit verbal or physical communication; however, both were aware of what the other was doing, which facilitated collaborative learning. For Ford, awareness of the activity of a more able peer provided a model that enabled him to perform at a level above that at which he would have been able to on his own. During the second task, Ford soon noticed that Emily had ceased her efforts, which caused him to inquire as to whether she had finished. It was perhaps this question that prompted Emily to monitor Ford's progress and ultimately provide him assistance in completing the task. During the third task, Ford stopped adding pieces when he completed $\frac{1}{10}$ red. Likely triggered by his pause, Emily glances over and then appropriates his discovery. Chris and Dave's activity was much more focused and integrated. The tabletop interface provided them a shared workspace enabling them to form a "common ground" of understanding and supporting a close coupling of actions, deictic dialogue, and gestures. As DigiTile provided *multiple linked representations* [15] of the fraction content, one could manipulate the central-tile representation while the other monitored the displayed fraction. As is common in tabletop tasks [8], Amy and Ben continuously provided narration. Between that verbal narration and the ability to see visual actions, Amy and Ben were aware enough of each other to both execute their own actions while still engaging their partner.

Unlike most educational technology (e.g., desktop computers, handheld devices, and even electronic whiteboards), interactive tabletops allow multiple users to interact simultaneously. This has several benefits. First, it empowers every participant. If Emily and Ford had worked on a desktop machine, it seems likely that Emily would have dominated the team; as is, Ford, though a less skilled partner, was actively able to contribute. At the beginning of the third task, his discovery of $\frac{1}{10}$ even directly helped Emily make progress. Second, it enables working in parallel. Both the pairs of Emily and Ford and Amy and Ben demonstrate how working in parallel can be effective for collaborative learning. Third, unin-

tentional interference of actions can provide an impetus for groups to engage with each other [8, 27]. As Chris and Dave work on the same part, they must negotiate their actions to prevent those actions from interfering with each other. For the other pairs, unintentional interference of actions only became a problem towards the end of the third task. When it arrives, neither Amy and Ben nor Emily and Ford deal with it as well as Chris and Dave have been doing. That is perhaps one reason why Chris and Dave are the only team to successfully complete the third task.

6.3 Implications of Diverse Group Dynamics

Whereas the conventional approach to the evaluation of tabletop systems has been to look for generalities in interactions with and around the table, we have deliberately focused on what was idiosyncratic and related to individual group dynamics. What this has highlighted is the diversity of ways that interacting with the DigiTile system can facilitate (and hinder) collaborative learning. Acknowledging the importance of group dynamics has implications for both the design and evaluation of such systems.

From a developer's perspective, the question is whether to embrace or spurn such diversity. All three of our cases focus on successful pairs. DigiTile works for these pairs, at least partially, because it supports a variety of collaboration styles. On the one hand, designers might thus benefit learning by supporting such diversity. On the other hand, other projects have demonstrated the value of encouraging (or even enforcing) particular collaborative behaviours [2, 16, 22]. For instance, if the system only allowed one person at a time to interact [9], this could focus the attention of the other person on the relevant activity. That would create an incentive for pairs to share a task focus, something considered beneficial for collaborative learning [6]. Such an interface might support Emily and Ford to coordinate more closely and for Emily to take a more active role in mentoring Ford; alternatively, it could have led to adverse clashes.

While all pairs were successful, Chris and Dave were the best example of collaborative learning—fully completing the third task

and displaying a joint task focus. The system could be changed to more subtly encourage their collaboration style. In this study, special effort was given to allow pairs to split up the tasks. All three challenges were designed to be split across different colors and half of the pairs used a software version where each palette only contained three colors (red, orange, green vs. brown, yellow, blue). It was hoped that such a condition would enforce collaboration through splitting the task; as it turned out, pairs did not need that incentive to divide the tasks. Considering that all the pairs chosen for this qualitative analysis based on their task performance and diversity of collaboration styles were in the other condition, it may have been a pedagogically poor choice to even encourage such splitting; however, both conditions showed similar improvements in learning gains [30]. A useful middle ground between supporting diversity and encouraging ideal behavior is to allow the teacher (or even the learners) to select the software features that best support the relative competence and social dynamics of the group.

In addition to having implications for the design of systems, such diversity has implications for how we analyze these interactions. For instance, previous work has shown that tabletops encourage a higher equity of participation than other interfaces [9, 22, 28]. While equity of participation is a good indicator of successful group work, it is not an absolute good. Chris and Dave demonstrate how a group can work well together even when one person dominates the action (i.e., low equity of physical participation). Enforcing equitable physical contributions (e.g., by enforced turn taking) would have only disrupted their successful group dynamics.

While it is interesting to consider how design features can explicitly address group dynamics, it is worth noting that other design choices can have significant implicit effects on those dynamics and the effectiveness of the system. Based on this study, DigiTile was altered to include a pie chart representation of the fractions. That representation is particularly useful for realizing that larger denominators imply smaller fractions, while larger numerators imply larger fractions. This could have helped Amy and Ben realize that they needed to add pieces to move from $\frac{1}{8}$ to $\frac{3}{8}$. It could have helped Emily to better explain fraction equivalence to Ford. Also, the software could be aware of the specific challenge and provide support based on that. For instance, when Amy and Ben completed the third task, DigiTile could have announced their success. While they might have been surprised by their success, such a scenario could have led to them to reflect on fraction equivalence.

7. ACKNOWLEDGEMENTS

This work was done as part of the ShareIT project funded by the EPSRC, grant number EP/F017324/1. We thank the schools we worked with and the children who participated in this study. We thank MERL for loaning us the DiamondTouch. We especially thank Kim Bryant for sketching the figures.

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