3 Scratching the Surface

Opportunities and Challenges from Designing Interactive Tabletops for Learning

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INTRODUCTION

The child computer interaction and educational technology communities are increasingly suggesting the suitability of tangible user interfaces (TUIs) and digital tabletops to support children's learning in domains. In particular these technologies are coming to be viewed as the technology of choice for computer-supported collaboration (Brave, Ishii, & Dahley, 1998) and more recently collaborative learning for children (Dillenbourg & Evans, 2011). A TUI is one interface in which a user interacts with a digital system through the manipulation of physical objects. Those objects act as a controller, *and* their physical or spatial qualities carry information which is essential to the system. That is, in addition to acting as controls for a digital system (like a remote control or game controller), their physical (e.g., color, shape, texture) and spatial properties (e.g., location) carry essential information. Digital tabletops are large, horizontal, interactive surfaces. They may support single touch, multi-touch, and/or interaction through tangible objects. In this chapter, we shall refer to tangible, multi-touch tabletops as simply digital tabletops.

Digital tabletops may be of the DIY variety or, increasingly, they may be commercially available models (e.g., Microsoft Surface, SMART Table). All tabletops share seven common interface attributes. First, because they are physical tables, they enable multiple learners to gather around the table. Learners can dynamically change their configuration during activity in order to see each other, to access different parts of the surface, or to see the displayed contents from different viewing perspectives. Second, compared to a desktop, laptop, or tablet display, the display surface is large and usually collocated with the input space. This provides for adequate space for input controls and output displays that can be used by several people, depending on the size of the surface. Third, tabletops are horizontal (unlike SMART Boards) so non-digital objects can be placed and used on the surface. Fourth, simultaneous multiple inputs enable more than one learner to interact at one time. Fifth, most tabletop systems recognize gestural input, either on the tabletop and/or above the surface. Sixth, many tabletops can track physical objects that may act as input controllers and/or carry physical or spatial information and bring social conventions around object use and ownerships to the table. And last, tabletops also contain physical structures, such as edges, which can be used during interaction with touches or objects.

Despite these opportunities, an increasing number of researchers are reporting results of studies of collaborative tabletop learning that are unexpected, difficult to interpret, or indicate that complex dynamics are at work in interaction. For example, Fleck et al. (2009) and Rick et al. (2011) found that such multi-input tabletop interfaces do not always promote effective collaboration since children can be engaged with their own respective tasks with little consideration for others nearby. The features of tabletop interfaces alone do not ensure positive social or collaborative activity.

The unique features of digital tabletops provide opportunities for collaborative interaction through shared physical objects and large working surfaces. They enable more than one child to participate in the digitally augmented activity and to do so in dynamic configurations (e.g., children can move around the table) that support face-to-face interaction. This is in contrast to single desktops, which typically enable only one child to interact using a mouse and utilize a vertical screen that often results in children focusing on the display rather than each other. Interactive tablets (e.g., iPad) share some of the interactional features of multi-touch tabletops, but they are smaller and support only single-touch interaction. The unique characteristics of tangible, multi-touch tabletops may enable interactional and social behaviors that support children in learning through collaborative activities.

To enable claimed benefits, designers and educators must design tabletop applications based on an understanding of how design choices, which result in specific design features, that in turn provide opportunities for interaction, can create, shape, and constrain opportunities for positive and effective social and collaborative activity with a tabletop application. To date, many researchers have focused on high-level validation of tabletops for learning (e.g., Buisine, Besacier, Aoussat, & Vernier, 2012; Dillenbourg & Evans, 2011; Rogers, Lim, Hazelwood, & Marshall, 2009) or have focused on guidelines for specific interface elements or aspects of interaction (e.g., Hornecker, Marshall, & Rogers, 2007; Marshall et al., 2009; Olson, Leong, Wilensky, & Horn, 2010; Price, Sheridan, & Pontual Falcão, 2010; Rick, 2012; Scott, Carpendale, & Inkpen, 2004). In contrast, we have found that it is combinations of design decisions and clusters of features that work together to encourage, enable, and sometimes enforce certain interactional behaviors that support social and collaborative activity (e.g., Antle, Bevans, Tanenbaum, Seaborn, & Wang, 2011; Antle, Tanenbaum, Bevans, Seaborn, & Wang, 2011; Antle, Wise, & Nielsen, 2011). Although it is not possible to examine such designs or broader learning situations with the kind of scientific rigor that is desirable, we feel that design practice can benefit from descriptions of these clusters of design features that we have found are correlated with positive outcomes in our studies of collaborative activity. We also suggest that despite researchers' best efforts to isolate design causes and interactional effects, some of the variation found in study results may be attributed to groups of decisions rather than individual ones. In this chapter, we will describe how we have used combinations of social, physical, interface, program, and learning features with tabletop applications to enable interactions that have been beneficial in supporting collaborative activity. For each cluster of design decisions, we will illustrate it with examples from our implementations and studies of tabletop systems.

COLLABORATIVE LEARNING

Collaboration is a process in which learners share and negotiate meaning through coordinated, synchronous activity. It is the result of continued effort to build and maintain a shared understanding of a situation or problem (Roschelle & Teasley, 1995). In learning design, tasks that enable collaboration are those that require coordinated and interdependent activity, where knowledge, tool use, and/or skills are distributed among learners, and when they work together, the learners are successful (Kreijns, Kirschner, & Jochems, 2003).

Computer-supported collaborative learning (CSCL) theories outline many important elements or precursors required to support collaborative learning. I have found that the following five elements are important in understanding how to design to support collaborative learning on tabletops. First, learners need to have *a motivation* or reason to negotiate with each other. Objects of negotiation are shared external representations that can be modified by individuals or a group during the learning process (Suthers & Hundhausen, 2003). In a CSCL environment, objects of negotiation may be explicitly included through the use of digital representations. In a collaborative digital game, the game board often acts as an object of negotiation. Second, learners need a *shared focus* around which negotiation and meaning making can occur. Referential anchors are context-specific objects, utterances, or gestures that support learners coming to common ground or understandings (Clark & Brennan, 1991). For example, the game status screen in collaborative digital games, which shows both individual and team progress, may serve as a referential anchor. It grounds the players' communication in shared understandings of what has been achieved in the game and what remains to be completed. Third, learners need to *share attention*. Learners must be supported to attend to what one another is doing in order to meaningfully negotiate and develop common understandings (Clark & Brennan, 1991; Wise, Padmanabhan, & Duffy, 2009). If learners have motivation to share attention, then a tabletop form can facilitate face-to-face or *heads-up interaction*. Fourth, metacognitive processes are required during group learning, including supports for analyzing, evaluating, and regulating both individual and group *shared understandings* (Duffy, Dueber, & Hawley, 1998). For example, status screens (e.g., life points remaining, challenge level achieved) in collaborative digital games enable learners to see and evaluate their progress individually and as a team. Lastly, true collaborative tasks typically require *positive interdependence*. Tasks can require interdependence in any or all of the knowledge, tools, or skills. This supports coordinated activity of multiple people for success (Kreijns et al., 2003). One way tasks have been structured to require interdependence in CSCL is through a script in which each learner has access only to part of the information needed to solve a collaborative task (Miyake, Masukawa, & Shirouzou, 2001). A script is a way of structuring interaction in order to scaffold collaborative learning through the use of roles, activities, and sequencing of activities (King, 2007). However, Dillenbourg (2002) also warns of the dangers of over-scripting, and highlights the importance of clearly conceptualizing the mechanism(s) through which constraints on collaboration are expected to positively influence learning interactions.

DIGITAL TABLETOP INTERFACES FOR LEARNING

In order to illustrate how these interactional behaviors may be supported by design features, I present two examples of digital tabletops. Both were developed to support middle school children (aged 9 to 11) to experience the complexity of sustainable urban planning. The first, *Futura*, was implemented on a custom-build, multi-touch tabletop. The second, *Youtopia*, was implemented with tangibles on a Microsoft Surface multi-touch tabletop. I describe these systems in order to refer back to specifics of their interfaces, content, programs, or learning elements to illustrate how clusters of features support desired collaborative behaviors.

We have focused on developing applications to help middle school children learn about sustainable land-use planning because the content area lies within our expertise and because meeting learning outcomes in this area can benefit from computational tools that model the complex spatial interrelationships between human and natural factors. In addition, learning from scenarios that highlight conflicting views of multiple stakeholders helps learners understand the complexity of the social as well as environment issues involved. In early work, we suggested that topics involving complexity, spatiality, and multiple viewpoints would be optimal places to start the study of collaborative learning on tabletops (Antle, 2007). In our recent work, we have focused on the use of interactive tabletop games because simulations enable us to use computer programs to model the complexity of sustainable development (Antle, Bevans, et al., 2011).

Example One: Futura Tabletop System

Futura is a multi-player simulation game played on a multi-touch tabletop (Figure 3.1a). The learning outcomes are to enhance learners' awareness of the complexity of sustainable development planning for a small river basin. The goal of the game is to work with the other players to support a growing population as time passes, while minimizing negative impact on the environment. Futura can be played by two to six players. A full system description can be found in Antle, Bevans, et al. (2011). A video of the Futura project is available.[1]

Like collaborative strategic board games (Berland & Lee, 2011), Futura has three distinct roles are that players can take: food, shelter, or energy supply. Each role has an individual toolbar oriented to each of the three sides of the table (Figure 3.1a–b). The goal of the game is to support the population living in the area without having a catastrophically negative effect on the environment. Players must decide what kinds of food, shelter, or energy producing facilities to construct, and attempt to achieve balance in terms of the population support: neither wasting resources nor failing to provide for the population's needs.

At the start of the game, there is a small base population present in the area. Over the course of the simulation, the population gradually grows. To meet the needs of the growing population, players drag facility tokens from the left side of their individual toolbars (e.g., housing, power plants, farms) onto the map. For example, Figure 3.1b shows that single-dwelling houses have been dragged from the left of the shelter toolbar onto the map. The game is won if players can add facilities in ways that meet the needs of a growing population without compromising the environment.

The main form of interaction is dragging facilities onto the map. Each facility has a cost to build and can be placed only if a player has enough money. Money is spent by placing facilities and slowly accumulates over time. Each facility can support a specific number of people and has a specific

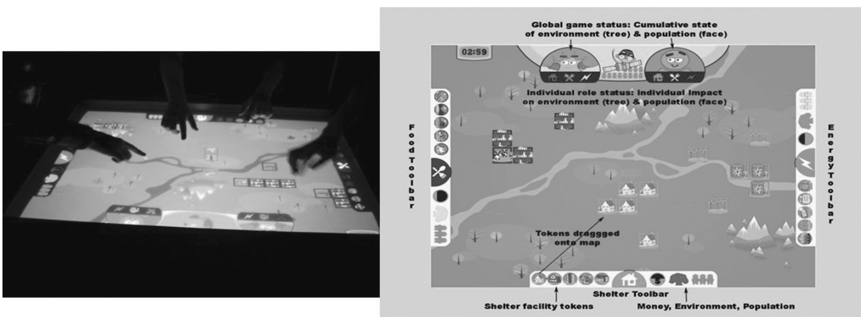


Figure 3.1 (a) Futura on custom tabletop (b) Map with individual toolbars (left, bottom, right) and global display console (top).

effect on the environment. Some facilities will produce more as time passes (i.e., will support a larger population), and some will produce less (i.e., support a smaller population). Information about different forms of environmental damage that may be caused by different facilities (e.g., physical waste, atmospheric pollution, chemicals in the water, pesticides in the food) is available through informational screens, which can be accessed before or during game play by touching and holding on each facility token on the toolbars.

In Futura, players receive continuous feedback on their progress in three ways. First, as the game progresses, the *cumulative environmental and population impacts* of all the facilities currently on the board are shown in a global status console area on the fourth side of the table, visible to all players (top in Figure 3.1b). This area shows this cumulative state of the game in terms of the environment (anthropomorphic tree) and population (face). The cumulative game state is also indicated through the changing colors of the main map interface and the tone of the ambient soundtrack. Second, the global display console also shows each role's status in terms of their *cumulative individual impact* on the environment up to this point in the game (indicated by color of role icon under tree) and their support of the current population up to this point in the game (indicated by color of role icon under face). For example, the red house on the left of the global display area indicates that the shelter player(s) has had a negative impact on the environment up to this point in the game. Third, each individual toolbar has an icon that represents how well that individual is meeting the needs of the population (Figure 3.1b). Food is a knife and fork. Shelter is a house. Energy is a lightning bolt. Again, color (red, yellow, green) is used to convey status. In addition, the game timer (Figure 3.1b, top left) shows the game time. The satellite is used to access game controls, such as pause and reset.

At the end of the game, a display informs the players of how they did. Summary information about group and individual outcomes is given through graphics and simple text. The game is designed to be played over and over so that players can adjust their strategies and learn from mistakes. It is possible, but non-trivial, to end with a balanced game world. Winning requires understanding both short- and long-term costs and effects of most of the shelter, power, and food facilities. Facilities that might look appealing when first placed (e.g., coal) have a long-term detrimental effect and produce less energy over time.

Futura was deployed at two university open house events and at a 2010 Winter Olympics cultural site. Thousands of people have played, and we have collected data related to understanding learning design, game design, interaction design, and collaboration in several studies: one focusing on design for public venues (Antle, Tanenbaum, et al., 2011) and one focusing on design for collaborative learning (Antle, Bevans, et al., 2011). We also developed two information tools based on difficulties players had understanding the cumulative human and environmental states in a fast-paced simulation game. The tools stop the timer and enable players to see an overview of either human or environmental state at any time. We developed tangible and touch versions of the tools, and compared social interaction between tangible and touch tool groups (Speelpenning, Antle, Doring, & van den Hoven, 2011). We found that the physicality of the tangible tools facilitated individual ownership and announcement of tool use, which in turn supported group and tool awareness. Based on this finding, and previous research we have done with tangibles (e.g., Antle & Wang, 2013; Antle, Wise, et al., 2011), we designed our next tabletop system, Youtopia, using both tangible and touch interaction.

Example Two: Youtopia Tabletop System

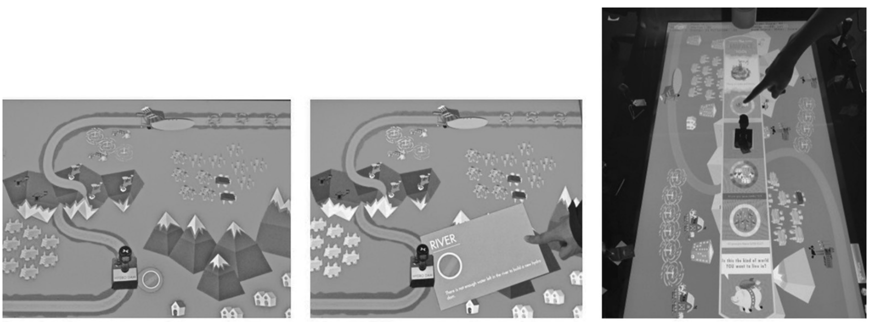
Youtopia is a multi-player land use planning activity played on a tangible, multi-touch Microsoft PixelSense Surface tabletop. The key differences from Futura are that it is a microworld rather than a time-pressured simulation and the primary form of input of resources and facilities is tangible stamps. The learning outcomes are similar to Futura, but are extended to include: analyzing the relationship between the economic development of communities and their available resources, understanding the differences between renewable and non-renewable resources, and understanding impacts of using living and non-living resources.[2] The goal of the activity is to work with the other players to create a world that the players agree that they would like to live in. This is different than Futura, in which there is a single winning state. In Youtopia players decide on a desired end state and work to achieve it. A complete system description can be found in Antle et al. (2013). A video of Youtopia is available.[3]

Similar to Futura, players must make decisions about how to provide shelter, food, and energy for a population in a river basin containing natural resources. However, the underlying system model was designed to support positive interdependence between players based on ideas outlined in Antle and Wise (2013). Specifically, since resources and facilities are interrelated in the real world, they are also codependent in the game. The system must sense multiple inputs to create certain developments. For example, trees must be turned to lumber before housing can be built. Positive interdependence between learners can be supported by assigning resource and facility stamps to different players, who must then work together to create developments. In addition, Youtopia was designed based on an educational behavior change model called *emergent dialogue*, in which the primary goal of activity is for learners to participate in dialogue about their values around social and environmental issues. This model is built into the game, using six 'design markers,' which are clusters of features that work together to support participation, dialogue, and value-based decision making (Antle, Tanenbaum, Macaranas, & Robinson, 2014; Antle, Warren, May, Min, & Wise, 2014).

Similar to Futura, there are different types of shelter, food and energy sources as well as nature reserves, each with different benefits and limitations. Pollution results from human developments. The map is of a small area of land, including mountains, valleys, grasslands, and a river. There are four maps, each with equivalent resources. Together, the different populations and maps add sufficient complexity to the application that children can play for long sessions.

The main method of interaction is through physical stamp objects that children use to 'stamp' different land use types onto an interactive map (Figure 3.2a). Stamps involve players taking a physical object with a tag and placing it on the tabletop to designate a selected location for that land use type. Players use these natural resource or facilities stamps to create human developments. There is no turn taking. Instead players work together to stamp land uses onto the map. If a facility is stamped without enough natural resources to support it, or placed in an incorrect location, then a feedback tab is displayed (Figure 3.2a). A player may then drag the tag away from the stamp to reveal the feedback message (Figure 3.2b). Feedback tabs are color- and symbol-coded so that over time the tab provides sufficient information for the players to correct their actions. Along with stamping, players may erase developments, which frees up resources. This supports a more exploratory approach than Futura, which enables learning during game play rather than having to replay the game to make new choices.

Because Youtopia is not a simulation, players can stop the game at any time to check their progress using the Impact Stamp (Figure 3.2c). This stamp displays a touch-sensitive overlay that graphically shows the level of pollution and how much of the current population's needs for shelter, food, and energy is currently supported, and asks if the players are satisfied with their world. When a player touches any of the rings (one each for pollution, food, shelter, and energy), the system highlights all of the resources and facilities that contribute to that effect. We added this feature to slow down



a. b. c.

Figure 3.2 (a) Learning tab appears (b) Pulling tab reveals message (c) Impact tool and touch display world state information.

interaction and enable players to understand the interrelationships between land use types and effects because in Futura players did not have time or information that would enable them to reflect and respond thoughtfully and determine their next steps.

Like Futura, information about each resource or facility is available on demand. At any time a player may place any stamp in the Info Ring. The system senses the stamp identity, freezes interaction, and displays an information overlay. The overlay graphically and textually describes what the land use needs, produces, and contributes to the world as well as constraints on usage, such as location. For example, placing the apartment stamp in the ring displays how much lumber is needed to produce an apartment complex, how many people the structure can shelter, and that it can be built in grasslands.

Youtopia was deployed at a university open house and in a lab experiment with 12 adults to explore the effectiveness of the codependent input design (Fan, Antle, Neustaedter, & Wise, 2014). We collected verbal and behavioral observational data and interview data. Findings suggested that assigning stamps to players supported more equitable verbal participation and physical interaction compared to an unassigned strategy where any player could use any stamp. We also deployed Youtopia in an experiment with 40 Grade 5 students at their school and studied how the codependent input design supported collaboration (Wise et al., under review) and how the design for emergent dialogue supported rich dialogue about children's values about sustainability (Antle, Warren, et al., 2014). We conducted a more open field study a year later at the same school, which included interviewing teachers about contextual factors that impacted the success of tabletop applications in the classroom.

DESIGNING FOR TABLETOP COLLABORATION

Research to date on interaction design for collaborative learning with tabletop applications has largely focused on suggesting benefits based on general attributes of tabletops or investigating individual interface factors that may be beneficial. We have identified six important ways that clusters of physical, social, interface, and learning application features of tabletops can be leveraged through purposeful interface and/or interaction design to support behaviors that enable one or more of the precursors for collaboration (discussed earlier). We refer to the two example systems (Futura and Youtopia, described earlier) to illustrate how clusters of design features enable beneficial behaviors.

Joining and Participating

Along with motivation to participate, learners need one or more ways to easily join in collaborative activity. Entry points in a digital tabletop system are characteristics that enable a learner to join the interaction.

Access points are characteristics that enable a learner to interact and to participate in an ongoing way in a group's activity (Hornecker et al., 2007). Although most tabletop designs enable several learners to actively use the system at the same time, previous research has shown that this alone does not ensure collaboration (Dillenbourg, 1999; Kreijns et al., 2003). Hornecker et al. (2007) suggest that a constrained input system (e.g., limited number of access points) may require sharing and coordination. However, Marshall et al. (2009) found that a limited number of access points can also lead to competitive behaviors. Rogers et al. (2009) found that tangible tabletops supported more equitable participation than multi-touch when both verbal and physical gestures were considered.

What clusters of design features might then enable multiple simultaneous users to effectively enter and access collaborative activity? First the social context or learning design must encourage or require group participation. Then, we have found two approaches that have enabled learners to quickly and easily join and participate in group activity. Both approaches leverage the physical size of our tabletops, the rectilinear shape, which includes flat surfaces along the edges, and the ability of a camera sensing system to sense multiple inputs (either fingers or objects).

Using touch-only tabletops, we have found that placing digital interactive objects (e.g., touchable buttons or toolbars) statically around the edges invites participation from all sides. By permanently locking buttons and toolbars meant for individual player use along edges, a single learner cannot move all the objects over to his or her side nor reach all of them, leaving space for others to join and participate. In Futura (touch-only) we implement this strategy by having three permanent toolbars, each aligned to one side of the active table surface, which is 103 cm by 68 cm. A player can approach any one of three sides and have immediate access to interaction through a toolbar. The positioning of each toolbar along the sides of the table, combined with the length and the distance across the table (to other toolbars), ensures that one player cannot take over all toolbars. This design enables room to enter and access the activity.

Using tangible input, we have also found that placing sets of unique input objects (objects or touchable controls) around the sides of the tabletop invites participation from all sides. The tabletop edges can be used to place tangible objects when they are not in use. The main form of interaction with Youtopia is through the 13 unique land use stamps. The stamp can be positioned at all four edges of the table, again enabling a learner to walk up and join in the activity. We designed the system so that once input objects are sensed, they need to be removed from the active surface. This encourages learners to place input objects back around the table edges, inviting others to use them, as seen in Antle, Warren, et al. (2014). Advantages of tangible input objects (versus touch) are discussed in the next two sections. In some cases, they are not practical. For example, tangibles may be more expensive to create and more intensive to program, and in a public setting physical input objects can easily go missing.

Attending to Each Other

The value of supporting learners to *attend* to each other by making actions visible and gaze-observable in supporting collaborative meaning making is well documented (Fernaeus & Tholander, 2006; Hornecker, 2005; Suzuki & Kato, 1995). When learners monitor what others are doing and what aspects of the system they are attending to, they may become *motivated* to coordinate their efforts with another learner. Alternatively, they may notice differences in what others are doing and initiate negotiation to restore a shared understanding of the collective activity. In either case, the presence of artifacts in a shared transaction space grounds the interaction by providing a referential anchor for conversation, which can be referred to by using both verbal and gestural communication channels (Suthers & Hundhausen, 2003).

What clusters of design features might then enable learners to attend to each other while working on the task? A face-to-face configuration can be enabled by designs that support learners to stay distributed around the tabletop once they have entered and accessed the tabletop from all sides (see design approaches earlier). For example, if an important interface element is placed in the center or at one of the short ends of the tabletop, children may situate themselves around the tabletop so they can all see and/or reach it. This in turn supports them to also be able to see each other, which will likely result in better awareness of what others are doing than if learners were all on the same side of a table or looking at a vertical display.

In general we have found that interface elements (e.g., instructions, feedback, controls) meant to be shared by group members must be accessible, reachable, viewable, and readable from as many sides of the table as possible (Antle, Bevans, et al., 2011). In addition, interaction opportunities or feedback about group activity needs to be centrally accessible. For example, if an important piece of interactive feedback relevant to the whole group activity is placed in a central location and is both visible and comprehendible from at least three sides of the tabletop surface, then children do not need to cluster on one side to view or interact with that information.

In consideration of this, in Futura, we placed the timer and the world state feedback, which shows if the learners will win the game before time runs out, at one end of the table (Figure 3.1b) (Antle, Bevans, et al., 2011). The world state display has large icons (tree, world, person) that are clearly visible from all sides of the table. The world state display acts as a referential anchor, grounding interaction and discussion by providing information about the discrepancy between the current and desired world state. In this case it is not interactive and not reachable, and therefore it can be placed at one side (the 'top') of the table (where non-players are meant to stand).

When we designed Youtopia we used a variation of this strategy to achieve the same effect of keeping players distributed. We did this in three ways. First, when any player places the Impact Stamp anywhere on the table, it causes the system to display the current world state information in the middle of the table, aligned along the long axis of the table. The information is depicted using words *and* graphical elements that can be 'read' from any direction (Figure 3.2c) (Antle, Warren, et al., 2014). This impact overly serves as a referential anchor for the group by providing the current state of the world, and freezing interaction (i.e., no other stamps work as long as the Impact Stamp is placed on the table). Because the feedback overlay is also interactive, it is placed centrally, rather than at one end of the table. Second, another way we keep players distributed is by placing the interactive control menu—which is used only occasionally—at the 'top' end of the table. The controls are visually represented, using pictorial thumbnails of control functions (e.g., choose new map, change population, quit) that can be understood from any angle. These controls can be used by any learner but are not needed frequently, so they can be out of reach, along the top edge. Lastly, we made textual content that appears during play rotatable. For example, the feedback cards (shown in Figure 3.2b) can be easily rotated 360 degrees, using one finger touch so that other players can read them (Antle et al., 2013).

We have also found that the 3-D manipulation space of tangibles often is associated with more heads-up interaction than a comparable 2-D, touch-only interface (Speelpenning et al., 2011). In part, this is why we used tangibles in our second system, Youtopia, rather than only touch. All of these strategies encourage learners to locate themselves around the tabletop so they have space to access the activity but also have motivation and access to attend to each other, the tangible objects, and the tabletop display.

Interacting within Collaborative Activity

Although learners need a *shared focus* around which negotiation and meaning making can occur, they also need to perform individual work within a collaborative activity. Supporting individual work in a group situation can be problematic. For example, in a study comparing physical and multi-touch objects for a collaborative task, Marshall et al. (2009) found that children used assertive and aggressive strategies to maintain control over individual objects in the multi-touch group. They suggest that this was because children were not able to maintain control of digital objects for individual use. In contrast, because they were more able to maintain ownership of tangible objects, their strategies for maintaining control during individual interaction were less aggressive. This finding was mirrored in a study comparing tangible and multi-touch tools for a collaborative game (Speelpenning et al., 2011). Participants asserted ownership over tangible tools by picking them up and holding them close to their bodies, which in turn prompted discussion about their use. How, then, can we support learners to interact individually within the context of collaborative activity in ways that are productive?

We have found a cluster of features that effectively support individual work interwoven with discussion and negotiation around collaborative tasks. This cluster includes the social practices around roles and objects ownership, the physical constraints of tabletop size, ambient feedback on a large, easily visible table surface, the time pressure of a simulation, and/or other learning design that requires collaboration. For example, if learners are explicitly assigned different roles and related responsibilities when using Futura (e.g., shelter, food, and energy) and each responsibility (or role) is associated with a side of the table, this gives the learner access to unique (role-specific) digital toolbars. Each learner can still see what the others are doing across the table surface. Since the distance to other toolbars is too far for children's arms to reach, only the learner responsible for shelter can access the tools to place condos, houses, and apartments on the map interface (Antle et al., 2011). We use a spatial constraint to minimize conflict over toolbar use. This design reduces conflict over mobile toolbars, such as that found in Olson et al. (2010). However, the static digital toolbars may result in a less flexible and more 'face-down' form of interaction (see earlier). We ameliorated this effect in Futura by using a learning design that *requires* individuals to work together. That is, in order to support a growing population base with enough food, energy, and shelter without seriously damaging the environment, learners in the different roles must coordinate their actions in a coherent strategy (before time runs out), which requires them to negotiate and collaborate as well as conduct individual work.

Another approach in Futura that encourages learners to focus on the overall collaborative task while interacting individually is by providing ambient world state feedback on the entire tabletop surface (Antle, Tanenbaum, et al., 2011). The world state is reflected in the color palette of the map (e.g., gray/brown/green depicts state of environment) as well as ambient sounds (ominous/upbeat). Individuals can see and hear what's happening overall while dragging and dropping items from their private toolbar onto the overall map. The use of ambient feedback provides a referential anchor that provides relevant information to spur discussion about next steps. This counters some of the heads-down effect of the static, digital toolbars.

In Youtopia we use social practices around object ownership to support both individual usage of stamps and group negotiation about land use decisions. We created a unique set of input objects (i.e., 13 unique land use stamps). For example, there is only one house stamp. Because of social norms around object ownership and turn taking with physical objects, learners are less likely to try to take physical objects from another learner compared to digital input objects (Speelpenning et al., 2011). For a learner to use a stamp either held by or close to the body of another learner requires negotiation, which is what we want. Social norms about turn-taking protocols enable opportunities for discussion and negotiation, which may or may not be successful, depending on the motivation to work together. It is important to design sharable objects in tandem with learning activities that either reward or enforce collaboration.

Pausing and Reflecting

Collaborative learning requires space for reflection as well as action. Metacognitive processes, such as analysis, evaluation, and regulation, all require time for reflection. Early studies found that children tended to get wrapped up in an activity using novelty interactive surfaces (Antle, Wise, et al., 2011; Harris, Phelps, Rogers, & Price, 2004). Price et al. (2010) discuss opportunities for reflection and action during a study of students exploring optics with a tabletop TUI activity. They suggest that the combination of visual feedback on the tabletop with both discrete actions (e.g., placing TUI objects on the surface) and continuous actions (e.g., dragging and dropping) enables action and opportunities to reflect on the consequences of that action. In their system, reflection and action are intertwined.

We have used two strategies to facilitate the kinds of interactions that support moving seamlessly from action to reflection and back to action. In Futura we provided opportunities for reflection *during* continuous action in a similar manner. We also provided opportunities for reflection *apart* from action, such as the world events that paused the game and provided a reason to reflect and discuss what was happening in the game. Reflection *during* action was largely an individual activity since a player's attention was likely on his or her actions and thinking about the results of these actions. Reflection *apart* from action was a collaborative activity. In this way, the Futura design supports both individual and social knowledge construction.

In Youtopia the Impact stamp freezes the map and displays status rings and text for pollution, shelter, food, and energy. Touching each status ring highlights all the resources and developments on the map that contribute to that state (Figure 3.2c). It displays an overlay showing the current state of the world in terms of what proportion of the population has its needs met for shelter, food, and energy, and how polluted the world is (expressed as partially filled-in rings; see Figure 3.2c). The pig (Figure 3.1c, bottom of image) asks, "Is this the world you want to live in?" By halting the ability to build new developments and providing world state information, this stamp provides a referential anchor that both provides time and content to support analysis of the current situation and evaluation against task goals, and enables learners to modify or formulate new plans (Antle, Warren, et al., 2014).

Working Together

Despite best our attempts to support collaboration, we have seen parallel individual play (e.g., (Antle, 2012). A powerful way to address this issue is to use learning designs that create positive interdependence in the collaborative learning situation by distributing information, skills, roles, or tools among learners such that they are required to work together to be successful (Järvelä, Häkkinen, Arvaja, & Leinonen, 2004). This approach may involve a collaboration script that constrains or guides the ways in which learners collaborate. This can support collaborative activity since the coordinated action of more than one child is needed to successfully enact a strategy (Dillenbourg & Jermann, 2007). With an interactive tabletop, this can be achieved by requiring either simultaneous or accumulated multiple actions to trigger digital events (Antle & Wise, 2013).

In our design of Youtopia, we explored designing to support positive interdependence using both social practices and system design. We used scripts that encourage roles through tangible tool assignment, combined with developing a system that senses and requires multiple sequential inputs for successful interaction (Antle, Warren, et al., 2014). Specifically, we designed inputs for this multiuser system that are codependent (Antle & Wise, 2013). Although each stamp is sensed individually, to successfully build anything requires two or more stamps placed in sequence. Typically, this is one or more natural resource stamps followed by a human development stamp. For example, since developments like the farm or garden require water, irrigation must first be placed on the map adjacent to the river. However, the river's water levels can be depleted, so developments that depend on its usage may be limited due to this constraint. In this case, a development that uses water has to be removed, then irrigation placed, and then a farm or garden placed. This strategy encourages children to coordinate stamps and actions and, in doing so, negotiate what they want to achieve.

CONCLUSION

Digital tabletops offer many unique opportunities to design applications that support collaborative learning. Until recently, little was known about how to make design decisions that leveraged the characteristics of tabletops within social and educational contexts to enable purported benefits. We have found that rather than relying on high general generalizations (e.g., tabletops support face-to-face activity) or focusing on individual design elements (feedback location), designers must make decisions that consider social, physical, interface, program, and learning factors to create tabletop applications that enable the kinds of behaviors that are precursors to collaborative learning.

Overall, we think that interactive tabletops—both tangible and touch-only—can provide many opportunities to learn in ways not supported by other media. For the field to mature, we need to see far more 'deep' learning applications developed with consideration of the interplay of factors, and deployed in real classrooms and informal learning environments. These need not focus solely on spatial domains. Indeed, some of our other work shows the benefit of mapping abstract domain learning to spatial environments (e.g., Antle, Corness, & Bevans, 2013). However, tabletops make sense for learning about environment and social issues, which are value-laden and often involve multiple conflicting viewpoints, because of their support for group interaction and system feedback about the results of decisions. We encourage designers of such systems to consider the emergent dialogue model and use our design markers (Antle, Tanenbaum, et al., 2014), which support learners to not only interact and collaborate but also engage in deep dialogue during learning about the difficult and pressing issues they will face as adults. The opportunities for supporting productive collaborative learning with tabletops are endless. Realizing such opportunities requires careful consideration of how clusters of social, learning, physical, interface, system, and contextual factors can be implemented to support key interactional behaviors: joining, participating, attending, interacting individually, reflecting, and working together. We look forward to seeing the field unfold and realize its potential in the years to come.

NOTES

1. www.antle.iat.sfu.ca/Futura.
2. The system was designed to meet learning outcomes for Grade 5 environment and sustainability topics (ages 10–11) from the Canadian curriculum.
3. www.antle.iat.sfu.ca/Youtopia.

REFERENCES

Antle, A.N. (2007). *The CTI framework: Informing the design of tangible systems for children*. Paper presented at the Conference on Tangible and Embedded Interaction, Baton Rouge, LA.

Antle, A.N. (2012). Exploring how children use their hands to think: An embodied interactional analysis. *Behaviour and Information Technology*, 32(9), 938–954. doi:10.1080/0144929X.0142011.0630415

Antle, A.N., Bevans, A., Tanenbaum, J., Seaborn, K., & Wang, S. (2011). *Futura: Design for collaborative learning and game play on a multi-touch digital tabletop*. Paper presented at the Conference on Tangibles, Embodied and Embedded Interaction, Funchal, Madeira, Portugal.

Antle, A.N., Corness, G., & Bevans, A. (2013). Balancing justice: Comparing whole body and controller-based interaction for an abstract domain. *International Journal of Arts and Technology*, 6(4), 388–409.

Antle, A.N., Tanenbaum, J., Bevans, A., Seaborn, K., & Wang, S. (2011). Balancing act: Enabling public engagement with sustainability issues through a multi-touch tabletop collaborative game. In P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque & M. Winckler (Eds.), *Lecture Notes in Computer Science: Vol. 6947. Human-Computer Interaction* (pp. 194–211).

Antle, A.N., Tanenbaum, J., Macaranas, A., & Robinson, J. (2014). Games for change: Looking at models of persuasion through the lens of design. In A. Nijholt (Ed.), *Playful user interfaces: Interfaces that invite social and physical interaction* (pp. 163–184). Berlin: Springer.

Antle, A.N., & Wang, S. (2013). *Comparing motor-cognitive strategies for spatial problem solving with tangible and multi-touch interfaces*. Paper presented at the Conference on Tangible, Embedded and Embodied Interaction, Barcelona, Spain.

Antle, A.N., Warren, J.L., May, A., Min, F., & Wise, A.F. (2014). *Emergent dialogue: Eliciting values during children's collaboration with a tabletop game for change*. Paper presented at the International Conference on Interaction Design for Children, Aarhus, Denmark.

Antle, A.N., & Wise, A.F. (2013). Getting down to details: Using learning theory to inform tangibles research and design for children. *Interacting with Computers, 25*(1), 1–20. doi:10.1093/iwc/iws007

Antle, A.N., Wise, A.F., Hall, A., Nowroozi, S., Tan, P., Warren, J., . . . Fan, M. (2013). *Youtopia: A collaborative, tangible, multi-touch, sustainability learning activity*. Paper presented at the Interaction Design for Children Conference, New York City. AuQ3

Antle, A.N., Wise, A.F., & Nielsen, K. (2011). *Towards Utopia: Designing tangibles for learning*. Paper presented at the Conference on Interaction Design for Children, Ann Arbor, MI.

Berland, M., & Lee, V.R. (2011). Collaborative strategic board games as a site for distributed computational thinking. *International Journal of Game-Based Learning, 1* (2), 65–81. doi:10.4018/ijgbl.2011040105

Brave, S., Ishii, H., & Dahley, A. (1998). *Tangible interfaces for remote collaboration and communication*. Paper presented at the 1998 ACM Conference on Computer-Supported Cooperative Work, Seattle, WA.

Buisine, S., Besacier, G., Aoussat, A., & Vernier, F. (2012). How do interactive tabletop systems influence collaboration?. *Computers in Human Behavior, 28*(1), 49–59. doi:http://dx.doi.org/10.1016/j.chb.2011.08.010

Clark, H.H., & Brennan, S.E. (1991). Grounding in communication. In L.B. Resnick, J.M. Levine & S.D. Teasley (Eds.), *Perspectives on socially shared cognition* (pp. 127–149). Washington, DC: American Psychological Association.

Dillenbourg, P. (1999). What do you mean by "collaborative learning"? In P. Dillenbourg (Ed.), *Collaborative learning: Cognitive and computational approaches* (pp. 1–16). New York: Elsevier Science.

Dillenbourg, P. (2002). Over-scripting CSCL: The risks of blending collaborative learning with instructional design. In P. Kirschner (Ed.), *Three worlds of CSCL: Can we support CSCL?* Heerlen: Open University of the Netherlands.

Dillenbourg, P., & Evans, M. (2011). Interactive tabletops in education. *International Journal of Computer-Supported Collaborative Learning, 6*(4), 491–514.

Dillenbourg, P., & Jermann, P. (2007). Designing integrative scripts. In F. Fischer, H. Mandl, J. Haake & I. Kollar (Eds.), *Scripting computer-supported collaborative learning: Cognitive, computational, and educational perspectives* (pp. 275–295). New York: Springer.

Duffy, T.M., Dueber, B., & Hawley, C.L. (1998). Critical thinking in a distributed environment: A pedagogical base for the design of conferencing systems. In C.J. Bonk & K.S. King (Eds.), *Electronic collaborators: Learner-centered technologies for literacy, apprenticeship, and discourse* (pp. 51–78). Mahwah, NJ: Lawrence Erlbaum Associates.

Fan, M., Antle, A.N., Neustaedter, C., & Wise, A.F. (2014). *Exploring how a co-dependent tangible tool design supports collaboration in a tabletop activity.* Paper presented at the International Conference on Supporting Groupwork, Sanibel Island, FL.

Fernaeus, Y., & Tholander, J. (2006). "Looking at the computer but doing it on land": Children's interactions in a tangible programming space. In T. McEwen, J. Guliksen, & D. Benyon (Eds.), *People and computers XIX—The bigger picture* (pp. 3–18). London: Springer.

AuQ4 Fleck, R., Rogers, Y., Yuill, N., Marshall, P., Carr, A., Rick, J. and Bonnett, V. (2009). Actions speak loudly with words: unpacking collaboration around the table. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces* (pp. 189–196). New York: ACM.

Harris, E., Phelps, T., Rogers, Y., & Price, S. (2004). *From snark to park: An overview of the design, practical and technological issues when developing novel learning and playing experiences for indoors and outdoors*. Paper presented at the Australasian User Interfaces Conference, Darlinghurst, New South Wales, Australia.

Hornecker, E. (2005). A design theme for tangible interaction: Embodied facilitation. In H. Gellersen, K. Schmidt, M. Beaudouin-Lafon & W. Mackay (Eds.), *ECSCW 2005* (pp. 23–43). Dordrecht, Netherlands: Springer.

Hornecker, E., Marshall, P., & Rogers, Y. (2007). *From entry to access—How shareability comes about*. Paper presented at the Conference on Designing Pleasurable Products and Interfaces, Helsinki, Finland.

Järvelä, S., Häkkinen, P., Arvaja, M., & Leinonen, P. (2004). Instructional support in CSCL. In J.W. Strijbos, P. Kirschner & R. Martens (Eds.), *What we know about CSCL* (pp. 115–139). Dordrecht, Netherlands: Springer.

King, A. (2007). Scripting collaborative learning processes: A cognitive perspective. In F. Fischer, I. Kollar, H. Mandl & J. Haake (Eds.), *Scripting computer-supported collaborative learning* (Vol. 6, pp. 13–37). New York: Springer.

Kreijns, K., Kirschner, P.A., & Jochems, W. (2003). Identifying the pitfalls for social interaction in computer-supported collaborative learning environments: A review of the research. *Computers in Human Behavior, 19*(3), 335–353.

Marshall, P., Fleck, R., Harris, A., Rick, J., Hornecker, E., Rogers, Y., . . . Dalton, N.S. (2009). *Fighting for control: Children's embodied interactions when using physical and digital representations*. Paper presented at the Conference on Human Factors in Computing Systems, Boston, MA.

Miyake, N., Masukawa, H., & Shirouzou, H. (2001). *The complex jigsaw as an enhancer of collaborative knowledge building in undergraduate introductory science courses*. Paper presented at the European Conference on Computer-Supported Collaborative Learning, Maastricht, NE.

Olson, I.C., Leong, Z.A., Wilensky, U., & Horn, M.S. (2010). *It's just a toolbar!:Using tangibles to help children manage conflict around a multi-touch tabletop*. Paper presented at the Conference on Tangible, Embedded, and Embodied Interaction.

Price, S., Sheridan, J.G., & Pontual Falcão, T. (2010). Action and representation in tangible systems: implications for design of learning interactions. In T. Pederson, O. Shaer, & R. Wakkary (Eds.), *Proceedings of the fourth international conference on tangible, embedded, and embodied interaction* (pp. 145–152). New York: ACM.

Rick, J. (2012). *Proportion: A tablet app for collaborative learning*. Paper presented at the Conference on Interaction Design for Children, Bremen, Germany.

AuQ5 Rick, J., Marshall, P. and Yuill, N. (2011). Beyond one-size-fits-all: how interactive tabletops support collaborative learning. In *Proceedings of the 10th International Conference on Interaction Design and Children* (pp. 109–117). New York: ACM.

Rogers, Y., Lim, Y., Hazelwood, W., & Marshall, P. (2009). Equal opportunities: Do shareable interfaces promote more group participation than single user displays? *Human-Computer Interaction, 24*(2), 79–116.

Roschelle, J., & Teasley, S. (1995). The construction of shared knowledge in collaborative problem solving. In C. O'Malley (Ed.), *Computer-supported collaborative learning* (pp. 69–197). Berlin: Springer Verlag.

Scott, S.D., Carpendale, M. S. T., & Inkpen, K.M. (2004). *Territoriality in collaborative tabletop workspaces*. Paper presented at the Computer-Supported Cooperative Work Conference, Chicago, IL.

Speelpenning, T., Antle, A.N., Doring, T., & van den Hoven, E. (2011). *Exploring how a tangible tool enables collaboration in a multi-touch tabletop game*. Paper presented at the INTERACT Conference, Lisbon, Portugal.

Suthers, D., & Hundhausen, C. (2003). An empirical study of the effects of representational guidance on collaborative learning. *Journal of the Learning Sciences, 12*(2), 183–219.

Suzuki, H., & Kato, H. (1995). *Interaction-level support for collaborative learning: AlgoBlock—An open programming language*. Paper presented at the Conference on Computer Support for Collaborative Learning, Bloomington, IN.

Wise, A.F., Antle, A. N., Warren, J., May, A., Fan, M. & Macaranas, A. (under review). *What kind of world do you want to live in?: Positive interdependence and collaborative processes in the land-use planning game* YouTopia. Paper submitted to the 2015 International Conference on Computer Supported Collaborative Learning (CSCL).

Wise, A.F., Padmanabhan, P., & Duffy, T.M. (2009). Connecting online learners with diverse local practices: The design of effective common reference points for conversation. *Distance Education, 30*(30), 317–338.