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"Whoa! We're going deep in the trees!": Patterns of collaboration around an interactive information visualization exhibit

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Abstract In this paper we present a qualitative analysis of natural history museum visitor interaction around a multi-touch tabletop exhibit called *DeepTree* that we designed around concepts of evolution and common descent. DeepTree combines several large scientific datasets and an innovative visualization technique to display a phylogenetic tree of life consisting of over 70,000 species. After describing our design, we present a study involving pairs of children interacting with DeepTree in two natural history museums. Our analysis focuses on two questions. First, how do dyads negotiate their moment-to-moment exploration of the exhibit? Second, how do dyads develop and negotiate their understanding of evolutionary concepts? In order to address these questions we present an analytical framework that describes dyads' exploration along two dimensions: coordination and target of action. This framework reveals four distinct patterns of interaction, which, we argue, are relevant for similar interactive designs. We conclude with a discussion of the role of design in helping visitors make sense of interactive experiences involving the visualization of large scientific datasets.

Keywords Learning · Collaboration · Evolution · Interactive tabletops · Information visualization

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Introduction

In natural history museums and other informal science institutions, interactive exhibits that invite open-ended exploration play a prominent role in the overall visitor experience (Allen 2004; Allen and Gutwill 2004; Crowley et al. 2001; Humphrey and Gutwill 2008; Q2 Oppenheimer 1976). These types of experiences often involve hands-on manipulation of physical artifacts, specimens, or phenomena. For example, visitors might use a microscope to examine a biological specimen or touch a "tornado" forming inside a chamber (e.g., Stevens and Hall 1997). With the increasing availability of large interactive computer displays such as multi-touch tabletops, designers now have the opportunity to create similar experiences that involve digital media. Typical examples include visitors interacting with digital photographs, videos, or text (e.g., Hinrichs and Carpendale 2011; Hornecker 2008), assembling puzzles (e.g., Horn et al. 2012), or playing games (e.g., Antle et al. 2011; Horn et al. 2012). In all of these cases, the primary method of interaction involves manipulating independent multi-media objects on the screen through the use of simple gestures like tap, drag, pinch, and rotate. And, in many ways, these digital experiences represent a comfortable and direct analog to physical interactive exhibit elements.

However, there are other types of experiences that museums might want to offer that go beyond the direct manipulation of physical objects or their digital counterparts. In particular, designers and researchers have begun to create experiences in which visitors can explore visualizations of large scientific datasets (e.g., Block et al. 2012; Louw and Crowley 2013; Ma et al. 2012; Roberts et al. 2014). These types of exhibits give visitors hands-on experiences that not only reflect the computational tools and methods employed in many scientific disciplines, but also create new opportunities for learning scientific concepts (Louw and Crowley 2013; Ma et al. 2012).

Creating these types of experiences represents a considerable design challenge. While large interactive displays might be attractive to designers of informal learning experiences in principle, supporting effective collaboration through the use of such devices is deceptively challenging in practice (Hinrichs and Carpendale 2011; Rick et al. 2011; Fleck et al. 2009; Hornecker 2008; Marshall et al. 2009; Olson et al. 2011; Snibbe and Raffle 2009). Without the constraint of a single input device (like a mouse or a keyboard) multiple individuals are free to interact at any time, independent of one another. Because of this, designers must balance the value of multi-user interaction with the confusion, disruption, and conflict that may also arise (Olson et al. 2011; Marshall et al. 2009; Hornecker 2008; Pontual Falcão and Price 2011). This design challenge is especially daunting in free-choice learning environments that lack the structure and guidance of teachers and curriculum. In these settings engagement times tend to be short (Humphrey and Gutwill 2005; Falk and Dierking 2000) and learning experiences must accommodate multiple entry points and differing levels of engagement. And although there is a growing body of research on the use of tabletops and other large displays to support collaborative learning in classrooms and other formal settings (Dillenbourg and Evans 2011; Higgins et al. 2011), there is very little existing research on informal science experiences involving the collaborative exploration of large scientific datasets and the types of learning that these experiences might foster.

We add to this literature with an analysis of the types of interactions such exhibits afford and the types of learning they might support. The current study involves an interactive tabletop exhibit called DeepTree (Fig. 1) that allows museum visitors to explore a phylogenetic tree of life containing over 70,000 species. The exhibit features a deep zoom interaction technique in which visitors can "fly" from the origin of life to a diversity of species that have inhabited the planet. Along the way, visitors encounter important evolutionary landmarks such as the

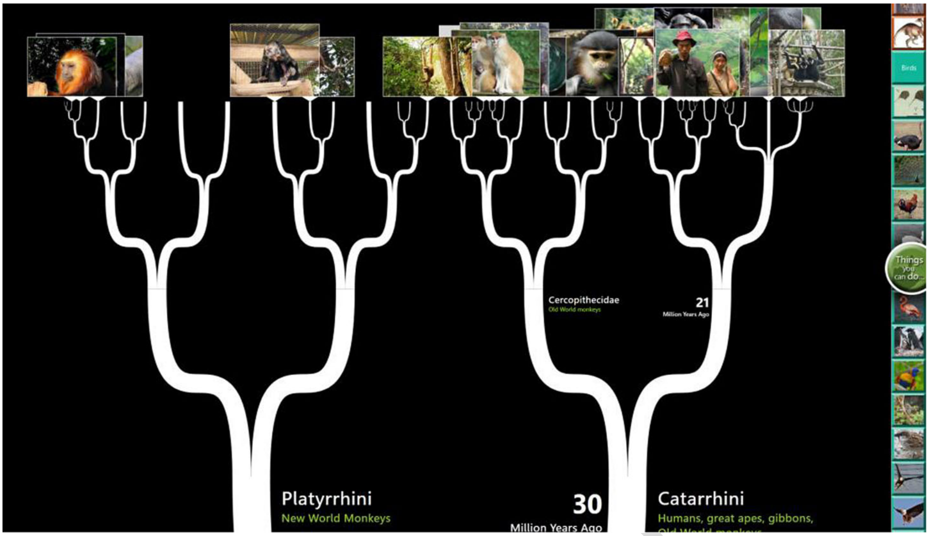

Fig. 1 Screenshot from the DeepTree exhibit

emergence of multicellular life, the evolution of jaws, and the move from oceans to dry land. These landmarks represent important traits that many modern-day species have inherited from distant ancestors.

In crafting this experience, we had several overarching design goals in mind. The first was to go beyond the superficial manipulation of multimedia objects and present visitors with an intuitive means to explore a large scientific dataset. Second, research shows that the quality of visitor social interaction is a critical factor that influences learning in such free-choice environments (Ash 2004; Crowley et al. 2000; Eberbach and Crowley 2005; Falk and Dierking 2000; Falk and Storksdieck 2005). As such it was important for us to create a collaborative experience in which groups of visitors interacted together around the same display. We therefore targeted *interdependence*—the mutual reliance of visitors on one another's actions—as a goal in interactions with our exhibit (Dillenbourg and Evans 2011; Higgins et al. 2011). As a specific example of this, we average all simultaneous touch input as visitors pan and zoom the display, thus necessitating some coordination of action to move through the visualization. Finally, keeping in mind that visitors come to museums with a variety of backgrounds, experience levels, and expectations (Falk and Dierking 2000; Falk 2009), we also avoided creating a scripted experience with a single entry point and fixed takeaway messages. Visitors can experience DeepTree in many different ways and with many different outcomes. Taken together, we see these design goals as describing a new type of museum experience that will become increasingly common as display technologies improve and visualizations of scientific data become more prevalent. The characteristics of these types of experiences are: 1) the key mode of interaction will involve exploration of a large information space (searching, filtering, layering, zooming, and panning); 2) exploration will prompt visitors to ask questions and seek their own answers (Ma et al. 2012); and 3) the information will be structured and annotated so as to foster personal connections and meaning making (Roberts et al. 2014).

This paper presents a qualitative analysis of youth dyads interacting with DeepTree at two natural history museums. Our analysis seeks to understand how pairs of youth interact with our exhibit together and what their patterns of interaction tell us about how to support learning through these types of designed experiences.

Research design

Research space: The DeepTree exhibit

The design of DeepTree was guided by several learning objectives related to evolution and biodiversity. Foremost is the idea that all of life is related through common descent. That is, by scanning back in time, visitors discover that *any* two groups of organisms share ancestors and inherited traits in common. Through our design we also hoped to instill a sense of wonder related to the immense timescales and the stunning levels of biodiversity that have resulted from millions of years of evolution. These learning objectives are difficult to realize. Despite its importance, evolution remains poorly understood by the general public, particularly in the United States (Rosengren et al. 2012; Miller et al. 2006). These challenges are amplified in museums where engagement times tend to be short and visitors have complete freedom to move from one exhibit element to the next (Humphrey and Gutwill 2005; Falk and Dierking 2000). Even depicting the evolutionary relationships of a small number of species can be confusing for learners (Matuk and Uttal 2012; Novick et al. 2012; MacDonald and Wiley 2010). While we embrace the usefulness of simplified representations of scientific concepts (Davis et al. 2013), it can be difficult to convey the vast scale and dynamic processes of evolution using simplified static representations alone. DeepTree uses an interactive zooming technique to try to achieve the best of both worlds. At any given time the screen displays a tree with a relatively small number of branches, but by zooming in and out visitors can fly through many hundreds of branching points in a few seconds.

As interactive display technology has continued to improve, multi-touch tabletops have received sustained attention from the CSCL community (Dillenbourg and Evans 2011; Higgins et al. 2011; Pontual Falcão and Price 2011; Price and Pontual Falcão 2011). Price and Pontual Falcão (2011), in particular, have developed pertinent analytic frameworks through the study of youth engagement with a tabletop learning environment on light and optics. Of relevance to the current study is their framework on attention and engagement, which suggests that children's attention alternates between exploring technical aspects of the system, playful engagement for entertainment, and attending to domain learning concepts. They note that these types of engagement often directly overlap or were complementary. For example, when youth focused on the technical capabilities of the system, it often coincided with exploring the possibilities of the interface, which, in turn, related to the target learning objectives (light and optics). While Price and Pontual Falcão's learning environment is quite different from the DeepTree environment that we describe here, we nevertheless observed similar forms of engagement on the part of our participants that we elaborate below. In particular, our patterns of interaction deal with the transition from mechanical to conceptual goals as dyads make sense of the DeepTree interface. In a related article, Pontual Falcão and Price (2011) further argue that *interference* between participants in shared interfaces can be productive for learning because it triggers argumentation and collective knowledge construction. Building on Weinberger and Fischer's (2006) framework on argumentative co-construction of knowledge in CSCL environments, Pontual Falcão and Price (2011) describe instances of interference that lead to situations in which students abandon their current course of action, integrate the choices of others, or ignore/undo the actions of others. In our data, we see each of these three patterns play out in dyads' interaction with the DeepTree. This is particularly evident in our Reactive pattern (explicated in later sections), where participants' goals tend to be mechanical in nature, but it is also visible in the other three patterns as well.

The DeepTree design was also informed by several related projects that combine multi-touch tabletop displays to help learners make sense of evolution and other biological concepts. For example, Phylo-Genie (Schneider et al. 2012) and G-nome Surfer (Shaer et al. 2011) are learning environments that introduce students to evolution, tree-thinking (Baum et al. 2005), and genomics using a combination of tangible and multi-touch tabletop technology. Several other projects have explored the use of tabletop technology in informal learning environments. Build-a-Tree (Horn et al. 2012) is a phylogenetic tree-thinking game that was deployed on a multi-touch tabletop in a natural history museum. An analysis of visitor interaction with Build-a-Tree showed that social practices of game play contributed to an engaging and enjoyable learning experience for visitors. Futura (Antle 2011) is a tabletop game on issues of environmental sustainability that was available to the public at the 2010 Winter Olympic Games.

The current study expands on this related work in two important ways. First, DeepTree visualizes several large scientific data sets. This makes it substantially different from games like Futura and Build-a-Tree, which are both targeted at informal learning audiences, but make use of simplified representations and scenarios. It also differs from learning environments like Phylo-Genie and G-nome Surfer that include visualizations of real scientific datasets, but are targeted at college-level students in university settings. And, second, the current study provides an in-depth analysis of dyadic interaction in order to understand how design factors might contribute to learning through collaborative interaction. This expands on the analytical frameworks of Price and Pontual Falcão (2011) by revealing four distinct patterns of interaction organized along two dimensions.

The DeepTree runs on a large multi-touch tabletop display and has three major components (see Figs. 1 and 2). The main display area allows visitors to zoom and pan through a tree of life visualization using standard multi-touch gestures. DeepTree adopts representational conventions of phylogenetic trees or cladograms, essential diagrams of modern biology (Baum et al. 2005; Catley and Novick 2008; Gregory 2008). Pulling the tree down from the top of the screen reveals more information, starting from the root of the tree to its canopy, displaying individual species. The tree uses a fractal-based layout algorithm so that branches emerge as the user zooms in or out. Unlike static depictions of trees that simplify information by limiting the number of species, the fractal design allows for the depiction of many thousands of species in the tree of life while reducing visual complexity. The second component is a scrolling image wheel along the right side of the screen containing a subset of 200 "star" species that represent important evolutionary groups. Visitors scroll through the images to select and pull out any species onto the main display. When a visitor holds an image down, a semi-transparent arc points to the location of that species in the tree while the system automatically zooms in toward it—we refer to this zoom as the "fly-through" (see Fig. 2). The final component is an action button located on the image wheel. When pressed, the action button reveals *find* and *relate* functions. The find function allows visitors to select a species from the image wheel and then automatically zoom to that species. The relate function allows visitors to select any two species from the image wheel and automatically fly to their most recent common ancestor. The exhibit then presents a simplified tree depicting the two species' shared lineage and highlighting major evolutionary landmarks (see Fig. 2, bottom). Touching these points reveals further information about common ancestors and major inherited traits. We developed DeepTree through an iterative process of design and evaluation with a team of computer scientists, learning scientists, biologists, and museum curators. Over the course of a year we implemented and evaluated twelve prototype designs with over 250 visitors in a two natural history museums.

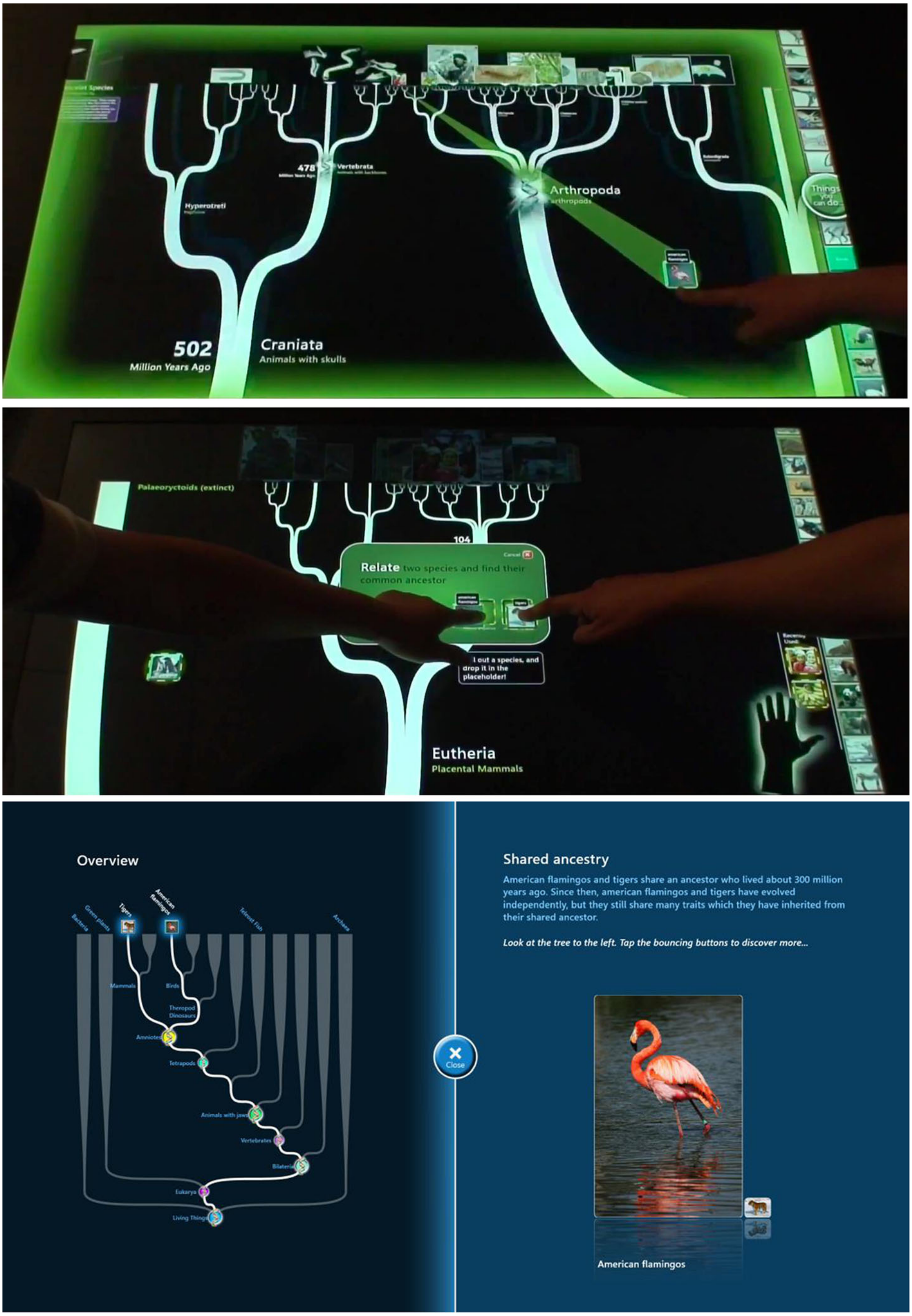

Fig. 2 A user holding down an image of a species, thus triggering the "fly-through" mechanic (*top*). A dyad collaborating to use the relate function (*middle*). A simplified tree depicting the two species' shared lineage and highlighting major evolutionary speciation points (*bottom*)

Study design and methodology

We recruited youth dyads consisting of friends or siblings who were visiting one of the two museums together as part of the same social group. In total we recruited 248 youth (129 girls and 119 boys) aged 8–15 years (mean age=11.56 years; SD=1.68), and randomly assigned them to participate in one of four conditions (Table 1). In the first two conditions, dyads freely interacted with different versions of DeepTree on a tabletop display for a fixed period of 10.5 min. The first version included an embedded activity on natural selection that was automatically triggered after the first four minutes of interaction. The second version consisted of the DeepTree application without the embedded activity. In a third condition, dyads watched a 10.5 min video on the same topics (see Prum 2008). Individual responses on a 53-item post-interview consisting of open- and closed-ended questions were then compared to responses in a fourth condition (baseline) in which dyads were interviewed directly after informed consent was obtained. The interview took approximately 20 min to administer and was audio recorded. We video recorded children's physical and verbal interactions in the DeepTree and video conditions in order to capture discourse, behavior, and collaboration. Dyads were paid $15 for participating in the study. While the dyads were interacting with the exhibit, parents completed a demographic form and questionnaire. There were no significant differences across conditions in youth ages, parent completion/non-completion of college, parents' or children's self-reported knowledge of evolution, religiosity, or compatibility of evolution with their religious beliefs.

This study design was meant to approximate a real museum experience. It was not entirely a free choice experience as we asked visitors to participate together for a fixed amount of time without interruption from other visitors. On the other hand, it was not exactly like a formal learning experience either as we offered no direction about content, learning objectives, or interaction. DeepTree had to function without the support of guided instruction, teachers, or curriculum.

Learning measures and outcomes

Our first objective was to determine whether DeepTree constitutes an environment in which learning takes place. In order to determine this, we performed a quantitative analysis of the children's interview responses across several evolutionary concepts. A full analysis of these results is forthcoming (Horn et al. Under Review), but we provide a brief summary here. Based on responses to five close-ended questions, youth in the DeepTree conditions were significantly more likely than those in the baseline groups to agree that humans, other animals, plants, and fungi had ancestors in common a long time ago (Common Ancestry). Furthermore,

Table 1 Participant numbers by condition, age, sex, and study site

Total participants		DeepTree 1	DeepTree 2	Video	Baseline	Total
Age	8–11 years	28	28	29	28	113
	12–15 years	31	34	34	35	134
Sex	Boys	26	31	31	32	120
	Girls	33	31	32	31	127
Site	Museum 1	29	32	31	32	124
	Museum 2	30	30	32	31	123

youth in the second DeepTree condition, which focused exclusively on common descent, were significantly better at interpreting a tree of life graphic on three close-ended questions (Tree Reading) than baseline participants. Similarly, individuals in the second DeepTree condition invoked concepts such as common descent and shared traits significantly more often in responses to ten open-ended questions than dyads in the baseline condition (Tree Concepts). They also used more macro-evolutionary terms in their responses to the same ten open-ended questions than dyads in the baseline condition (Tree Terms). Participants in the video condition also consistently scored higher than the baseline participants on these measures of macroevolution understanding. However, none of the differences for the video condition were significant. Our post-interview also assessed a number of microevolution concepts such as natural selection, adaptation, inheritance, and variation within populations. While older youth performed significantly better on our measures of microevolution than younger youth, there were no significant differences between the four conditions.

In sum, our quantitative analysis indicated consistent learning outcomes for the DeepTree conditions for important concepts of macroevolution such as common descent and the ability to interpret phylogenetic tree diagrams. Given these results, our second objective was to understand how dyads' experiences interacting with DeepTree led to these learning outcomes. This paper provides a qualitative analysis of how dyads interacted with DeepTree and how the design mediates this interaction to support collaborative learning. The remainder of this paper focuses on two questions. First, how do dyads negotiate their moment-to-moment exploration of the exhibit? Second, how do dyads' make sense of evolutionary concepts through their interaction with one another and the tabletop exhibit?

In the following sections, we first describe our analytical framework and methods used to uncover patterns of interactions across the dyads. Then we provide four sample cases that exemplify the patterns we found. After this, we discuss how the design of DeepTree mediates this interaction in order to achieve learning outcomes. Finally, we discuss how the lessons of DeepTree can be generalized into design principles for multi-touch tabletops for supporting collaborative learning in museum environments.

Analytical framework

In order to begin the process of answering the questions outlined above, we adopted the methodological approach of *interaction analysis* (Jordan and Henderson 1995). Interaction analysis uses video as a primary data source and involves repeated viewing in order to provide an in-depth analysis of the interactions that shape thought and behavior through talk, nonverbal cues, and artifacts. Several grounding assumptions structured our analysis. First, as the dyads participating in our study are familiar with one another—being friends or siblings—we argue there is both a social consequence and pressure for them to work together in some way while interacting with the exhibit. As is commonly noted in studies of collaborative tabletop interaction (Dillenbourg and Evans 2011), their actions are not merely individual and internal, but either intentionally or inadvertently communicative as well. We do not assume these interactions are in lock step, so we pay close attention to how trouble arises in interaction and how dyads work to repair conflicts. Finally, we recognize the shifting and often fleeting nature of interaction, especially in free choice environments like museums. Therefore, following Price and Pontual Falcão (2011), we paid close attention to the temporality and periodicity of interactions on a micro-level. That is, we carefully attempted to determine the beginnings and endings of particular micro-interactions from the participants' point of view. So, the dyadic interactions are not treated as a single interaction, but the accumulation of many periods of interaction of various lengths of time.

Analysis of interaction

Our first analytical step was to create content logs—rough descriptions of the action with annotations of particularly compelling sections—of each dyad video. Three researchers then took a subset of ten randomly chosen dyads and individually logged each video in more depth. These logs contained empirical descriptions of action as well as initial conjectures to explain how the dyads negotiated their exploration of the exhibit. With these logs in hand, the three researchers watched the 10 selected videos and worked together to gradually come to consensus regarding the dynamics patterns of the participants' interactions. Through this process we progressively narrowed our analytical foci in several ways.

One of our refined analytical foci was the formulation and execution of each participant's goals. Goffman (1974) treats interaction as activity performed to accomplish goals, whether tacitly or explicitly. Multiple people in an interaction bring their own individual goals, but they also work together to form a definition of the situation that works to give the interaction coherence. Based on this we attempted to understand how dyads negotiated their individual goals in their interaction.

Jordan and Henderson (1994) emphasize that events have a structure and that a first part of understanding this structure is to uncover how the events begin and end. We therefore logged instances of interactions that represented the beginning and ending of goal negotiation sequences. We used both overt actions (e.g., one participant moving the other's hand in order to touch a different part of the screen) and verbal announcements of intentions (e.g., "Let's try this now") to define the beginning and ending of these sequences. These instances of goal negotiation occurred at varying levels of granularity and timescale. Some goals were independent and isolated (a few seconds long), while others consisted of several related sub-goals that played out over a minute or more. These characteristics made it untenable to simply decompose the video data into regular intervals (chunks) for a line-by-line analysis.

As we worked together to agree on instances of goal negotiation we developed the following definition: Each instance of goal negotiation began when one participant initiated a new action with the table. This initiation could be verbal (e.g., "let's go there"), gestural (e.g., pointing to an action button), or touch (e.g., actually tapping the button). An instance of goal negotiation ended when the initiating participant either abandoned the action or initiated a new and distinct action. During this time, the non-initiating youth could take up the initiating partner's action, attempt to initiate an alternative action, or remain passive.

In order to interpret the meaning of goal negotiations, we sought to understand what participants were attempting to accomplish and how their negotiation played out in interaction. This led us to assess instances of goal negotiation along two dimensions: the level of coordination between participants and the target of each participant's moment-to-moment actions with the table. These combine to represent the focus of their joint interaction. In our analysis, we paid special attention to the level of coordination between participants. While coordination is a spectrum with many intermediate levels, we found that determining whether there was high or low coordination was sufficient to reveal high-level patterns of interaction. Low coordination was evident when simultaneous actions on the table were in conflict. For example, when one child attempted to scroll through the tree while the other child tried to enlarge images of organisms. In contrast, high coordination occurred when two users' actions were directed at the same target and complemented one another. For example, when both children were working together to scroll through the tree, or when one child gestured toward an action button and the other child followed this lead to touch it. Coordination reflects the alignment of participants' goals.

In determining the target of each participant's action, we found it most useful to determine whether his or her goals were mechanical or conceptual in nature, in other words, whether an individual action on the table was concerned with interaction mechanics of using the table or with the conceptual content. For example, the act of shrinking and enlarging a few images seemingly at random would be seen as a mechanical goal. This means that the child's action had no target beyond the surface-level interaction with the table. Of course, the participant may have had some underlying conceptual motivation, but our categorizations are based only on those reasons that are apparent in observed behavior. If that same behavior of shrinking and enlarging images had been accompanied by a vocalized statement of intent—such as "Look how different these fish look from one another!"—then it would instead be viewed as a conceptual because the underlying behavior appears to concern biological concepts such as the physical appearance of organisms.

Based on our iterative analysis we derived four patterns of interactions. These patterns represent progressive levels of interactional complexity and vary both in the dimensions of level of coordination and target of action. It is important to note that both of these dimensions are meant to be descriptive and in no way prescriptive. The nature of dyadic interaction means that children will sometimes be highly coordinated and other times not. Productive interactions are not confined to one category or another (e.g., Marshall et al. 2009). Furthermore, the nature of interaction with a novel technology that encourages negotiation means that dyads will sometimes focus on conceptual goals and sometimes focus on mechanical goals—mechanical goals are essential for understanding how the interface works. Finally, we present these dimensions as analytical foci, not as a coding scheme. That is, we believe it is essential to provide these concepts as they helped guide us in the interpretation of our data (Hall 2000; Hammer and Berland 2014), and provided us with a shared vocabulary to describe the patterns of interaction that we uncovered.

After deriving an agreed upon description of four patterns of interaction, we selected four dyads as demonstrative cases of these patterns using purposeful, intensity sampling (Miles and Huberman 1994). These four cases were chosen because they clearly and richly express the qualities of their representative patterns. There were also clear differences in the level of social interaction of these four cases. As a crude measure, we looked at the total number of words spoken during each session and found that they were each separated from one another by roughly 200 words spoken. Dyad A spoke 309 words, Dyad B spoke 533 words, Dyad C spoke 719 words, and Dyad D spoke 895 words (see Table 2).

Table 2 Participant age and demographic information

Dyad	Pattern / Case	Words	Names	Age	Sex	Reported race/Ethnicity
A	Reactive	309	Anna	12	F	Asian American
			Diego	12	M	Asian American
B	Autonomous	533	Chloe	9	F	African American
			Braden	11	M	African American
C	Planning	719	Leo	13	M	White
			Hope	9	F	White
D	Contemplative	895	Gabrielle	12	F	Asian American
			Max	14	M	Asian American

Description of patterns of interaction

Based on our analysis, we have identified four repeating patterns—*reactive*, *autonomous*, *planning*, and *contemplated* (Fig. 3). These patterns do not necessarily describe a dyad's session as a whole, but rather smaller chains of events—a single dyad may employ one or more modes during their session. However, these patterns are distinct enough and occur often enough that describing them seems important to understand children's collaborative exploration of this kind of exhibit.

The reactive pattern

The first category, which we call the reactive pattern, is characterized by long strings of low coordination between the participants and a focus on mechanical goals. This was the most common pattern, particularly evident early in dyads' interactions as they attempted to understand how to use the exhibit. Interaction in this category was often driven by reciprocal reaction to partner actions on the table. We present the case of Diego and Anna as a typical example of this reactive pattern. During their interaction with the exhibit, Diego and Anna seldom spoke to one another—using only 309 words in their 10-min session. They also frequently seemed to be working at cross-purposes in their interaction as the following excerpt illustrates.

Time	Segment Markers	Actor	**Quote** or [*Action*]
[00:24.10]	Begin	Anna	[Anna reaches for the table with her right hand]
		Diego	[Diego moves his right hand beneath Anna's hand, between it and the table.]
[00:26.17]		Diego	[Diego enlarges an image on the table with his thumb and forefinger.]
[00:28.11]	End	Anna	[Looking at the image Diego has enlarged] **I don't know what that is.** [Anna moves her right hand away from Diego's and touches the background of the display, causing the tree to zoom slightly.]
[00:30.06]	Begin	Anna	[Anna again touching the background to scroll the tree.] **Oh hey look.**
		Diego	[Looking at a different area of the table than Anna, Diego touches the table and attempts to scroll through the tree.]
[00:32.14]	End	Anna	[Anna also tries to scroll a different part of the tree. The tree moves very little due to interfering input.]
[00:33.12]	Begin	Diego Anna	[Diego and Anna simultaneously move their left hands toward the table.]
[00:34.04]		Diego	[Diego touches the table with both hands and uses a spreading motion to zoom into the tree.]
[00.35.11]		Anna	[Anna moves her hands towards the table.] **Wait wait wait.** [Anna uses her right hand to push Diego's hand away from the table.]
		Diego Anna	[As Anna moves her hand back to the table, Diego does the same. Anna touches the table, but nothing happens as Diego's movement is in conflict with her own.]
[00:37.20]		Anna	[Anna firmly grabs Diego's hand and holds it away from the table.]
[00:40.04]		Diego	[As soon as she lets go, Diego touches the table again.]
[00:41.17]	End	Anna Diego	[Anna touches the table with both hands and Diego moves his hands away from the screen.]

This exchange typifies the reactive pattern. In the beginning of this segment, Anna reaches toward the table. However, Diego reacts to her action by moving his hand under her hand to block her touch of the table. Anna gives an obvious signal of her intention, which Diego seems to reject and instead implements his own goal (enlarging the image). Anna watches this for a moment and

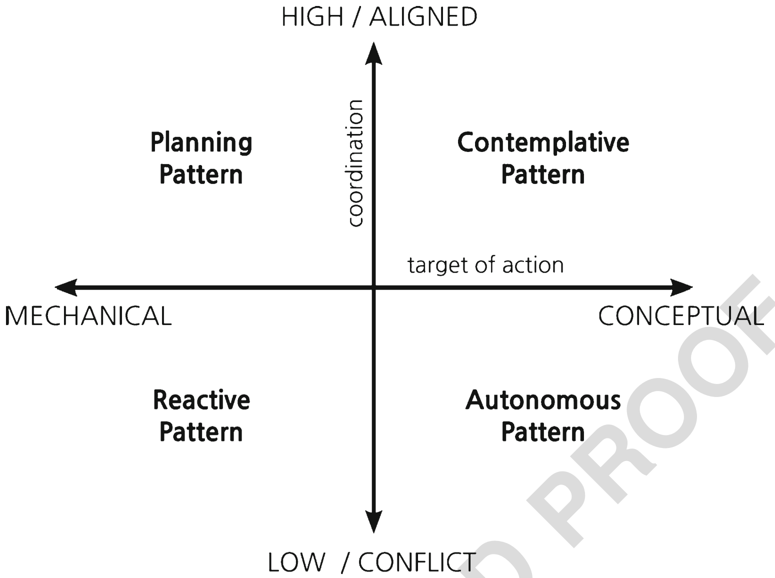

Fig. 3 Four interaction patterns along two dimensions: target of action and coordination

then says, “I don’t know what that is.” This statement can be interpreted in a few ways. Anna might simply be expressing her lack of knowledge about the species in the image, but her actions immediately after this statement also suggest a rejection of Diego’s goal. By immediately disengaging from Diego’s actions, and starting her own, she appears to be reacting to Diego usurpation of her initial action with a dismissal of her own. Here Anna and Diego have very little coordination, and their interaction is driven by reciprocal reactions in an effort to control the table.

After this opening section, Anna and Diego work independently for a few moments. Then Anna says, “Oh hey look.” This mild imperative statement attempts to draw Diego’s attention and could be interpreted as an attempt to repair trouble in their collaborative interaction. In other words, she sees their lack of coordination and tries to re-coordinate with Diego, albeit around her goal rather than his. Diego does not react to this statement and continues his previous actions. Anna does the same, and their independent actions cancel each other out as they each try to make the tree move in their desired way with little effect. The lack of coordination impedes their mechanical goals.

This pattern continues as both Anna and Diego try to use the table without coordinating their efforts (Time: [00:33.12] to [00.35.11]). Anna again uses an imperative statement (“Wait wait wait”), but this time it is a stronger instruction. Anna does not wait for Diego’s reaction and forces his hand away from the table. This only lasts a moment as Diego again starts touching the table. They spend the remainder of this exchange attempting to make the tree move based on their independent goals, which seems unsatisfying for both of them.

What this case demonstrates is a pattern of interaction with little coordination and a focus mostly on mechanical goals involved in making the table react as intended. The participants may have had conceptual goals, but they are not evident in the data. This is an example of divergent goals that clash and require negotiation between the actors. This negotiation takes the form of active attempts at repair along with cursory dismissals. Similar patterns were cited in Pontual Falcão and Price’s (2011) systematic analysis of interference in students’ interaction with tangible manipulatives on a digital tabletop. Throughout Diego and Anna’s interaction we see a cycle of parallel goals that conflict when both require simultaneous use of the table. There are fleeting moments of negotiations wherein one goal overrides the other, only to start the cycle anew.

One important thing to point out is that this segment of interaction was not as fruitless as it may first appear. Even though Anna and Diego are largely in conflict, they are watching one another's action intently and learning—at least at a mechanical level—how the table exhibit works. Anna's actions around 30 s into the session causes them both to realize that the tree can be panned and zoomed by touching the background of the screen. This is consistent with Pontual Falcão and Price's (2011) observations that instances of interference between participants can lead to unexpected revelations about interface functionality or even about target learning objectives. As we will discuss below, these reciprocal conflicting actions eventually led to conceptual-level discoveries.

The autonomous pattern

Similar to the reactive pattern, the autonomous pattern is characterized by low coordination between the table users. However, whereas the reactive pattern involves mostly back-and-forth conflicts around mechanical goals, the autonomous pattern is comprised of segments in which one child adopts a conceptual goal while the other either stays with mechanical goals or detaches from the interaction entirely. The autonomous pattern was fairly common across dyads. To demonstrate this pattern, we present the case of siblings Chloe and Braden. This dyad was frequently in the reactive pattern, but on several occasions appears to fit the autonomous pattern as illustrated in the following excerpt[1]:

Time	Segment Markers	Actor	**Quote** or [*Action*]
[01:20.04]	Begin	Chloe Braden	[Chloe and Braden both enlarge a text box on the "Modern Human" branch of the tree. After they have zoomed in on the box, they move their hands away from the screen simultaneously.]
[01:22.18]		Chloe	[*Reading.*] Humans are (1.0) re::lat::ed to chimps and gorillas–
[01:25.27]		Braden	[*Interjecting.*] –**Homo sapiens**
[01:31.26]	End	Chloe	[*Continuing reading.*] –Unlike other living apes.
		Braden	[*Interjecting.*] –**Modern humans** –Humans. Really?
[01:31.26]	Begin	Braden	[Braden uses his right index finger to move the tree causing the text box to move off screen.]
		Chloe	**Primates have a voice** [Chloe uses her right index finger and thumb to pull the text box back on screen and holds it there.] **(1.2) box:es that allow speech**
[01:36.07]	End	Chloe	[Chloe still holds her finger on the screen and reading. Braden taps the screen several times.]
[01:37.21]	Begin	Braden	[Braden pushes Chloe's hand away from the screen.]
		Chloe	Human's also have bra:::ins (.) that are much–
[01:39.18]		Braden	[Braden touches the screen and zooms the tree out.] [Still attempting to read]–**longer than**
[01.40.25]		Chloe	I can't r:::ead [Chloe zooms back in to the text box.] (1.1) than other apes. These traits have hoped-helped–
		Braden	–Seriously?
		Chloe	–create the tools, lang::uages, a::nd (0.5) cultures.
[00:37.20]	End	Braden	[Once Chloe stops reading, Braden zooms back out to the larger tree.]

[1] Note: In transcribed excerpts, numbers in rounded parentheses represent pauses in seconds (e.g., (0.7) connotes a pause of 7 tenths of a seconds), parentheses surrounding a period represent a micro-pause, and colons within words (e.g., re::lat::ed) describe degrees of elongation in speech.

This exchange begins with Chloe and Braden being fairly well coordinated. They work together to fly to the "Modern Humans" branch of the tree and enlarge the associated text box. As Chloe reads the text, Braden anticipates her having trouble with the term "Homo sapiens" so interjects to read it for her. Chloe continues to read. When she reaches the word "humans", Braden interrupts again to repeat the word and add the question, "Really?" Unlike his previous interjection, this one does not seem to be attempting to help, and the tone of his question suggests frustration. This interpretation is corroborated when Braden then disengages from Chloe and tries to move the text box off screen. Chloe attempts to keep the box in place, so that she can continue reading. Braden then tries to tap and move the tree several times. This shows that they are no longer well coordinated, and Braden has moved on from their previously shared goal to initiate a new goal. For her part, Chloe is still trying to read and understand the text, which can be considered a conceptual goal.

This pattern of interaction continues as Braden pushes Chloe's hand away from the screen while she reads the text. Braden tries to zoom out from the text, but Chloe zooms back in so that she can continue reading. Braden voices his frustration by saying "Seriously?" in a tone that suggests exasperation. This can be interpreted as his frustration with Chloe's reading ability. When Chloe stops reading, Braden takes over the table to zoom the around the tree.

In this case we see an example of how the autonomous pattern of interaction can play out. During these periods of time, the child with the conceptual goal dominates the interaction. Chloe is adamant about reading the text and does not allow Braden to alter her task. In this case, their goals are independent, but Chloe's conceptual goal takes precedent over Braden's mechanical goal. And, while there is certainly conflict between their actions of the table, more often than not the struggle for control is more like turn taking than the simultaneous use seen in the reactive pattern.

The planning pattern

Where the autonomous pattern often contains moments of attempted repair when dyads recognize periods of low coordination, the planning pattern can be seen as dyads actively articulating their goals through speech or gesture in order to attain high coordination. Goal negotiation in the planning pattern generally involves less independent interaction than the reactive or autonomous patterns. The planning pattern is defined by strings of high coordination, generally beginning with mechanical goals that often lead to conceptual goals. This can be seen in the case of Leo and Hope:

Time	Segment Markers	Actor	**Quote** or [*Action*]
[00:36.15]	Begin	Hope Leo	[Hope reaches her right hand toward the table and pauses for 0.8 s. She then taps the START button. Leo looks right toward the ACTION button and lightly taps it.]
[00:42.15]		Leo	[Leo and Hope both look at the center of the table. Hope's hand is hovering above the surface.] **So, uh, wh-where do you want to start?**
[00:44.17]		Hope	**Uh. Le::t's start by–** [Hope moves her hand from left to right above the screen.]
		Leo	[Leo moves his hand next to Hope's and follows along with her movements.]
[00:48.07]		Hope	**-Getting right** [Hope and Leo point spot on the table and tap the screen simultaneously] **(2.2) there? or like that.**
[00:53.08]	End	Leo	That's pretty cool.
[00:54.22]	Begin	Hope	[Hope moves an image to the center of the screen.] **Let's do this.** [As she says this, she taps the image.]

[00:56:28]		Leo Hope	[Leo and Hope pause for a few seconds. When Hope's tap does not cause the table to react, they both move their hand forward to touch it again. Together they hold on the image while it zooms]
[01:01:46]	End	Hope	[Hope removes her finger. She and Leo both lean in toward the table. Hope inaudibly reads the text on the screen]
[01:12.35]	Begin	Leo	**Wow.** [Leo reaches toward the table.]
[01:13.25]		Hope	Oh my gosh.
		Leo	[Leo pulls his hand back.]
		Hope	Two thousand (0.3) five hundred and tw:enty degrees Fahrenheit temperatures
[01:21.05]	End	Leo	[Leo starts to scroll on another part of the screen.]

This exchange occurs at the very beginning of Leo and Hope's interaction with the table. Hope begins the action by touching the start button. After the tree appears, both Leo and Hope look at it momentarily and Hope hovers her hand above the tree. Leo then asks Hope where she wants to start, signaling that their action will be mutual. When they begin their actions, their movements are synchronized—Leo follows Hope's hand as they both touch the screen in unison. This is highly coordinated action that allows them to align their goals.

As they begin to explore the table mechanics, all of their actions remain coordinated. They touch the screen at the same time, lean back together, pause simultaneously, and hold images together to make them zoom. At first these interactions seem to reflect mechanical goals. As would be expected, at the beginning of interaction they are working to understand how the table works. Eventually their mutual action leads them to a surprising concept, and they both vocalize their responses to one another.

In this short example, we can see how in the planning pattern dyads decide together what they should do, resulting in higher levels of coordination. While their goals begin as mechanical, their coordinated action allows them to find and explore conceptual goals together. In the planning pattern, we also see more moments of goals being actively articulated between participants—often in response to a direction from the table, such as a "touch here" label appearing over the action button. Overall, the planning pattern involves higher levels of talk and purposeful coordination. The planning pattern was fairly common in the beginning of table use as visitors negotiate their first actions.

The contemplative pattern

The final pattern was also the least common in the videos that we reviewed in depth. During their interactions, dyads occasionally vocalized explicit overarching goals for their explorations and then negotiated or refined these goals through verbal exchange. We call this the contemplative pattern. In the planning pattern we saw a dyad vocalize immediate goals. The contemplative pattern is similar to the planning pattern but goes beyond moment-to-moment goals and immediate action. Instead it involves setting higher-level, longer-term goals that result in more complex interaction. This pattern can be identified by long strings of high coordination and conceptual goals, with occasional moments of low coordination where refinements to the overarching goal are negotiated. The best illustration of the contemplative pattern is the dyad of Gabrielle and Max. Less than two minutes into their interaction with the table Gabrielle says, "Let's try…" then glances at the pulsating action button, points at it and finishes, "let's go to things you can do." Max then presses the button and chooses the relate function (Fig. 3). At this point the interaction appears very similar to the planning pattern. Gabrielle then says, "Ok, relating to…? What could we relate to?" In this exchange Gabrielle quickly shifts the focus from mechanical to conceptual goals, while, at the same time, establishing an overarching purpose to the activity. With this overarching goal agreed upon, they then had to negotiate the shorter-term goals of which specific species to compare in each iteration of their experiment. A typical negotiation follows:

Time	Segment Markers	Actor	**Quote** or [*Action*]
[06:59.16]	Begin	Gabrielle	[Gabrielle and Max lean back from the table. Gabrielle moves her right arm across Max's body and points at the SPECIES WHEEL.] **Maybe, let's (0.2) relate to something else. Can we?**
		Max	[Touches the SPECIES WHEEL.] **Yeah.**
[07:04.11]		Gabrielle	Let's tr:::y (0.3) [*Gabrielle turns to look at Max. Max is scrolling through the SPECIES WHEEL.*] Maybe something that you would think would be the total opposite. See, if, some-somewhere that you think would be the total opposite that you think would never relate.
		Max	So something with four legs, or no legs.
		Gabrielle	Yeah
		Max	[*Still scrolling*] So let's try a fish.
[07:19.20]		Gabrielle	A:gainst a four-legged animal (1.2) ok.
		Max	[Scrolls through the SPECIES WHEEL while Gabrielle watches him.]
[07:28.08]		Max	**Try- I want to try** [Drags the MODERN HUMANS image into the RELATE box] **humans**
		Gabrielle	Oh yeah. Ok.
		Max	[Scrolling through the SPECIES WHEEL again] **And I want fish.** [Scrolling past other taxa on the SPECIES WHEEL.] **Amphibians, reptiles, dinosaurs–**
		Gabrielle	–I think it would be interesting to look at dinosaurs–
		Max	–birds–
		Gabrielle	–So let's just go to them
[07:40.17]		Max	I want to do a fish. Let's just do clown fish, 'cause that's just
		Gabrielle	Yeah, they're kind of regular. O::k.
[07:46:08]		Max Gabrielle	[Both Max and Gabrielle lean forward over the table to watch as the tree zooms out and highlights the shared traits of humans and clown fish.]
[07:51.23]		Max	[*Holding out two fingers.*] Humans have two legs. They have a brain.
		Gabrielle	[*Looking at Max.*] Do fish have brains?
		Max	I'm pretty sure. (2.3) Of some sort.
[08:00.01]		Gabrielle	[Gabrielle reaches toward the table and points. The tree is still moving out to reveal the relationship.]
		Max	[*Looking at the tree.*] Oh wow. They're connect:::ed. Oh wow.
[08:06.54]		Max	[Leaning closer to the table.] **Oh wow! They're actually far apart, see?** [Max points at the shared traits in turn, counting them off. Gabrielle points with him and silently mouths the numbers] **One, two, three, four. Wow.**

At the beginning of this segment Gabrielle and Max lean back from the table as they finish comparing the relationship between two species. Gabrielle takes up this signal to suggest that they try another two species. Here Gabrielle is initiating a new goal, but one that is nested in already agreed upon activity. Next, Gabrielle suggests a possible point of comparison that she seems to think will have surprising results (something that they would think would be opposites). Max agrees and proposes a more specific comparison (fours legs versus no legs) and then offers a fish as the type of animal with no legs.

Gabrielle and Max then scroll through the species wheel to find what species in particular they want to compare. After seeing humans on the wheel, Max says he wants to look at how they relate to another species. This is the introduction of a slightly new goal. They had agreed to compare a four-legged animal to a no-legged animal, and humans obviously did not fit either category. Despite this, Gabrielle quickly agrees. In the reactive or autonomous goal, this sort of goal shifting might result in conflict or disengagement. However, Gabrielle and Max have already agreed on an overarching goal of comparison, and Max's independent introduction of humans still fits this goal. So the activity is not disrupted and this new sub-goal is accepted with little conflict. Pontual Falcão and Price (2011) note similar instances in which interference can lead to "integration-oriented" consensus building.

For the remainder of this segment, Max and Gabrielle negotiate the details of the current comparison they want to make. Max lists possible types of animals from the species wheel. Gabrielle is interested in using dinosaurs, but Max goes back to his original suggestion of a fish, and selects Clownfish. Gabrielle accepts this and they lean in together to watch the comparison unfold. Throughout this interaction, Gabrielle and Max are highly coordinated. Even during disagreements on details, they still maintain the general agreement on the activity, so they do not have to struggle for control.

This agreement also allows them to explore more conceptual goals. Gabrielle wonders aloud whether fish have brains. Max shows surprise first that fish and humans are connected through shared ancestry, and then how distant this relationship is. They even count the branches of divergence on the tree. This exploration eventually leads them to suggest new comparisons that start the cycle of negotiation over again.

These cycles of negotiation guided by an agreed upon overarching goal defines the contemplative pattern. The back-and-forth acceptance and refinement of goals allows Gabrielle and Max to demonstrate mutual understanding that leads to engagement in the new task. Setting higher order goals in the beginning guided their moment-by-moment exploration and allowed it to run smoothly. Having an overarching structure in place puts them both on the same page, so the possible space of sub-goals is constrained and easier to refer back to when small disagreements arise.

While the reactive and autonomous patterns generally seemed to result in undirected exploration of the table, the contemplative pattern appears to lend itself to experimentation. In the above exchange, Gabrielle's first suggestion presents an implicit hypothesis—opposites are not related—that they work together to test. They discover that species they think are opposites still share common ancestors.

Supporting learning across the patterns of interaction

The four patterns of interaction described above lead us to examine how DeepTree supports collaborative learning in each situation. Our claim is that these observations represent general patterns associated with interactive tabletop museum exhibits, particularly those involving visualizations of scientific datasets. These patterns also appear hierarchical, with the most common and least collaborative (reactive) on the bottom, and the most rare and most conceptual (contemplative) at the top. Based on these descriptions it might seem that designers could simply choose a target interactional pattern and aim to encourage it. However, as mentioned previously, successful free-choice learning experiences provide multiple entry points to challenge learners at different levels. All of these patterns might play out when an interactive tabletop is placed in a museum. The challenge of design is to support learning through each pattern. With this in mind, we turn to a discussion of how to support learning in these interactions using examples of both successful and unsuccessful learning supports. While the specific examples come from a single design, we believe that these observations are general enough to help understand and support learning through similar experiences that encourage collocated collaboration.

Encouraging "what if?" questions

We first consider the contemplative pattern. In the example presented above, we see how Max and Gabrielle offered ideas to one another about species to compare, leading to their discovery about how fish and humans are related. Throughout their interactions Max and Gabrielle repeated this pattern—discussing ideas, refining comparisons, and discovering new information. While we believe that it is important to encourage this kind of interaction, it was nonetheless rare in our data. Therefore, we want to understand how best to support and encourage learning for those participants who do enter into the contemplative pattern of interaction.

Most instances of the contemplative pattern occurred around the relate function. The idea of relating two species seemed to help dyads establish an overarching conceptual goal while the large number of species that could be compared seemed to encourage repeated testing of hypotheses about how different species are related. In essence, the relate function provides a space that encourages asking "what if" style questions.

In Max and Gabrielle's interaction we see many variations on what-if questions. Gabrielle's suggestion that they test the relationship between two species "that you think would be the total opposite that you think would never relate" is a good example. With this statement he infers that things that look like very different are not closely related, and he implicitly wonders whether this is the case. In our data, what-if questions drive hypothesis testing, encourage the negotiation of sub-goals, and allow for a deeper exploration of content.

The relate function is one example of a way to support what-if explorations that is well suited for understanding shared ancestry. Other information-rich interactive tabletops must find their own hooks for supporting and encouraging learners to ask and experiment with what-if questions. In creating these hooks, there are three design principles that seem important. First, the functionality should be accessible to learners. The relate function in DeepTree builds on learners' intuitive understandings of relationships (for example family relationships) and expands it to phylogenetic relationships. Second, the functionality should be interesting or surprising to learners. In our case, the idea that vastly different kinds of species (such as humans and bananas) are related at all, comes as something of a surprise to many visitors. This initial surprise can then encourage the repeated exploration of the dataset. Finally, the answer to what-if questions should come from the underlying dataset itself. For example, Roberts et al. (2014) exhibit based on US Census data explores questions about population shifts based on a number of demographic variables. Visitors can ask questions and see the answers in visualized in the geo-spatial information. Similarly, with DeepTree, information on phylogenetic relationships is extracted from the underlying biological datasets and visualized on the tabletop display.

Imparting a sense of discovering something cool

As we have mentioned, the contemplative pattern is just one rare entry point into conceptual exploration. How then can we support learning in the most common, and seemingly least fruitful interactions, the reactive pattern? The reactive pattern emerges when the dyads both try to use the table for different simultaneous and largely mechanical goals. In many ways this pattern is inevitable. Using a novel representation like DeepTree that invites simultaneous multi-user input involves a certain learning curve as visitors become familiar with the mechanics involved with making the table function. The danger is that users will never move beyond the mechanical stage to explore the target concepts.

In order to avoid this, one strategy is to incorporate gentle guidance (Humphrey and Gutwill 2005) that naturally pulls users towards interesting content. In DeepTree we have built in a "fly-through" mechanic that launches when a user holds down an image of a species. The idea behind the fly-through is that it should be easy (or even accidental) to initiate this effect. So, when Anna and Diego are both trying to tap and scroll through the tree, Anna rests her finger long enough on an image that the fly-through is launched for a brief moment. But this is long enough for them to get the idea and touch and hold the image a second time, watching as the tree zoomed past hundreds of branches to find the location of the target species. Anna and Diego's reactions are vocalized affective response, in which both say "wow!" Most dyads voice similar affective responses, such as "Wow, how far is this?", "Dang, that was a lot!", and "Whoa! We're going deep in the trees!" This affective response characterizes "discovering something cool".

In reactive cases where little headway is being made toward content, mechanics that are easily launched can impart a sense that there is something cool to be discovered in the information space. The fly-through is one example of such a mechanic. For other information spaces, it is not difficult to imagine similar features that can be easily or accidentally initiated, maintain a sense of discovery on the part of the user, provoke an affective response, and lead to conceptual goals.

Shifting from mechanical to conceptual

In addition to imparting a sense of discovery, the fly-through mechanic was intended to shift the learners' mechanical goals to conceptual goals. Mechanical goals are necessary and useful in and of themselves, but the goal of the exhibit is to support learning around concepts in evolution. While the fly-through mechanic was successful in supporting some content learning, it often failed to shift the users to conceptual goals. Frequently, the dyads reverted back to reactive interactions, only to rediscover the fly-through again. Likewise, dyads that displayed a planning pattern of interaction often failed to shift toward conceptual goals. As we saw in the case of Leo and Hope, planning often did lead to conceptual content, but it was usually fleeting. Again, this is not necessarily problematic, however, DeepTree could have done a better job of nudging users towards conceptual goals. One potential improvement would be to have the fly through take users to a more engaging end point. Currently users see an image and a bit of text about the target species. In contrast, the end point of the relate function appeared to be much more engaging. Users see a new screen with a simplified training tree (Fig. 2, bottom), several images, short video segments, and an opportunity to go deeper. Providing a similar end point for the fly through might be a more effective way to shift visitors towards conceptual goals.

Providing "personal" objects

Perhaps the most problematic pattern from a collaborative learning standpoint is the autonomous pattern. This is because the autonomous pattern involves conflicts that can result in one user completely detaching from the activity or disrupting the learning of other users. As we discussed in the introduction, one of our main design goals was to encourage collaboration as multiple users interact with the tree. The idea behind this goal was to prevent a "single input" exhibit in which only one person could drive the experience at a time. This is not to say that single-input experiences cannot be effective (e.g., Scott et al. 2003), but it does not appear to be a natural way to treat large multi-touch displays. In order to achieve this, we designed DeepTree to average multiple touches on the tree to their geometric center. This was obviously a tradeoff on our part to remove user independence for the sake of collaboration.

Unfortunately, one result of this choice is that some dyads get stuck in the autonomous pattern. In our example, Chloe is trying to read a text box in order to learn more about modern humans, but her brother, Braden, abandons this goal and tries to scroll away from the modern human branch. This has the effect of moving the text box while Chloe is reading it, possibly impacting her ability to understand the content. In this instance, the collaboration that the tree encourages backfires so that neither user has an optimum learning experience.

One way to address this problem might be to provide users with “personal objects” for independent action on the tabletop. Similar ideas have been proposed for tabletop use in classrooms as well (Higgins et al. 2011). For example, DeepTree might have allowed Chloe to “save” the text box she was reading, either by keeping it in place as Braden scrolled away, or letting her drag it to a “safe location” on the screen. If this were the case, then Chloe might have been able to continue reading the text uninterrupted while Braden continued to explore the tree. If such a design feature existed, it would add flexibility to support localized moments of independence in an otherwise collaborative environment.

Discussion

To characterize the challenge of designing an interactive museum experience based on the visualization of large scientific datasets, we have found the analogy of a tandem kayak to be useful. Suchman (2007) uses an analogy of a person confronting river rapids in a canoe as a way to illustrate the concepts of *planning* and *situated action*. We extend this analogy to consider dyads interacting with the DeepTree and other interactive exhibits. Imagine two inexperienced paddlers in a tandem kayak floating in the middle of a large body of water. Each person has a paddle that can be used to immediate effect—move the paddle in the water and the boat moves in response, if not necessarily in a predictable way. Because both kayakers are inexperienced, they are still learning how to most effectively steer the boat in a desired and consistent direction. And, since both paddlers are interacting at the same time, coordination is required. This is complicated by the fact that it can be difficult to figure out how each person is causing the boat to move if both partners are paddling at the same time. So, the kayakers must simultaneously figure out how to use the paddles (the interface), decide on a mutually agreeable direction (a goal), and figure out how to coordinate actions (negotiation and reciprocal learning). Inevitably, novice paddlers spend a period of time splashing around and not making much progress in any discernable direction. We hope that the relationship between the tandem kayak and dyadic interaction with tabletop exhibits is clear. The body of water corresponds to the information space that visitors explore with the *DeepTree* exhibit. The paddlers are the users themselves, and the paddles are their fingers, hands, and arms (the input devices). The analogy illustrates coordination and the difference between conceptual and mechanical goals. Mechanical goals relate to how to use paddles to move the kayak in a desired direction. Whether or not that direction has been agreed upon or articulated by the paddlers reflects the level of coordination. Conceptual goals, on the other hand, relate to using the kayak to experience the surrounding terrain.

With this analogy in mind, let us rethink the relationship between design, interaction, and meaning making. First imagine an information space as the open body of water. A completely open information space allows for free form exploration that, while appropriate for scientists, may be unlikely to result in any of the conceptual encounters that we have in mind for learners, especially for short periods of engagement. So, like the open body of water, the information space needs boundaries. Effective design shapes the information space by providing landmarks, banks, and a gentle but persistent current. These landmarks are the collection of appealing and strategically placed features that invite attention in a design. Earlier we mentioned that Diego and Anna are often reactive in their goal negotiation. They are like two rowers each paddling in their own direction, at their own speed, and with their own intentions. This could result in a great deal of effort with no discernible outcome. However, because opposing movements on the table cancel each other out, the table forces their goals into conflict, requiring them to negotiate and coordinate their efforts. In fact, Diego and Anna's independent movements result in the table zooming. While this was not intended by either of them, the result causes them to both hold the image to fly through the tree and have the *wow* moment discussed earlier. In this instance, the exhibit design guided their exploration and, in so doing, allowed them to spontaneously find and make meaning out of a "landmark"—the fly-through that portrays biodiversity. So, for learners in a reactive pattern, the table guides their exploration and, in effect, sends them toward interesting features of the exhibit—just as the river's current pulls rowers past interesting viewpoints downstream. In other words, we can view the triadic relationships between design, interaction, and meaning making as analogy to the relationship between the river, the rowers, and the landmarks. So, how does analogy help us as designers?

In our analysis we found two patterns of interaction—reactive and autonomous—that could be considered undesirable at first blush. They are both defined by a lack of coordination and focus largely on mechanical rather than conceptual goals. However, we provided qualitative evidence that these patterns still result in some level of understanding of the evolutionary concepts embedded in the design. The design feature that allowed this to happen is the "fly-though," which is triggered during surface-level interactions with the tree. So, even if the paddlers never coordinated their actions, or if they are not interested in most of the landmarks, the flow of the river can get them to meaningful features that might have seemed initially unappealing. This happens in a way that preserves the visitors' sense of discovery. In other words, it is the actions of the dyad that trigger this event, even when this action is uncoordinated.

What about dyads who adopt the planning and contemplative interaction patterns? As previously discussed, Gabrielle and Max explicitly articulated higher-level goals that drove their moment-by-moment interaction with the exhibit. This dyad can be viewed as tandem paddlers who are more in harmony in terms of the direction they wish to pursue (even if they are still learning how to paddle more effectively). They work together to explore and experiment with the exhibit, directed by their well-articulated goals. But, just as with the discordant rowers, the exhibit is not merely an inert tool. Though Gabrielle and Max control the direction of their kayak, the current of the river brings them to their goal more rapidly than they would have achieved on their own. More contemplative dyads, such as Gabrielle and Max, quickly move past the surface level, and the exhibit guides them to a feature, such as the relate function, that allows them to dive more deeply into the content and construct richer understandings. The role of the design here is to provide a tool (the relate function) that adequately supports in-depth interactions of visitors who have already moved past surface-level interactions.

Conclusion

The goal of this study is three-fold. First, we sought to understand how dyads negotiate their moment-to-moment interaction with a visualization of large amounts of scientific data presented on a large interactive display. We propose a two-dimensional categorization of interaction that reveals four distinct patterns—reactive, autonomous, planning, and contemplative. Next, we describe the types of meaning making resulting from these interactions. Meaning making took many forms, including drawing connections between the exhibit and prior experience and spontaneously discovering exhibit features. Dyads also extracted meaning through sustained conceptual engagement framed by their own overarching goals. Two prominent forms of meaning making were the *wow* moment and what-if questions. The *wow* moment was a pervasive feature found in many of the dyadic interactions, which involved the "fly-though" mechanic of the design, creating a sense of awe at the sheer immensity of the tree of life. What-if questions involved instances in which dyads pursued experimented together through the use of the relate function.

Early in this paper we discussed the difficulties of learning about evolution, particularly in informal environments such as museums where visitors have freedom to interact in any way that appeals to them. In free choice environments it is often less important to control interaction than it is to provide useful entry points and pathways for meaning making. By understanding the various patterns of interaction that might take place with a multi-user learning environment, we can design tools that provide many paths to meaning making. Therefore, our kayak analogy frames design as facilitating meaning making within each pattern of interaction. In other words, we argue that designers of learning environments should be aware of, and embrace diverse patterns of interaction. The goal then is to carefully select the details of content that can most faithfully be embedded in the design to encourage meaning making at all levels of interaction.

In developing this framework of interaction and meaning making, our intent is to generalize beyond this particular exhibit and content area. We believe that interactive exhibits that invite groups to explore large information spaces will become increasingly common in the years to come. We hope this work contributes to future design and research in this area of computer-supported collaborative learning.

References

Allen, S. (2004). Designs for learning: Studying science museum exhibits that do more than entertain. *Science Education, 88*(1), 17–S33.

Allen, S., & Gutwill, J. (2004). Designing with multiple interactives: Five common pitfalls. *Curator: The Museum Journal, 47*(2), 199–212.

Antle, A. N., Tanenbaum, J., Seaborn K., Bevans, A., & Wang, S. (2011). Futura: Design for collaborative learning and game play on a multi-touch digital tabletop. In *Proceedings of Conference on Tangible, Embedded and Embodied Interaction (TEI'11)* (pp. 93–100). ACM Press.

Ash, D. (2004). How families use questions at dioramas: Ideas for exhibit design. *Curator: The Museum Journal, 47*(1), 84–100.

Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree-thinking challenge. *Science, 310*, 979–980.

Block, F., Horn, M., Phillips, B. C., Diamond, J., Evans, M., & Shen, C. (2012). The DeepTree exhibit: Visualizing the tree of life to facilitate informal earning. *IEEE Transactions on Visualization and Computer Graphics (TVCG), 18*(12), 2789–2798.

Catley, K. M., & Novick, L. R. (2008). Seeing the wood for the tree: An analysis of evolutionary diagrams in biology textbooks. *Bioscience, 58*(10), 976–987.

Crowley, K., Callanan, M. A., Jipson, J. L., Galco, J., Topping, K., & Shrager, J. (2001). Shared scientific thinking in everyday parent–child activity. *Science Education, 85*(6), 712–732.

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

Eberbach, C., & Crowley, K. (2005). From living to virtual: Learning from museum objects. *Curator: The Museum Journal, 48*(3), 317–338.

Falk, J. H. (2009). Identity and the museum visitor experience. Left Coast Press.

Falk, J. H., & Dierking, L. D. (2000). Learning from museums: Visitor experiences and the making of meaning. Altamira Press.

Falk, J., & Storksdieck, M. (2005). Using the contextual model of learning to understand visitor learning from a science center exhibition. *Science Education, 89*(5), 744–778.

Fleck, R., Rogers, Y., Yuill, N., Marshall, P., Carr, A., Rick, J., & Bonnett, V. (2009). Actions speak loudly with words: Unpacking collaboration around the table. In *Proc. interactive tabletops and surfaces ITS'09* (pp. 189–196). ACM Press.

Gregory, R. T. (2008). Understanding evolutionary trees. *Evolution Education and Outreach, 1*, 121–137.

Hall, R. (2000). *Video recording as theory. Handbook of research design in mathematics and science education* (pp. 647–664).

Hammer, D., & Berland, L. K. (2014). Confusing claims for data: A critique of common practices for presenting qualitative research on learning. *The Journal of the Learning Sciences, 23*(1), 37–46.

Higgins, S. E., Mercier, E., Burd, E., & Hatch, A. (2011). Multi-touch tables and the relationship with collaborative classroom pedagogies: A synthetic review. *International Journal of Computer-Supported Collaborative Learning, 6*(4), 515–538.

Hinrichs, U., & Carpendale, S. (2011). Gestures in the wild: Studying multi-touch gesture sequences on interactive tabletop exhibits. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 3023–3032). ACM.

Horn, M., Atrash Leong, Z., Block, F., Diamond, J., Evans, E. M., Phillips, B., & Shen, C. (2012, May). Of BATs and APEs: An interactive tabletop game for natural history museums. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2059–2068). ACM.

Horn, M. S., Phillips, B., Evans, E. M., Block, F., Diamond, J., & Shen, C. (Under Review). Bringing "big data" to the table: Learning science in museums through an information visualization. *Manuscript submitted for review.*

Hornecker, E. (2008, October). "I don't understand it either, but it is cool"-visitor interactions with a multi-touch table in a museum. In *Horizontal interactive human computer systems, 2008. TABLETOP 2008. 3rd IEEE International Workshop on* (pp. 113–120). IEEE.

Humphrey, T., & Gutwill, J. P. (2005). *Fostering active prolonged engagement: The art of creating APE exhibits.* San Francisco: Left Coast Press.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *The Journal of the Learning Sciences, 4*(1), 39–103.

Louw, M., & Crowley, K. (2013). New ways of looking and learning in natural history museums: The use of gigapixel imaging to bring science and publics together. *Curator: The Museum Journal, 56*(1), 87–104.

Ma, J., Liao, I., Ma, K. L., & Frazier, J. (2012). Living liquid: Design and evaluation of an exploratory visualization tool for museum visitors. *IEEE Transactions on Visualization and Computer Graphics, 18* (12), 2799–2808.

MacDonald, T., & Wiley, E. O. (2010). Communicating phylogeny: evolutionary tree diagrams in museums. *Evolution: Education and Outreach,* 1–15.

Marshall, P., Fleck, R., Harris, A., Rick, J., Hornecker, E., Rogers, Y., Yuill, N., & Dalton, N. S. (2009). Fighting for control: Children's embodied interactions when using physical and digital representations. In *Proc. ACM conference on human factors in computing systems, CHI'09* (pp. 2149–2152). ACM Press.

Matuk, C. F., & Uttal, D. H. (2012). Narrative spaces in the representation and understanding of evolution. In K. Rosengren et al. (Eds.), *Evolution challenges: Integrating research and practice in teaching and learning about evolution*. New York: Oxford University Press.

Miles, M. B., & Huberman, A. M. (1994). Qualitative data analysis: An expanded sourcebook. Sage.

Miller, J. D., Scott, E. C., & Okamoto, S. (2006). Public acceptance of evolution. *Science, 313*, 765–766.

Novick, L. R., Stull, A. T., & Catley, K. M. (2012). Reading phylogenetic trees: Effects of tree orientation and text processing on comprehension. *BioScience, 62*, 757–764.

Olson, I. C., Leong, Z. A., Wilensky, U., Horn, M. S. (2011). It's just a toolbar!: Using tangibles to help children manage conflict around a multi-touch tabletop. In *Proc. tangible, embedded, and embodied interaction TEI'11* (pp. 29–36). ACM Press.

Oppenheimer, F. (1976). Everyone is you… or me. *Technology Review, 78*(7).

Pontual Falcão, T., & Price, S. (2011). Interfering and resolving: How tabletop interaction facilitates co-construction of argumentative knowledge. *Computer-Supported Collaborative Learning, 6*, 539–559.

Price, S., & Pontual Falcão. (2011). Where the attention is: Discovery learning in novel tangible environments. *Interacting with Computers, 23*, 499–512.

Prum, A. J. (Producer). (2008). Discovering the Great Tree of Life. Available from the Peabody Museum of Natural History, Yale University, P.O. Box 208118, New Haven, CT. http://archive.peabody.yale.edu/exhibits/treeoflife/film_discovering.html.

Rick, J., Marshall, P., & Yuill, N. (2011). Beyond one-size-fits-all: How interactive tabletops support collaborative learning. In *Proc. interaction design and children IDC'11* (pp. 109–117). ACM Press.

Roberts, J., Lyons, L., Cafaro, F., & Eydt, R. (2014). Interpreting data from within: Supporting human-data interaction in museum exhibits through perspective taking. In *Proceedings of Interaction Design and Children* (pp. 7–16). ACM Press.

Rosengren, K. S., Brem, S. K., Evans, E. M., & Sinatra, G. M. (Eds.). (2012). *Evolution challenges: Integrating research and practice in teaching and learning about evolution*. New York: Oxford University Press.

Schneider, B., Strait, M., Muller, L., Elfenbein, S., Shaer, O., & Shen, C. (2012). Phylo-Genie: Engaging students in collaborative "tree-thinking" through tabletop techniques. In *Proc. human factors in computing systems (CHI'12)* (pp. 3071–3080). ACM.

Scott, S. D., Mandryk, R. L., & Inkpen, K. M. (2003). Understanding children's collaborative interactions in shared environments. *Journal of Computer Assisted Learning, 19*, 220–228.

Shaer, O., Strait, M., Valdes, C., Feng, T., Lintz, M., & Wang, H. (2011). Enhancing genomic learning through tabletop interaction. In *Proc. human factors in computing systems (CHI'11)* (pp. 2817–2826). ACM.

Snibbe, S. S., & Raffle, H. S. (2009). Social immersive media: Pursuing best practices for multi-user interactive camera/projector exhibits. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1447–1456). ACM.

Stevens, R., & Hall, R. (1997). Seeing tornado: How video traces mediate visitor understandings of (natural?) phenomena in a science museum. *Science Education, 81*(6), 735–747.

Suchman, L. (2007). *Human-machine reconfigurations: Plans and situated action*. Cambridge: Cambridge University Press.

Weinberger, A., & Fischer, F. (2006). A framework to analyze argumentative knowledge construction in computer-supported collaborative learning. *Computers and Education, 46*(1), 71–95.