Interpreting Data from Within: Supporting Human-Data Interaction in Museum Exhibits Through Perspective Taking

Jessica Roberts
University of Illinois at Chicago
1240 W. Harrison St.
Ste 1570
Chicago, IL, USA
jrober31@uic.edu

Leilah Lyons
University of Illinois at Chicago/New York Hall of Science
1240 W. Harrison St.
Ste. 1570
Chicago, IL, USA
llyons@uic.edu

Francesco Cafaro
University of Illinois at Chicago
851 S. Morgan St.
M/C 152
Chicago, IL, USA
fcafar2@uic.edu

Rebecca Eydt
New York Hall of Science
47-01 111th St.,
Corona, NY, USA
reydt@nysci.org

ABSTRACT

As data rather than physical artifacts become more commonly the product of modern scientific endeavor, we must attend to human-data interactions as people reason about and with representations of data increasingly being presented in museum settings. Complex data sets can be impenetrable for novices, so the exhibit presented here was designed to give visitors control over a personalized "slice" of the data set as an entry point for exploration. Personalized control and collaboration can often be at odds in exhibits, however. This paper presents a study of two alternate approaches to designing an embodied interaction control for the exhibit that serves both needs. The results demonstrate that interaction design can affect children's perspective taking as they interact with a Census data map museum display, and that the perspective taken by individuals is correlated with their operation of the interactive exhibit and the kinds of reasoning they employ while investigating data.

Categories and Subject Descriptors

H.1.2 [**Information Systems**]: User/Machine Systems – *human factors, human information processing*; K.3.1 [**Computers and Education**]: Computer uses in Education – *collaborative learning*

General Terms

Design, Human Factors

Keywords

Museum exhibit design, embodied interaction, data interpretation, personalized interaction, actor perspective, GIS.

1. INTRODUCTION

Museums can serve many societal purposes: as places of scholarship, as homes of conservation, as places to gather, as sites of public outreach, and as cradles of informal learning. Given the diversity of museums it can be hard to make generalizations about their missions, but science museums, in particular, are often engaged in bringing the general public into contact with emerging scientific artifacts and practices [47]. Science has been evolving away from a purely material culture to embrace a virtual culture, where the "stuff" of science is no longer limited to vitrines of taxonomically organized artifacts, but can also be large data sets. Concomitantly, scientific practices have grown to include visualizing and interpreting these data sets. If large data sets are the artifacts of modern science, museums need to learn how to exhibit them to a diverse audience.

Data are rarely presented to people, particularly the general public, in raw form; instead they are abstracted into more accessible formats, often visualizations. New ways of visualizing data are constantly emerging, but one of the oldest and still most popular formats is the data map. Spatially referenced data are increasingly presented as maps shared online, in the news, and in textbooks, yet even though these maps have been used to convey information for more than a hundred years, people still have a hard time interpreting them correctly. Now thanks to the proliferation of easily accessible geographic information systems (GIS) tools, many of these maps are made by individuals without in-depth understanding of GIS and data representation, resulting in authoritative-looking maps that grossly distort their underlying data [24]. Since maps touch on so many activities that are relevant to our daily lives, the skills required for data map interpretation should be encouraged in the general population.

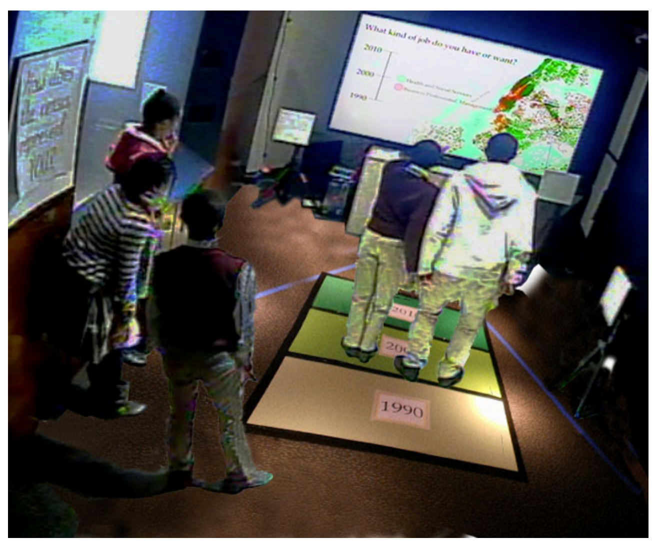

Figure 1. Museum visitors interacting with CoCensus

We do not yet know how people, especially children, reason about the data presented in these maps. Particularly, we know very little

IDC'14, June 17 - 20 2014, Aarhus, Denmark

ACM978-1-4503-2272-0/14/06⋯$15.00.
http://dx.doi.org/10.1145/2593968.2593974

about how these maps are interpreted collectively in informal environments like museums, where the social aspect of the experience is one of the prime components of the visit for many visitors. Sociocultural perspectives on learning stress the importance of communication for learning, positing that concepts must be articulated in the social space before they can be truly incorporated into an individual's understanding [52]. Museums are thus an ideal setting for the collaborative exploration of ideas. Collaboration is defined by [46] as being "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem." They constructed their definition in the service of studying in-school problem solving, but many of the component activities – coordination, the construction and maintenance of a shared understanding – are also common to the shared use of museum exhibits. When we describe the collaborative use of an exhibit, then, we refer to activities that involve coordination and which lead to the development of a shared understanding.

The CoCensus project (see Figure 1) described in this paper leverages embodied interaction to allow museum visitors to collaboratively explore the U.S. census on an interactive data map. We hypothesized that we could provide an "entry point" into this large data set by encouraging visitors to identify exclusively with a much smaller subset of the data and that we could in turn help visitors identify with "their" data subset by utilizing the affordances of embodied interaction over a large shared display [44]. Visitors are "reflected" on a map as scaled centroids showing the locations in the region of other people sharing their responses to census questions. The dynamic interface allows visitors to explore the data with the other visitors in the room, not just those with whom they are attending the museum. The emergent discussions that visitors have with one another as they compare and contrast "their own" data sets against the data sets of others in a common interaction space affords a type of collective, collaborative meaning-making that would be highly unlikely to occur with an exhibit that presented similar data via a single-user interface.

In this paper we discuss the interface design strategies we used to encourage visitors to collaboratively and interactively interpret large data sets in a museum. In particular, we will describe how we explored different methods to promote engagement with the data through perspective-taking and to encourage collective reasoning about the data, and the changes in user behaviors these design strategies produced during *in situ* testing at a mid-size science museum. In our discussion of our findings, we present some recommendations for how designers can affect perspective-taking and data reasoning within an interactive experience through embodied interaction design.

2. BACKGROUND AND PRIOR WORK

The aim of CoCensus is to support reasoning about census data by providing access to an accessible "slice" of the data that is mapped over the local environment and presented in a collaborative, social setting. It is widely accepted that a goal in museum educational communities is to move visitors from knowledge-based, fact-regurgitation exercises to richer ways of engaging with content like synthesis, interpretive reasoning, and inquiry, e.g. [11, 39, 40, 1]. When dealing with large data sets such as the United States census, the sheer size and complexity can be overwhelming to people not familiar with this type of data. The myriad of ever-changing categories used by the census to count people over time makes for a "high floor" for understanding the data, and it is likely that many museum visitors will be unwilling to do the work to engage deeply with the data in an informal social setting. Children are especially challenged when confronted with census data, because in addition to the difficulties of decoding a data map in general, they are likely to be unfamiliar with this particular data set, making it even more difficult to bridge the gap between their current knowledge about the world and what the map is depicting. Lack of understanding about the purposes of the census may translate to lack of motivation in exploring its data, thereby making deep reasoning difficult.

2.1 Facilitating Personalization and Perspective-Taking

2.1.1 Customized Profile Creation

When presenting esoteric topics, museums often try to show visitors a connection between their personal lives or interests and the presented content. To enhance the ability of visitors to personally connect to the data, we allowed them to take a simplified "mock census" survey that we developed as a mobile tablet application (see Figure 2) which would be used to customize the data set they controlled within the exhibition. This customization process involves creating a mini-profile comprised of four categories of data collected by the census: your race or ancestry, the number of people in your household, your housing type (e.g. single family home, apartment building with 50+ units), and the industry in which you work or want to work. These questions were chosen from the available census categories because they are applicable to both children and adults, they connect in some way to identity or lifestyle, and they are relatively self-explanatory. The available options were simplified somewhat from the full array provided by the census, such as by trimming the over 250 reported race and ancestry groups to a moderately more manageable 67 options.

Figure 2. Screenshots from CoCensus profile selection tablet application. Visitors had the choice of selecting a preconfigured profile or answering four census questions themselves to view personalized data.

This tablet application for our "mini-census" allowed participants to select not only their own answers to questions but also the color they wished to have represent their data sets on the display. In order to provide a quicker access option to visitors, and to allow visitors to engage with census data without sharing their own information if they wished, we added an additional feature of preconfigured tags of public figures that people could select easily to allow them to proceed more quickly to the interaction. While not fully customized, we reasoned that selecting a favored public figure would still rely on personal preference and thus engender something of a personal connection to that personage's data set. The options initially tested were politicians President Barack

Obama and Mayor Bill de Blasio, scientists Marie Curie and Albert Einstein, celebrity Jennifer Lopez, and fictional character Dr. Sheldon Cooper.

Regardless of whether they chose a preconfigured or custom profile, visitors were allowed to select the color they wished to have represent them on the display. Based on work showing that the personalization of avatars in video gaming led to stronger connection and engagement, e.g. [49], we posited that this small extra personalization would increase children's feeling of connection while relieving them of the extra work of interpreting a key to determine "who is who."

2.1.2 Embodiment and Perspective-Taking

Our prior work with adult visitors [47] demonstrated that encouraging visitors to take a personalized perspective on census data increased the depth of their interest in the data maps, and affected the way they went about interpreting the data maps. In particular, establishing a physical connection through motion sensing technologies altered the way visitors positioned their perspective with respect to the data set [47]. Whereas in pilot testing when the embodied interaction components were not in place, visitors spoke of the data exclusively from an *Onlooker* or third-person perspective (e.g. "The Germans are all over the North Side."), once visitors were physically embodying individual data sets, some took on an *Actor* perspective, speaking from the perspective of someone in the map, for example, "I'm along the Lake."

In some cases, visitors used their Actor positioning as a springboard for creating stories about the "characters" they were embodying. This creative playful talk led to deep engagement in the data and helped them move past simple data interpretation to hypothesis generation and inference making. This type of rich engagement is the type of interaction CoCensus is hoping to support. There is some evidence that perspective-taking in general, and a first-person or personalized perspective-taking in particular, may hold special benefit for reasoning about data, as the next section will discuss.

2.2 Perspective-Taking and Data Interpretation

One linguistic tactic utilized by expert scientists when interpreting their complex data is to alter the perspective they use when discussing their phenomena. For example, [41] found that expert physicists talking about a graph representing data collected about a particular particle they were studying utilized what they termed a *blended identity* "composed of both the animate physicist and the inanimate entity" in order to interpret findings. Rather than discussing an inanimate entity in the third person, for example by saying, "When it comes down, it is in the domain state" when discussing this particle, [41] noted the lead physicist on the project saying, "When *I* come down, *I'm* in the domain state. (*emphasis added)"* In this utterance, this expert physicist (the principle investigator of the project) uses the personal pronoun "I" to describe what the inanimate object (the particle) is doing – coming down – and its state – the domain state. This type of *indeterminate reference* is found to be common among physicists, "used non-problematically by scientists in their everyday interpretive work." Looking at their data from multiple perspectives – as a physicist examining a particle and as the particle itself – aided the scientists in reasoning about the complex data.

Furthermore, Enyedy et al. note that children investigating physics phenomena in an embodied classroom simulation employed similar linguistic tactics in interpreting their friction models [20]. As they physically embodied a ball undergoing forces in a simulation, students utilized a first-person perspective in order to discuss and make sense of the physical forces at play. This affordance was a deliberate design decision by the researchers because the resulting perspectives "created a qualitatively different set of resources from which to reason and were found to be productive in model and theory building" [20]. Therefore an exhibit that affords this type of perspective-taking where the visitor "becomes" part of the data – hereafter called the *Actor perspective,* as used by [12] – has the potential to facilitate reasoning about data in the museum environment. It also holds the possibility of enhancing collaborative reasoning – taking an actor perspective, especially when one's actor perspective is unique, is very much like the museum experiences that assign roles to visitors, a strategy known to encourage collaborative interactions.

2.3 Support for Collaborative Meaning-Making in Museums

Personalization may motivate an individual's interest in an interactive experience, but it can complicate the interaction design when the experience is intended to be shared amongst multiple simultaneous users. There is inherent tension between designing an experience which is particular to each user while still supporting shared use, especially when each user is expected to have some degree of control over the exhibit.

Of course, not all museum exhibit experiences need to be shared [9], but one of the most powerful ways visitors can learn at museums is through meaning-making conversations with their companions [33, 40, 57]. Unfortunately, the designs of many digital "interactives" in a museum promote machine-human interactions while simultaneously limiting the social interactions of visitors [25]. In the early days of computers in museums, this lack of support for collaborative use was understandable – the form factor of kiosks with trackballs and small displays limited how well a digital interactive could include multiple visitors in the experience [17]. As the scope of interactive technologies has widened, there are fewer technical constraints on support for collaborative use, so the continued presence of exhibits that do not support collaborative interactions amongst visitors during exhibit use [25] suggest that the challenges seem to lie in designing for collaborative museum experiences. Here we review some of the design strategies that have been explored for supporting collaborative meaning-making during digital museum experiences.

2.3.1 Divide-and-Conquer Strategies

A common approach is to give visitors a shared challenge and parcel it out to participants, as a shared problem is known to provide opportunities for collaborative meaning-making [46]. One such strategy is to engage visitors in role playing with the goal of inducing interdependence among visitors, and which designers often facilitate with mobile devices [13, 32, 35]. A more specific role-play strategy involves engaging some visitors in interaction while others, usually parents, are in supervisory roles [7, 50]. Another approach to engaging visitors in a shared task is to divide the challenge itself up into parallel tasks, in the form of multi-question quizzes [26, 55] or via collaborative games with large shared displays that visitors use to coordinate their actions [29, 18].

All of the strategies described so far have been built around exhibits that have clearly defined goals, but others have addressed the challenge of how to engage visitors in experiences that are more about shared exploration than shared achievement. For example, there are a number of exhibits that allow visitors to explore shared virtual realities, like re-created archaeological ruins [55], or Augmented Reality (AR) visualizations of physical phenomena [56]. Others have employed technologies like AR [53] and laser pointers [37] to let visitors collectively reveal hidden aspects of artifacts. In all of these examples, however, though the interaction is exploratory in nature, the exhibits have been designed to lead groups of learners to specific museum-defined outcomes or discoveries.

2.3.2 Parallelization Strategies

Other designers have looked into the problem of how to support collaborative meaning-making while visitors explore their own personal interests, as opposed to pursuing goals defined by the museum. One strategy is to help visitors coordinate the tandem pursuit of their individual interests. With PEACH, visitors used mobiles to configure profiles of their individual interests, so that when a group approaches an exhibit, different members of the group may receive content specialized to their interests [48]. Receiving differential content can encourage visitors to share what they have individually learned with one another. A related strategy is to create privileged channels of audio communication [6, 55] so that visitors can separate and visit different places within a museum while still being able to share their experiences with one another verbally.

2.3.3 Aggregation as a Means to Share Control

When visitors attempt to follow their personal interests within a shared interaction space, though, there is always a risk of inducing conflict, as visitors' agendas for what to do with an exhibit may differ. While it can be possible for users interfering with each other to be productive for learning [21], this seems to be true mostly for scenarios where the opportunities for controlling the shared state of the exhibit are distributed amongst participants. Conflict over different personal goals is far less productive when one user "hogs" control of the interactive exhibit [51]: mutually-exclusive controls are a bad idea.

In our exhibit design, CoCensus, while we intend the experience to be exploratory, we are also borrowing the idea of "lightly" inducing interdependence to encourage collaborative meaning-making. True interdependence arises from imposing a shared goal. Since our exhibit is open-ended, we give no fixed "goal" to visitors, but the fact that the presence of each new visitor adds a new data subset to the shared display means that the actions of visitors still impact one another. Their presence and actions change and broaden the nature of the observations, comparisons, and questions that the data visualization can support in what we dub an "aggregational" fashion [36].

2.4 Discoverability, Usability, and Design Metaphors for Embodied Interaction in Museums

As mentioned above, we found in our prior work that when we allowed visitors to control data sets with their body movements they seemed to take on a more personalized, Actor perspective [47]. E*mbodied interactions* [19] have been gaining popularity in museums, partly due to the novelty of the interactive technologies that support such interactions, partly because many designs do not require visitors to use devices (e.g., trackballs, light pens, etc.) which may get damaged or lost, but also because of the ability of such controls to promote interactive learning and sociability. By moving the site of interaction away from the virtual space of a screen and into the physical and social space of the exhibit gallery, designers can exploit the natural performative characteristic of museum visits [38], where visitors are known to watch what one another do in galleries [51].

Developing embodied interaction designs that are easily discoverable is a nontrivial problem, however. As we expanded the set of controls possible with our exhibit, we knew that we would need to address the discoverability challenge. In standard WIMP (Windows Icon Menu Pointer) interfaces, available control activities are discoverable and often distributed in meaningful spatial patterns on the screen. For many embodied interaction experiences, especially whole-body interaction experiences, available control activities are hidden, as they are literally embedded in the body of the user. This means designers run the risk of creating a system which is not highly discoverable. This is a particular problem for a museum context, where visitors need to be able to quickly learn how to use the interface lest they give up and walk away [29]. For this reason, with CoCensus we opted to frame at least some of the control actions in a visible, spatial way: by using the labeling regions of the floor of the exhibit gallery to allow it to serve as a "control surface" of sorts. Other whole-body interaction exhibits have also successfully used the strategy of making the floor part of the interface [50]. Marking the control areas on the floor can help make the interface more discoverable, but may not be enough to make it usable. To help us tackle the usability challenge, we turned to a design principle from Human-Computer Interaction literature: consistency.

2.4.1 Designing Embodied Interfaces with Consistency

One commonly accepted design principle for making interfaces more usable is known as "Consistency" [42]. The idea is to make it easier for a learner to figure out what control actions he or she might initiate by making a new interface consistent with existing user expectations. These user expectations may be developed by interacting with other parts of the interface (internal consistency), or by interacting with prior interfaces (external consistency), or via users' interactions with analogically similar situations (metaphorical consistency). Internal consistency is most useful for rich interfaces with many related control activities – since most museum exhibits have relatively limited control sets, we deemed it not very applicable.

2.4.2 Metaphorical Consistency and Embodied Metaphors

Metaphorical consistency succeeds when users are easily able to detect the underlying analogical metaphor. An alternative approach for embodied interaction design that many embodied interaction designers have begun relying on is a special version of metaphorical consistency called embodied metaphors [8, 3, 4, 5, 27]. The core theory underlying embodied metaphors is that humans develop strong kinesthetic metaphors via their early childhood, constructivist explorations of the physical world [30]. For example, people often conflate physical concepts like "balance" with more abstract concepts like "justice." In our case, one of the control design challenges we faced was how to allow visitors to change the year of the Census data they were viewing. We were particularly interested to see if the embodied metaphors people bring to their conceptions of time could be used to design an embodied control of the time of the data sets being viewed.

People often refer to events in time using reasoning patterns that commonly apply to space: space and time share "enough relational structure" to allow spatial "schemata" [28] to be used in alternative to temporal schemata [10]. As described in [22], there are two common metaphorical mappings between space and time in English: (1) the "ego-moving" metaphor, in which a person (the "observer") progresses along a time-line towards his/her future, where the future is ahead; (2) the "time moving" metaphor, in which time is seen as a conveyor belt on which events are moving from the future to the past. People use ordered words such as "front" and "back" (rather than symmetric terms such as "right" or "left"), when spatial terms are used in the domain of time [22]. We know that these metaphors can be influential because people who are primed with different space to time metaphors exhibit different reasoning patterns [22]. For instance, in the study presented in [10], participants who were primed with the "ego-moving" metaphor thought that a meeting scheduled on Monday was actually on Friday, while those primed with the "time moving" metaphor exhibited the opposite bias [10]. It is worth noting that the metaphor chosen should be kept constant: as illustrated in [22], moving from one metaphorical system to the other slows down people in fulfilling their task.

We designed a time control strategy using this "ego moving" embodied metaphor for time (hereafter called the Vertical (V) strategy). Visitors move forward in the exhibition gallery towards the display to move the date of their data set forward in time, and step backwards to move the date of their data set backwards (see Figure 3, left). We hypothesized that the design of the interaction space may strongly influence not only the usability of the embodied exhibit, but also further enhance users' personal identification with "their" data sets. By using an ego-moving metaphor, we suspected that visitors would come to personally identify with their data sets more strongly. Egocentric perspective-taking is a concept also successfully used in an exhibit on orbital mechanics [34], and we thought it might be helpful for reasoning about data. This design does offer risks, however: foremost that visitors still might not find it usable (owing to their lack of prior experience with a similar interface designs). The other risk is that by allowing each visitor to control the time of his or her data separately, visitors might engage in meaningless data interpretation (e.g., attempting to compare the distribution of Finance jobs in 2010 to the distribution of Service jobs in 1990). For this reason, we also explored a time control strategy using a different approach based on external consistency.

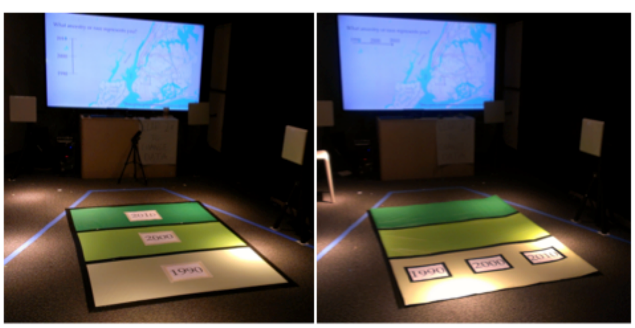

Figure 3. The two CoCensus configurations. Left: Vertical (V); Right: Horizontal (H)

2.4.3 Embodied Interfaces and External Consistency

External consistency has been a very successful design strategy for WIMP interfaces, since users usually have had so many prior experiences with WIMP interfaces. Unlike WIMP interfaces, however, there are far fewer accepted schemas for mapping user movements into system controls [54], so designers might need to look to other familiar, but non-embodied, interfaces for exemplars. We reasoned that most users would be very familiar with the concept of a horizontal timeline – with years marked as "ticks," moving from older years to the left to newer years towards the right of the scale. The timeline is itself a metaphor, but it is such a common interface element, using it fulfills both the principles of external and metaphorical consistency. We implemented this control scheme by literally marking out a timeline horizontally (parallel to the display) on the exhibit floor, and echoing it in the visualization display (see Figure 3, right). We intentionally designed the system to be mutually exclusive (only one user can set the decade on display at a time), so it would be more in keeping with existing timeline controls (external consistency), and to prevent users from making nonsensical cross-decade comparisons (e.g. comparing two different data sets at two different points in time). We felt confident that users would find this control scheme (hereafter called the Horizontal (H) configuration) usable, but given the known issues with mutually-exclusive controls potentially leading to non-productive interactions at exhibits, we thought it would pose an interesting contrast to compare against the V configuration.

3. INVESTIGATION AND METHODS

The two layout configurations discussed here were tested over two days in mid December 2013 *in situ* at a mid-sized urban science museum. Participants were recruited off the museum floor by members of the research team and asked to test out a new display showing census data. Due to the nature of the display, recruitment was limited to visitors who appeared to be age ten or older, and due to the social nature of the exhibit, visitors were recruited in groups of two or more. Each visitor used a tablet running the survey application (Figure 2) to complete the "mini-profile" configuration, asking questions of the researcher as necessary. Upon completion of the configuration, the visitors' responses were sent to the display's server via PHP in order to allow the display to show personalized information. Visitors were then given a lanyard to wear around their necks which held both an RFID card to associate them with the data [15] and a clip microphone for audio recording and were sent into the interaction space in a room separated from the main museum floor by a partial wall.

Researchers stayed outside the room to allow naturalistic interactions. In some cases participants called the researchers in to address a particular problem (such as the wrong information being displayed if the system had failed to reset for a new user) or general confusion about how the system worked. In those instances the researcher answered questions and offered explanations to the satisfaction of the participants and then left the room. The exception is that one member of the research team stayed in the room but out of sight of the participants in order to implement the changing of the question (ancestry, household size, etc.) being displayed. Participants were told to clap twice to change the data set, but as the automated control was not yet implemented, we utilized a "Wizard of Oz" approach for this feature.

Participants were allowed to interact with the system as long as they wanted, and upon leaving were asked to complete a one-page survey to gauge their perceptions of control and enjoyment of the display, comprised of 5-point Lickert scales and open-ended comment sections. Visitors typically explored the exhibit for 2-3 minutes, which is typical for interactive science museum exhibits [16]. Interactions were recorded using five video cameras and a microphone mounted in the space.

3.1 Sessions and Participants

Recordings were split into sessions, with the beginning of a session marked by the entrance of the first visitor into the interaction space and the end when the final overlapping visitor exited the space or removed his RFID tag. Over the course of two days, 35 sessions were recorded. Sessions in which visitors entered the space without RFID tags and sessions consisting of only one user were discarded from this analysis, as were those comprised of adult visitors, museum staff, and sessions in which one of the researchers answered more than trivial questions and ended up playing a major role in interpretation for the visitors. Fifteen sessions were transcribed and analyzed, though one session was later discarded from the analysis because it consisted of five users in multiple overlapping groups and could not be considered comparable with the other cases. The remaining fourteen sessions ranged in duration from 33 seconds to over 5 minutes, with an average duration of 2.51 minutes. Each session consisted of a pair of users for a total of 28 participants. Six of the sessions (12 participants) interacted with the V condition and eight sessions (16 participants) used the H condition. Each pair in this analysis consisted of two student classmates recruited from school groups ranging in age from 10 to 14 years old. Because the paired students were classmates, they were similar to each other in age and knew each other prior to the interaction.

3.2 Transcriptions and Coding

Fifteen sessions were transcribed for speech using Inqscribe and for interactivity using NVivo and Inqscribe. Videos were coded for interaction by recording instances of clapping (the means of switching between census categories) and timeline control (when visitors stepped into the control regions marked on the floor). Verbal transcripts were coded for perspective-taking and data interpretation.

Perspective codes marked instances of visitors making statements about the data from either an Onlooker perspective in which data were referred to in the third person, for example, “There are so many Puerto Ricans,” or from an Actor perspective in which visitors used first-person pronouns to describe the data, such as, “We are totally not even a minority. We’re like less than that.”

Interpretation coding was meant to elucidate the reasoning children were doing about the data. While there are a number of ways of componentizing reasoning about spatialized data, (e.g. [23, 24, 31], in analyzing visitors’ reasoning around our display, we drew upon work analyzing students’ reasoning about GIS census maps in classrooms [43], as it was a close analogue to the types of reasoning found in our exhibit. An initial round of coding looked for eight unique codes related to data interpretation.

After reviewing the resultant coding, researchers refined the scope to a set of three codes that most clearly articulated the types of interpretive acts in which children were engaging in the space:

- Comparison across **Time** (periodicity, growth, development, change): Remarks that indicate an acknowledgement of difference (or lack of difference) between one decade and another. Marked by words like “now,” “back then,” “still,” “used to,” “before.” Not including statements about control such as “I’m stepping in 1990” or “Go to 2010.”
- Comparison between **Datasets**: Remarks discussing similarities or differences between two data sets, such as the number of single family homes compared to apartments. Can include comparisons of their quantities (e.g. “I slaughter you”) or distributions (“You’re by the lake and I’m not”)
- **Spatial** Characterization or Comparison: Remarks related to location (e.g. Manhattan or the west side), distance (“far apart,” “all grouped together”), distribution (“spread out” “all in Manhattan”), can be relative to location of other data set (“I’m here and you’re there”)

Findings related to the interplay among perspective-taking, interaction, and data interpretation are discussed below.

4. FINDINGS

Analysis of the visitors’ sessions focuses on the relationships between the three types of codes: interaction, perspective, and data interpretation. In each case, the analysis relies on frequencies, not counts, of codes to account for the varying length of sessions. Here we will discuss in detail our three key findings: 1) The perspective taken by visitors is correlated with the data interpretation remarks visitors made during the interaction, with the Actor perspective strongly correlated with a higher incidence of both temporal reasoning and comparisons between data sets; 2) The configuration of the space and the distribution of control directly impacted the perspective taken by visitors in using the display; 3) The Actor perspective is significantly correlated with timeline use, while the Onlooker perspective is not correlated with either use of the timeline or clapping to change the data set.

4.1 Role of Perspective in Data Interpretation

Of key interest to this analysis was whether the perspectives taken by each visitor correlated with the frequencies of data interpretation statements made by that participant during the interaction. A Pearson product-moment correlation coefficient was computed to assess the relationship between frequency of perspective taking (Actor or Onlooker) and data interpretation statements (Time, Dataset, and Spatial reasoning). As expected, there was a positive correlation between taking an Actor perspective and the overall frequency of data interpretation statements (r =0.822, n = 28, p < 0.000). Interestingly, Onlooker perspective was also significantly correlated, although to a lesser degree, with data interpretation overall (r = 0.433, n = 28, p < 0.021). See Table 1 for complete correlation statistics.

Table 1. Pearson's Correlation for Perspective-taking and Data Interpretation Statements, all cases (N = 28 individuals)

	Actor Perspective	**Onlooker Perspective**
Total Data Interpretation	0.828**	0.433*
Time Comparison	0.705**	0.048
Dataset Comparison	0.837**	0.474*
Spatial Characterization	-0.143	0.463*
** Correlation is significant at the 0.01 level (2-tailed).		
* Correlation is significant at the 0.05 level (2-tailed).		

Looking more deeply, we find that the Actor Perspective is highly correlated with dataset comparison, (r = 0.837, n = 28, p < 0.000) nearly twice as much as the Onlooker perspective, (r = 0.474, n = 28, p < 0.011), which is what we would expect given that we were intentionally asking visitors to personalize their datasets so that they might identify more strongly and thus engage more deeply with “their” datasets. The Actor perspective is also strongly correlated with comparisons across time (r = 0.705, n = 28, p < 0.000), while there is no correlation between an Onlooker perspective and time comparison, an interesting contrast that will be returned to in the next section. There is no correlation with an Actor perspective and spatial reasoning, even though there is a correlation between the Onlooker perspective and spatial reasoning, (r = 0.463, n = 28, p = 0.013), which is again what we would expect, since the types of remarks we coded for spatial properties required the visitors to "take a step back" and be sensitive to the entirety of the data represented on the map, and not just a personalized portion of the data. It is important to note, however, that only three instances of spatial characterizations were coded throughout the sessions. This suggests that though spatial characterizations were occasionally made, they were too infrequently used to be able to draw deep conclusions from this data set. It also suggests that the current design of the display does not adequately afford the types of spatial characterizations we would hope to elicit, an issue that is being addressed by ongoing design work. Still, these results show that perspective-taking and data reasoning are clearly tightly linked, and that the *type* of perspective-taking is linked to different types of data interpretation.

4.2 Role of Control Configuration in Data Interpretation and Positioning

This study compared children's perspective taking and interpreting data in two conditions: the Vertical (V) condition in which each user was able to individually manipulate the data year for his personally embodied data set by moving front to back, and the Horizontal (H) condition in which a single user controlled the timeline for all users in the space by moving side to side on a timeline. This section discusses impacts of the two configurations on both data reasoning and perspectives.

4.2.1 Configuration and Data Interpretation

The 16 sessions utilizing the H configuration contained a total of 20 statements coded as data interpretation, compared to 36 data interpretation statements coded in the 12 V sessions. This contrast is especially striking when considering that the H sessions were overall longer than the V sessions, with the mean duration of H sessions at 2.90 minutes, compared to 2.12 minutes average for the V configuration sessions. Frequencies of data reasoning statements by condition are illustrated in Figure 4. These differences were significant for overall data interpretation $t(26)=2.33$, $p<0.03$, as well as time comparison $t(26)=2.00$, $p <$ 0.04, and dataset comparison $t(26)=2.00$, $p < 0.03$.

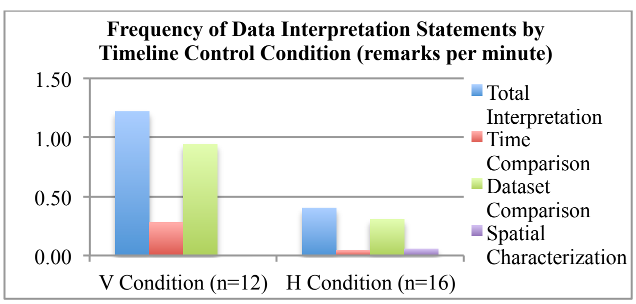

Figure 4. Participants in the vertical (V) condition had higher frequencies of time comparison and dataset comparison statements compared to the horizontal (H) condition.

4.2.2 Configuration and perspective-taking

Multiple independent-samples t-tests were conducted to compare frequencies of each perspective (Actor and Onlooker) in the two conditions (V and H). The frequencies of each are shown in Figure 5.

Participants used the Actor perspective significantly more in the V condition (M = 1.1, SD = 1.3) than the H condition (M = 0.2, SD = 0.4), $t(26)$ = 3.22, p = 0.00. There was no significant difference in the frequency of the Onlooker perspective between the V (M = 0.4, SD = 0.7) and H (M = 0.2, SD = 0.4) conditions, $t(26)$ = 1.00, p = 0.35.

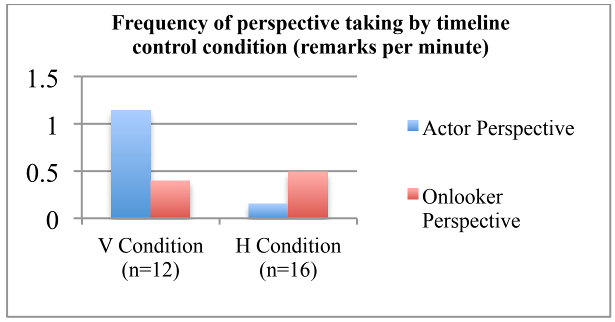

Figure 5. The Vertical condition elicited significantly higher frequencies of actor positioning than the Horizontal setup.

4.3 Relationship between Perspective and Control Actions

While the Actor perspective has been shown to enhance reasoning about the data set, as the exhibit is designed to be interactive it is crucial to understand the relationship between visitors' perspectives and their interactions with the display. Table 2 shows the correlations between visitors' perspectives and their control actions.

Given the significantly higher frequency of Actor perspective-taking in the V condition (see Section 4.2.2), and the significant correlation between the V condition and overall data interpretation frequency (see Section 4.2.1), one might wonder if the significant correlation seen here between the Actor perspective and total control actions is due to visitors in the V condition. In fact, for the V condition Actor perspective-taking is not significantly correlated with interacting with the exhibit overall, which seems surprising until one digs more deeply. The Actor perspective *is* correlated with time change actions in the V condition (n=12, r=.767, p < 0.004), while there is, if anything, a negative (although non-significant) correlation with data change interaction events. This suggests that visitors who make use of the timeline also take on the Actor perspective, while those who change the data set are less likely to have an Actor perspective, which is exactly the effect our design intended to produce. There is no correlation with the Onlooker perspective and any interaction activity, suggesting that there is no relationship between engaging in exhibit control actions and taking an Onlooker perspective on the data, which is what we would expect in an exhibit that is attempting to personalize data exploration via interaction design.

Table 2. Pearson's correlations between control actions and perspective-taking, for all cases (N = 28 individuals)

	Total Actions	Data Change Actions	Time Change Actions
Actor Perspective	.489**	0.044	.637**
Onlooker Perspective	-0.093	0.041	-0.16
** Correlation is significant at the 0.01 level (2-tailed).			

5. DISCUSSION

Based on prior work we expected that locating control of the display within the body of the user would elicit the Actor perspective in visitors [45], and that this perspective could potentially facilitate reasoning about the data, as it has been shown to do for expert physicists [41] and students [20]. We found that children interacting with CoCensus engaged in two primary kinds of reasoning about the census data: comparisons over time and comparisons across data sets. Analysis of the dialogue between children while interacting demonstrated a strong correlation between instances of those reasoning utterances and the Actor perspective.

These findings underscore the value of utilizing personalization and embodiment to give children an access point to understand an otherwise complex and overwhelming data set.

5.1 A Tight Tie between User and Locus of Interaction Elicits Actor Perspective

The richness of the learning experience offered by embodied interaction exhibits is directly affected by how much control visitors have over the interaction, and the transparency of that control [2]. However, controlling the exhibit with gestures and body movements, rather than with traditional input devices (such as a keyboard or mouse) can be a challenge. As illustrated in [14], part of the problem lies in the separation between the locus of the interaction (the user's body) and the focus of the interaction (the screen). In traditional WIMP (Windows, Icon, Mouse, Pointer) interfaces, user's interaction was framed by the input device and the interface. Mouse movements, for instance, are generally mapped to cursor movements on the screen. Users can typically rely on prior experiences with the same software (internal consistency) or with other software (external consistency) or on analogies (metaphorical consistency) to help them figure out what control actions are possible and the effects of those actions.

With the horizontal timeline (H), which relied mostly on external consistency, the user was the "input device": like a mouse, she/he had to select the year that she/he wanted to explore. The user's body was used as a mouse cursor, to select a decade on a timeline on the floor; and the floor was the locus of that interaction. Similarly, with the vertical timeline (V), which relied more strongly on metaphorical consistency, the user her/himself was the input device; however, the locus of interaction was no longer on the floor: it was the user's body itself. Children no longer selected a decade by stepping on a specific, button-like spot on the floor, but instead did so by moving their body through space (under V, the floor markings function more like guidelines than controls). Visitors needed to embody a timeline, and to directly control the focus of the interaction (i.e. the data on the screen) by walking back and forth within the interaction space (i.e. "forward" and "backward" in time). Visitors easily adopted this mode of interaction. By choosing an embodied metaphor to establish metaphorical consistency, we also served to reinforce the users' sense of "self" within the interactive space, which seemed to result in the marked increase in Actor perspective-taking.

5.2 The Value of Multiple Perspectives

Though some of the data interpretation we hope to support with this exhibit is strengthened by the Actor perspective, this work also demonstrates that adopting an Onlooker perspective is associated with other types of desirable reasoning, like spatial reasoning. The very few instances of spatial characterizations, for example, were all correlated only with Onlooker perspective-taking. These findings strengthen the need to support multiple perspectives, even by a single user. In this study, 18 of the 28 participants took on at least one perspective during the interaction, and six participants utilized both perspectives during their interactions. It is worth noting that the 10 participants who took on neither an Actor nor an Onlooker perspective also contributed no remarks coded under any of the data interpretation categories. Given the benefits of these perspectives, especially the Actor perspective, demonstrated here, design considerations moving forward should seek to further support this perspective-taking, as well as to explore other types of perspective-taking.

6. CONCLUSIONS AND FUTURE WORK

It was expected based on prior work that supporting visitors in taking an Actor perspective as they engaged with the display would support their reasoning about the data presented in the exhibit. The extent of this correlation, and the dramatic differences between the two design approaches in inducing this perspective, however, were unexpected. This strongly suggests that embodied interface design can play a large role in helping shift the way learners might interpret an interactive experience.

Visitors were able to easily make use of the vertical timeline (V) to explore the data representations. This interaction design seemed to encourage visitors to take on an Actor perspective much more strongly, which in turn affected the ways they reasoned about the data. We suspect that the tight tie between the User and the Locus of Interaction in V, and the alignment of this embodied metaphor with the visitors' data set personalization, may have been the reason for the children's increased use of the Actor perspective. It may also explain the lack of difficulty visitors had with using the timeline control in V, despite the design not echoing existing designs as H did (external consistency). Reflecting on this, it seems part of reason may be related to the design principle we initially deemed irrelevant: internal consistency. Although encountering the embodied timeline control is hardly like encountering a new tool in the Adobe Photoshop tool palette (a common example of internal consistency), it was much more in keeping with the personalization theme the rest of the exhibit was encouraging (e.g., via data set customization). The lesson for embodied interaction design is twofold: (1) designers should consider the internal consistency of their embodied interaction designs even if the set of possible actions is quite small, and (2) that internal consistency need not just reside in the embodied interaction modality – it can and should span other aspects of the interface design as well.

Future work seeking to facilitate reasoning about data should seek to provide opportunities for users to adopt multiple perspectives. For example, were we to engage visitors with data without data set customization, e.g., by asking them to control different aspects of the visualization style (like the scaling or colorization of data representations), combined with other interaction metaphors, one might see better success at inducing an Onlooker perspective. The value of multiple perspectives for encouraging learners to tap into different types of reasoning also needs to be explored, as some have also begun to do for other problem spaces. For example, [34] is using perspective-taking to encourage an understanding of orbital mechanics, and [20] is exploring its use in physics education. Both of these learning environments provide interactive simulacra of real phenomena, however. We suspect that because data visualizations are themselves abstract representations, there are even wider opportunities for taking advantage of embodied metaphors, since the expectations for the control actions to conform to the "physics" of a simulated world do not apply in the same way.

7. ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under NSF INSPIRE 1248052.

8. REFERENCES

[1] Allen, S. 2002. Looking for learning in visitor talk: A methodological exploration. *Learning conversations in museums*, 259-303.

[2] Allen, S. 2004. Designs for learning: Studying science museum exhibits that do more than entertain. *Science Education 88*, S1, 2004, S17-S33.

[3] Antle, A.N., Droumeva, M., and Corness, G. 2008. Playing with The Sound Maker: Do Embodied Metaphors Help Children Learn? *Proceedings of the 7th int'l conference on Interaction Design & Children IDC 08*, 178–185.

[4] Antle, A.N., Corness, G., Bakker, S., Droumeva, M., Van Den Hoven, E., and Bevans, A. 2009. Designing to support reasoned imagination through embodied metaphor. *Proceeding of the seventh ACM conference on Creativity and cognition CC 09*, 275.

[5] Antle, A.N., Corness, G., and Bevans, A. 2011. Springboard: Designing image schema based embodied interaction for an abstract domain. *Human-Computer Interaction Series*: *Whole Body Interaction*, Springer, 7-18.

[6] Aoki, P. M., Grinter, R. E., Hurst, A., Szymanski, M. H., Thornton, J. D., & Woodruff, A. 2002. Sotto voce: exploring the interplay of conversation and mobile audio spaces. In *Proc of the SIGCHI Conf on Human Factors in Computing Systems*. CHI '02. ACM, New York, NY, 431-438.

[7] Asai, K., Sugimoto, Y., and Billinghurst, M. 2010. Exhibition of lunar surface navigation system facilitating collaboration between children and parents in science museum. In *Proceedings of the 9th ACM SIGGRAPH Conference on Virtual-Reality Continuum and its Applications in Industry*, ACM, New York, NY, 119-124.

[8] Bakker, S., Antle, A. N., & Van Den Hoven, E. 2012. Embodied metaphors in tangible interaction design. *Personal Ubiquitous Comput.,* 16, 4, 433–449.

[9] Ballantyne, R., & Packer, J. 2005. Solitary vs. Shared: Exploring the Social Dimension of Museum Learning. *Curator,* 48, 2, 177-192.

[10] Boroditsky, L. 2000. Metaphoric structuring: understanding time through spatial metaphors. *Cognition*, 75, 1, 1–28.

[11] Borun, M., Chambers, M., & Cleghorn, A. 1996. Families are learning in science museums. *Curator, 39*(2), 262-270.

[12] Brunyé, T. T., Ditman, T., Mahoney, C. R., Augustyn, J. S., & Taylor, H. A. 2009. When you and I share perspectives pronouns modulate perspective taking during narrative comprehension. *Psychological Science, 20*(1), 27-32.

[13] Cabrera, J. S., Frutos, H. M., Stoica, A. G., Avouris, N., Dimitriadis, Y., Fiotakis, G., et al. 2005. Mystery in the museum: collaborative learning activities using handheld devices. In the *Proceedings of the 7th international conference on Human computer interaction with mobile devices & services*. ACM, New York, NY.

[14] Cafaro, F., Lyons, L., Kang, R., Radinsky, J., Roberts, J., and Vogt, K. 2013. Framed Guessability: Using Embodied Allegories to Increase User Agreement on Gesture Sets. *Procs of the 8th Int'l Conference on Tangible, Embedded and Embodied Interaction*, ACM, 197–204.

[15] Cafaro, F., Panella, A., Lyons, L., Roberts, J., and Radinsky, J. 2013. I see you there!: developing identity-preserving embodied interaction for museum exhibits. *Proceedings of the 2013 ACM annual conference on Human factors in computing systems*, ACM, 1911–1920.

[16] Carlisle, R. W. 1985. What Do School Children Do at a Science Center? *Curator, 28*(1).

[17] Diamond, J., Bond, A., Schenker, B., Meier, D., & Twersky, D. 1995. Collaborative multimedia. *Curator* 38, 3, 137-149.

[18] Dini, R., Paternò, F., & Santoro, C. 2007. An environment to support multi-user interaction and cooperation for improving museum visits through games. In the *Proceedings of the 9th international conference on Human computer interaction with mobile devices and services*. ACM, New York, NY.

[19] Dourish, P. 2001. *Where the action is: the foundations of embodied interaction*. Cambridge, MA, USA: MIT Press.

[20] Enyedy, N., Danish, J. A., DeLiema, D. 2013. Constructing and Deconstructing Materially-Anchored Conceptual Blends in an Augmented Reality Collaborative Learning Environment (full paper). In S. Puntambekar, N. Rummel, M. Kapur M. Nathan (Eds.), Proceedings of the 10th International Conference on Computer Supported Collaborative Learning. Madison, WI.

[21] Falcão, T. P., & Price, S. 2009. What have you done! The role of 'interference' in tangible environments for supporting collaborative learning. In Proceedings of the *Conference on Computer Supported Collaborative Learning.* CSCL'09. ISLS, 324-334.

[22] Gentner, D., Imai, M., & Boroditsky, L. 2002. As time goes by: Evidence for two systems in processing space → time metaphors. *Language and Cognitive Processes*, 17, 5, 537-565.

[23] Golledge, R. G. 1995. Primitives of Spatial Knowledge. In Nyerges T. L., D. M. Mark, R. Laurini, & M. J. Egenhofer (Eds.), *Cognitive Aspects of Human-Computer Interaction for Geographic Information Systems* (pp. 29-44), Dordrecht: Kluwer Academic Publishers.

[24] Goodchild, M. F., & Janelle, D. G. 2010. Toward critical spatial thinking in the social sciences and humanities. *GeoJournal*, *75*(1), 3-13.

[25] Heath, C., & Vom Lehn, D. 2008. Configuring 'Interactivity' Enhancing Engagement in Science Centres and Museums. *Social Studies of Science*,*38*(1), 63-91.

[26] Hope, T., Nakamura, Y., Takahashi, T., Nobayashi, A., Fukuoka, S., Hamasaki, M., et al. 2009. Familial collaborations in a museum. In the *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. ACM, New York, NY.

[27] Hurtienne, J. and Israel, J.H. 2007. Image schemas and their metaphorical extensions. *Tangible and Embedded Interaction*, ACM Press 127.

[28] Janelle, D.G. and Goodchild, M.F. 2011. Concepts, Principles, Toolse, and Challenges in Spatially Integrated Social Science. In Nyerges, T.L., H Couclelis, and R. McMaster (Eds.) The Sage Handbook of GIS & Society. Sage Publications. pp 27-45

[29] Jimenez, P. and Lyons, L. 2011. An Exploratory Study of Input Modalities for Mobile Devices Used with Museum Exhibits. In *Proceedings of the 29th international conference*

on Human factors in computing systems. CHI '11. ACM, New York, NY, 895-904.

[30] Johnson, M. 1987. *The Body in the Mind*. *The body in the mind*. The University of Chicago Press.

[31] Kaufman, M. M. 2004. Using Spatial-Temporal Primitives to Improve Geographic Skills for Preservice Teachers. *Journal of Geography,* 103(4), 171-181

[32] Klopfer, E., Perry, J., Squire, K., & Jan, M. 2005. Mystery at the Museum – A Collaborative Game for Museum Education. In the *Proceedings of the Conference on Computer Supported Collaborative Learning.* CSCL '05. ISLS, 316-320.

[33] Leinhardt, G., Crowley, K., & Knutson, K. (Eds.). 2002. *Learning Conversations in Museums*. Mahwah, New Jersey: Lawrence Erlbaum.

[34] Lindgren, Robb. 2012. Generating a learning stance through perspective-taking in a virtual environment. *Comput. Hum. Behav.* 28, 4 (July 2012), 1130-1139.

[35] Lyons, L. 2009. Designing Opportunistic User Interfaces to Support a Collaborative Museum Exhibit. In Proceedings of the *Conference on Computer Supported Collaborative Learning*. CSCL '09. ISLS, 375-384.

[36] Lyons, L., Cafaro, F., Radinsky, J., Roberts, J., Vogt, K. (2014). Aggregating Agency to Support Collaborative Learning in a Museum Exhibit at Chicago. Paper presented at *American Education Research Association (AERA '14)*. Philadelphia, PA, USA.

[37] Macedonia, M. 2003. Revitalizing museums with digital technology. *Computer 36*(2), 94-96.

[38] Meisner, R., Lehn, D.V., Heath, C., Burch, A., Gammon, B., and Reisman, M. 2007. Exhibiting Performance: Co-participation in science centres and museums. *International Journal of Science Education,* 29, 12, 1531 - 1555.

[39] National Research Council. 2007. Taking science to school: Learning and teaching science in *grades K-8.* Committee on science learning, kindergarten through eighth grade. R. A. Duschl, H. A. Schweingruber, & A. W. Shouse (Eds.). Board on Science Education, Center for Education. Division of Behavioral and Social Sciences and Education. Washington, D.C.: The National Academies Press.

[40] National Research Council. 2009. *Learning Science in Informal Environments: People, Places, and Pursuits*. The National Academies Press, Washington, DC.

[41] Ochs, E., Gonzales, P., & Jacoby, S. 1996. "When I come down I'm in the domain state": grammar and graphic representation in the interpretive activity of physicists. *Studies in Interactional Sociolinguistics*, *13*, 328-369.

[42] Olson, D.R. 2010. *Building Interactive Systems: Principles for Human Computer Interaction (1st Ed.)*. Florence, KY: Cengage Learning.

[43] Radinsky, J., Melendez, J., Roberts, J. 2012. Do the Data Strike Back? Students' Presentations of Historical Narratives about Latino Communities using GIS. In Josh Radinsky (Chair), Tools for Constructing Historical Narratives: Teaching African American and Latino Histories With GIS Census Maps. Symposium conducted at the meeting of the American Educational Research Association, Vancouver, B.C., Canada.

[44] Roberts, J., Lyons, L., Radinsky, J., Cafaro, F. 2012. Proceedings from ICLS 2012. *Connecting Visitors to Exhibits through Design: Exploring United States census data with CoCensus*. Sydney, Australia.

[45] Roberts, J., Cafaro, C., Kang, R., Vogt, K., Lyons, L., & Radinsky, J. 2013. That's Me and That's You: Museum visitors' perspective-taking around an embodied interaction data map display. In *Proceedings of the 10th International Conference on Computer-Supported Collaborative Learning*. Madison, WI, USA. 343-344.

[46] 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.

[47] Semper, R. 2008. Science museums as environments for learning. *Physics Today* 43, 11 (Jan. 2008), 50–56.

[48] Stock, O., Zancanaro, M., Busetta, P., Callaway, C., Kruger, A., Kruppa, M., et al. 2007. Adaptive, intelligent presentation of information for the museum visitor in PEACH. *User Modeling and User-Adapted Interaction*, 17, 3, 257 - 304.

[49] Suh, K. S., Kim, H., & Suh, E. K. (2011). What if your avatar looks like you? dual congruity perspectives for avatar use. *MIs Quarterly*, *35*(3), 711-730.

[50] Tscholl, M., Lindgren, R., and Johnson, E. 2013. Enacting orbits: refining the design of a full-body learning simulation. In *Proc of the 12th Int'l Conference on Interaction Design & Children.* IDC '13. ACM, New York, NY, 451-454.

[51] vom Lehn, D., Heath, C., & Hindmarsh, J. 2001. Conduct and Collaboration in Museums and Galleries. *Symbolic Interaction,* 24, 2, 189-216.

[52] Vygotsky, L. 1987. Zone of proximal development. Mind in Society: The Development of Higher Psychological Processes, 52-91.

[53] Wagner, D., Schmalstieg, D., & Billinghurst, M. 2006. Handheld AR for Collaborative Edutainment. Proceedings of the International Conference on Artificial Reality and Telexistence. ICAT '06. IEEE, 85-96.

[54] Wobbrock, J.O., Morris, M.R., and Wilson, A.D. User-defined gestures for surface computing. 2009. In *Proc of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. ACM, New York, NY, 1083–1092.

[55] Yatani, K., Sugimoto, M., & Kusunoki, F. 2004. *Musex: A System for Supporting Children's Collaborative Learning in a Museum with PDAs.* Paper presented at the the 2004 IEEE International Workshop on Wireless and Mobile Technologies in Education, Taoyuan, Taiwan.

[56] Yoon, S. A., Elinich, K., Wang, J., Steinmeier, C., & Tucker, S. 2012. Using augmented reality and knowledge-building scaffolds to improve learning in a science museum. *International Journal of Computer-Supported Collaborative Learning, 7*(4), 519-541.

[57] Zimmerman, H. T., Reeve, S., & Bell, P. 2010. Family sense-making practices in science center conversations. *Science Education, 94*(3), 478-505