Seeing *Tornado*: How *Video Traces* Mediate Visitor Understandings of (Natural?) Phenomena in a Science Museum

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ABSTRACT: This article reports an exploratory study of how people see and explain a prominent exhibit *(Tornado)* at an interactive science museum (the *Exploratorium*). Our data was assembled using a novel, technically mediated activity system *(Video Traces)* that allowed visitors to reflect with an interviewer on video records of their own visits to the exhibit. We present qualitative data comparing initial visits to the exhibit with those in the *Video Traces* environment to argue that *Video Traces* offers a promising means of exploring visitors' current understandings of exhibit phenomena, as well as mediating new understandings of these phenomena. We illustrate this argument with two vignettes drawn from our data that show the flexibility of *Video Traces* for supporting different forms of inquiry. Finally, we discuss how an expanded *Video Traces* system could provide ongoing opportunities for representation and inquiry at interactive science centers. *Sci Ed* **81:**735–747, 1997.

INTRODUCTION

A persistent question for educators at interactive science centers like the Exploratorium is what do visitors learn from their experiences with the exhibits. A related question is how can new opportunities for learning be created. With both these questions in mind and with a firm understanding that the pedagogical goals of Exploratorium educators differ in important ways from most classroom educators (Duensing, 1987), we set out to explore the experiences of Exploratorium visitors at a single, highly popular exhibit called *Tornado*. As part of this study, we introduced a novel technical arrangement we call *Video Traces*.

Our approach to providing new learning opportunities was driven by a theoretical interest in how learners make and use representations, one of the few forms of interaction undersupported in the wildly interactive setting of the Exploratorium. Except in ephemeral forms of talk and gesture, visitors have few opportunities to record, inspect, or leave a trace of their activity while engaged

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with exhibits in the museum. However, representational action—the selective transformation of experience into material forms—is fundamental to both scientific work practices (Goodwin, 1993, 1994, 1995; Lynch, 1990; Star, 1983) and learning (diSessa, Hammer, & Sherin, 1991; Hall, 1996).

More generally, we approach learning and the role of representational action in this paper in terms of inquiry learning (Dewey, 1938; Roschelle, 1992). By this we mean a process that: (a) begins with the learner's experience of a puzzling phenomena; (b) progresses through detailed examination and analysis of the phenomena; (c) allows the learner to construct new understandings by refining and restructuring ideas through action, representational or otherwise; and (d) results in a new, hopefully deeper, understanding of the principles and elements at work in the phenomena, thereby resolving the initial puzzle.

To provide opportunities for representational action as part of inquiry learning, we arranged audio–video recording and playback equipment in a booth near the *Tornado* exhibit. This technical arrangement, which we call *Video Traces,* allowed us to record visitors' interaction with the exhibit. We could then bring these same visitors to the booth to watch and discuss an audio–video record of their recently completed interaction. In addition to basic questions about how visitors understood the exhibit phenomena, we began our study with the hypothesis that the combined effect of extended conversation, the features of the technological arrangement, and the fact that visitors were observing themselves interacting with the exhibit would support new ways of seeing and understanding *Tornado.*

Our study proceeds as follows: (1) we describe the Exploratorium *Tornado,* and the technical arrangement of *Video Traces;* (2) we report our early results about visitors' activity in the *Video Traces* booth, comparing these with baseline records of their initial visits to *Tornado* and, more generally, to conversations typical in science centers; (3) we illustrate the possibilities of *Video Traces* with two vignettes drawn from our corpus of interviews; and (4) we conclude that *Video Traces* offers a promising sociotechnical arrangement for investigating current understandings and mediating new understandings of exhibit phenomena in interactive science centers. We end the study by describing how *Video Traces* could be expanded to support different kinds of representational activity.

VIDEO TRACES: AN EXPERIMENT IN MEDIATED PERCEPTION

The Setting: The Exploratorium

The Exploratorium describes itself as "a museum of science, art, and human perception." Unlike typical museums that are divided into different galleries, the Exploratorium is a cavernous open space, with interactive, thematically grouped exhibits located throughout the exhibit hall. Also, unlike traditional museums, where hushed tones prevail, the exhibit hall echoes with boisterous noise from people and exhibits.

The principles that guide exhibit design at the Exploratorium are varied, but they share an emphasis on creating an environment in which visitors have "direct experiences" in "a woods of natural phenomenon" (Oppenheimer & Exploratorium, 1986). Exhibits reflect these principles in at least two ways. First, there is almost always something to do with an exhibit, something to touch or some way of locating your body to have a vivid or unexpected perceptual experience. Second, very little instructional text or visual representation accompanies an exhibit, and these absences are by design. As Duensing (1993) writes:

> Creating direct experiences with nature continues to be a fundamental exhibit development principle of the Exploratorium. As much as possible, we exhibit the actual phenomena rather than a model. There is something intrinsically interesting in the "real thing" . . . (p. 2)

The Exhibit: *Tornado*

One of the museum's most engaging and beautiful exhibits, *Tornado* is a 15-ft.-high cylindrical chamber in which a water vapor vortex mimics the morphology of an actual tornado, albeit an inverted one (see Figs. 1 and 2). Masses of water vapor leave the base of a disk-shaped platform and are drawn upward by a fan at the top of the chamber. The chamber is partially enclosed on two opposite quarters of the cylinder and is open on the two other opposite quarters. Two opposing, vertical tubes stand just inside the enclosed portions and blow air silently along the insides of the cylindrical walls. This causes air to rotate in a horizontal plane, and the combined effect of the horizontal rotation and the updraft from the fan creates the vortex. The platform at the bottom is elevated about a foot, and people can climb inside the chamber to interact with the vortex. At the front (i.e., the open quarter where most people approach) there is a button that stops the fan and thereby the vortex. The label that accompanies the button simply states, "Push to stop," with no mention that the button stops the overhead fan. A description of the exhibit, including pictures and drawings of tornadoes, is posted behind the exhibit. During our observations at the museum, visitors seldom read this description, either before or after interacting with *Tornado*.

While *Tornado* mimics much of the morphology of a real-world tornado on a small scale, an account of its sociotechnical design history (Oppenheimer & Exploratorium, 1986) reveals that it is an iteratively crafted object. Designer Ned Kahn arrived at the current form of the exhibit, which appears to visitors as a graceful, natural tornado-like vortex, only after a series of four quite different design prototypes. The details of this story show how *Tornado* got its shell—the partial, enclosing cylinder in which blowing air circulates and allows the vortex to form. Over multiple design iterations, Kahn experimented with electric frying pans, twisted plexiglass, Styrofoam peanuts, fog, other designers and their notebooks, gigantic fans, multiple smaller fans, shifts in conceptualization of scale, extremely expensive dry ice, and inexpensive ultrasonic humidifiers. In this sense, the story of the exhibit's design parallels the kind of human persistence that is usually necessary for scientists to make "natural" events visible or reportable (Gilbert & Mulkay, 1984; Knorr-Cetina, 1981; Latour 1987a, 1990; Lynch, 1990).

The Experimental Apparatus: *Video Traces*

After observing visitor traffic in the Exploratorium for several days and talking with museum staff, we decided to build a technical arrangement that would allow visitors to record and manipulate audio–video traces of their interaction with *Tornado.* We focused one video camera on *Tornado,* recorded visitors' interactions with the exhibit, and then invited visitors to watch these recordings with us. A sign informed visitors that the exhibit was being filmed as part of our study. In a nearby booth, we arranged playback decks, a television monitor, and a second camera. Using the second camera, we recorded viewing activities and conversations inside the booth. Figure 1 shows the arrangement of the *Video Traces* booth in relation to the exhibit.

After groups or individuals visited the *Tornado,* we approached those who had spent at least a minute at the exhibit and asked if they would be interested in seeing and talking about a video record of their interaction with the exhibit. Some visitors declined, but all those participating in the study gave informed consent for us to use both video records (exhibit and booth) for research purposes. The resulting data consist of 14 interviews conducted with individuals or groups during a week of afternoon visits during April 1994.

Conversations/interviews in the booth were semistructured (Burgess, 1984). We asked questions similar to those textually displayed at *Tornado* and most of the exhibits: What did you notice? What do you think is going on here? What do you think makes the tornado spin?

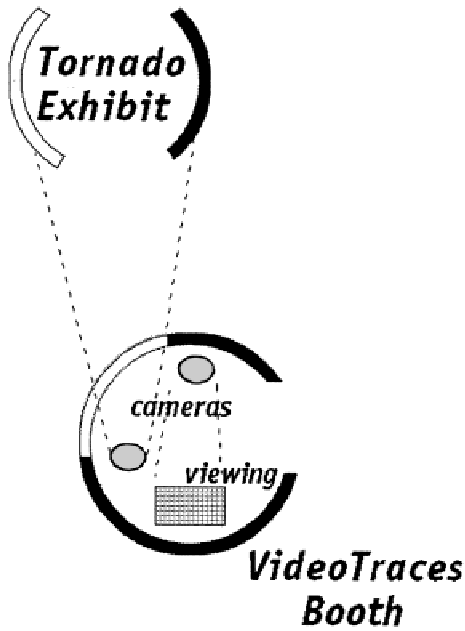

Figure 1. Layout of the *Video Traces* booth in relation to the *Tornado* exhibit. White arcs show transparent enclosures; black arcs show opaque enclosures. The *Video Traces* booth was a closed cylindrical dome with a drape covering the door, shielding our interviews from ambient noise on the museum floor.

During conversations about the video records, we used remote controllers for the playback deck to view recorded action in slow motion, to freeze frames that were particularly interesting, and to rewind and review strips of interaction that were visually interesting or puzzling. Given such fine-grained and repeatable access to a video record of interaction, visitors' representational resources in the booth were quite different from those at the exhibit. For example (see Vignette 1 and Fig. 3a), if a visitor stands inside *Tornado* and disrupts the vortex with her breath, she may not even notice the results, because the displaced water vapor appears on the opposite side of the vortex and disappears almost immediately. In contrast, a video record of these events, taken from an observer's perspective, can be an optimal medium for noticing dynamic phenomena, stretching their temporal duration, and investigating how they are formed. We expected these differences to support inquiry by providing new resources for representational action as visitors moved back and forth between the exhibit and the *Video Traces* booth.

RESULTS

Visitors' Initial Interactions with *Tornado* (Prior to *Video Traces*)

Fourteen groups or individuals participated in our pilot study, after visiting *Tornado* as part of their own path through the Exploratorium. Thus, we recorded initial visits by four family groups of adults and children, four male–female couples, five individual men, and one individual woman. Many unaccompanied minors visited the exhibit during our study, but because we could not obtain informed consent, we did not invite them into the *Video Traces* booth or record their interactions with the exhibit. The mean duration of initial exhibit visits by the 14 groups was 2.2 minutes (range 40 seconds to 4.5 minutes). This agrees with general findings about the duration of exhibit visits at science centers which last an average of only 2 minutes (Falk & Dierking, 1992).

The qualitative character of behavior we observed during initial visits to *Tornado* (i.e., prior to entering the *Video Traces* booth) also resembled behavior reported in other studies of interactive science centers. Parents use conversations at the exhibit to discipline and maintain their children's social behavior (Diamond, 1980; Falk & Dierking, 1992) and to focus on the familiar (Taylor, 1985). At exhibits designed to be physically handled, adults often did not touch the exhibits nor allow their children to do so (Falk & Dierking, 1992). While adults in our sample did not completely prohibit bodily interaction with *Tornado,* they did regulate how their children entered and interacted with the exhibit and often expressed concern that their children were overly physical when interacting with it. For example, in Vignette 1, parents only allowed their children to get inside *Tornado* after agreeing that the Exploratorium was a "hands-on kind of place." Unlike most children, adults rarely attempted to get inside *Tornado.* Figure 2 shows two images from our video records of initial visits that exemplify differences in the ways that adults and children interacted with the exhibit.

Finally, our analyses of the video records of initial visits (as well as our prior observations) suggested that little sustained inquiry learning happens at *Tornado.* Other studies of learning at science exhibits report similar findings, describing the knowledge visitors acquire as "concrete" (answering questions like "what is it?") rather than "abstract" (answering questions like "what are the principles involved?") (Falk & Dierking, 1992) and at the level of "effects" rather than "explanations" and "understanding" (Stevenson, 1991). There may be many reasons for this, but two stand out in our observations of visitors' activity at *Tornado.* First, because the exhibit is so popular, there is considerable pressure to finish one's turn when others are waiting. Second, the vortex is easily disrupted when visitors enter the exhibit, and a well-developed vortex can take several minutes to re-form. Somewhat paradoxically, these environmental features both shorten visit duration and make it possible for visitors to take actions that have highly visible physical consequences.

In our view, this makes the *Tornado* exhibit an excellent candidate for adding a *Video Traces* arrangement, because dramatic visual changes of short duration can be preserved, reviewed, manipulated, and repeated. More generally, providing enhanced opportunities for inquiry learning without disrupting existing patterns of visitor interaction is an ongoing research

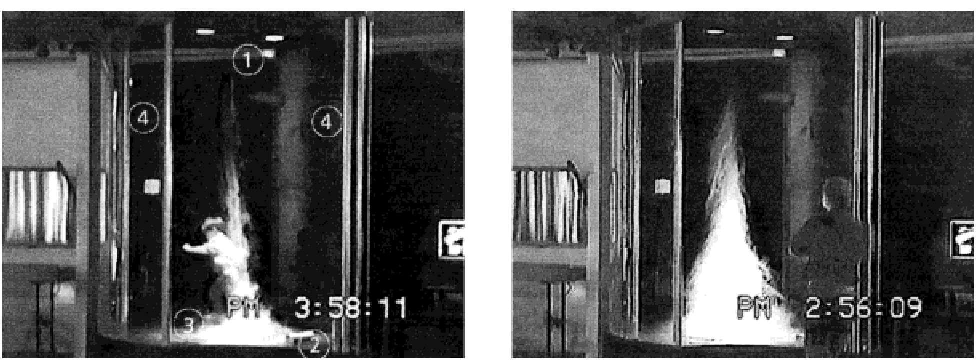

Figure 2. Two images showing a common difference in the way that children and adults interact with *Tornado*. The right image shows an adult male, standing outside to watch the vortex form. The left image shows a child inside the exhibit, running around the vortex (i.e., with the direction of spin). The left image also shows locations for relevant mechanisms: (1) a fan draws air up; (2) visitors may push and hold a button to stop the fan; (3) fog comes up through a grating in the floor, and (4) two vertical tubes with small holes blow air silently around the chamber.

and design challenge at the Exploratorium. Rob Semper, Associate Director at the Exploratorium, describes this as designing “activities [that] support in-depth, extended learning experiences that are somewhere in between a casual museum visit and a class setting” (Semper, 1990, p. 56).

Visitors’ Interactions with *Tornado* using *Video Traces*

Our general finding is that the duration and quality of visitors’ interactions in the *Video Traces* booth differed markedly from their initial visits to *Tornado*. Our claim, partly supported by the present study, is that combining more durable (but still plastic) resources for representational activity (i.e., video capture and replay) with open-ended conversations about what makes an interactive exhibit work can effectively support inquiry learning in an interactive science museum like the Exploratorium. We now turn to more specific, comparative findings.

The mean duration of visits to the *Video Traces* booth was 16 minutes (range 8.5 to 26 minutes), compared to about 2 minutes during participants’ initial visits to the exhibit. Conversations, set in motion by simple questions about “What do you notice?” and “What is going on here?” were largely conceptual in content, with visitors offering explanations for the phenomena and asking questions of their own. Most importantly, the video record provided access to the microstructure of the *Tornado* phenomena (e.g., the shape of the vortex, its components, and activities that disrupt it) with resources for representational action that were unlikely or even impossible at the exhibit itself. These resources made phenomena accountable (Garfinkel, 1967)—observable and reportable—in a new way. This capacity to capture and examine phenomena in more durable media—enhancing the visibility of selected features for detailed exploration—is basic to many (if not most) contemporary scientific practices (Gordin & Pea, 1995; Latour, 1990; Lynch, 1990).

The initiating event of an inquiry learning process is the presentation or discovery of a puzzling experience that leads a person to subsequent detailed investigations. Conversations centered around puzzles were the norm in the *Video Traces* booth. Most of the experiences that became puzzling for visitors were brought into conversation after noticing and visually inspecting them in the initial video record. In conversation, the interviewer and the visitors puzzled over and pursued questions such as: What makes *Tornado* spin? What gives the vortex its hollow core? (see Fig. 2a). Why does the core remain a constant diameter while the diameter of the entire vortex changes? Why does the vortex “snake” laterally within the chamber? Why is *Tornado* upside-down by comparison with a real-world tornado?

More than simply watching the phenomena and one’s interaction with it, the capacity to talk about a visual record when its time-scale had been altered, either by running it slower or freezing a single video frame, provided unique resources for inquiry-based conversations. For example, in two different interviews where the video record played at ⅕ real-time speed, participants narrated the sequence of events through which the vortex formed. Watching the phenomena in slow motion also allowed one visitor to notice that vapor furthest from the center of the vortex fell down while vapor closer to the center spiraled upward. This led the visitor to discuss competition and collaboration of mechanical, centrifugal, and gravitational forces. In other interviews (e.g., Vignette 1), freezing the video record on a single frame at a critical moment enabled conversation about the forces at work in the exhibit and led visitors (e.g., a father and his children) to suggest returning to the exhibit for simple experiments.

While visitors talked about puzzles with the interviewer in the booth, they were also willing to return to the exhibit and investigate the phenomena with new questions. This represents a second crucial aspect of an inquiry learning process: taking opportunities for reflection and new forms of action in pursuit of resolutions to previous puzzles. Of the 14 groups or individuals, five were invited to return to the exhibit to answer a question that came up in the interview, and none declined the invitation. One additional participant group suggested a return to the exhibit themselves. Of the 14 participant groups, seven returned to the exhibit on their own after the interview was concluded. (In the next section, two specific examples of returns are provided in Vignettes 1 and 2.) We take it to be a particularly important result that *Video Traces* in combination with a compelling exhibit set up an iterative system of activity for doing inquiry in the museum.

A final result in this study concerns one type of explanation offered by adult participants when asked "What makes it spin?" After learning that the button was not directly responsible for this phenomenon, adult visitors frequently attributed the cause of spinning to "natural" forces like heat, the Coreolis force, ambient air currents on the museum floor, or to the circular shape of the exhibit as the "simplest shape in nature." Although some of these natural causes are relevant to the production of real tornadoes (Eagleman, 1983; Miller, 1987; Grazulis, 1991; Fraser, 1996), none provides an accurate explanation for what makes *Tornado* spin. As a designed artifact, the exhibit produces a spinning vortex because (in combination) a fan draws water vapor upward and forced air from opposing vertical tubes makes this vapor rotate along a horizontal plane. Both of these phenomena (uplift and rotation) are found in natural tornadoes, but there are important differences between the exhibit and the natural phenomenon it is designed to model (e.g., the mechanisms that cause uplift and rotation, and the inverted shape of the vortex). Ironically, the same adults who appeal to natural causes typically stand outside the exhibit to watch it, thus missing bodily experiences that would help them notice designed causes (e.g., inside the exhibit, you can feel the forced air).

By reporting these misattributions of natural cause, we are not arguing that adult visitors have faulty conceptions of the natural world (they may, of course), nor are we claiming that *Tornado* is a misleading science exhibit (this depends upon how people use it). Instead, we think important issues concerning the production and dissemination of scientific knowledge are highlighted by our study participants' accounts of how the exhibit works. First, it is not a trivial matter to disentangle the role of humans and machines in the production of scientific knowledge claims, as a growing body of research in science and technology studies (STS) has shown. (see Latour [1987a] and Pickering [1992] for surveys of these types of studies). Second, our analysis of visitors' activity in and out of the *Video Traces* booth suggests that the contingency of scientific accounts is (or can become) relevant to museum visitors. Furthermore, it is likely that any form of sustained inquiry into how scientific models work (e.g., What makes *Tornado* spin?) quickly leads to questions about what is included in the model, what is excluded from the model, and why. In our view, these are good questions to be asking when one learns about science.

If *Video Traces* is a flexible system for mediating perception of exhibit phenomena in the Exploratorium and settings like it, it should be usable for pursuing puzzles of many types. These include puzzles that can be resolved by appealing to natural forces (gravity, air, friction, etc.) but also to sociotechnical forces (silent air tubes, fans, gift store humidifiers, etc.). Both forces can be found everywhere in science museums and, if we are to believe STS accounts, everywhere in nature as presented by scientists.

Two Vignettes

We now turn to the two vignettes that demonstrate the possibilities of *Video Traces* for mediating perception of exhibit phenomena and for creating occasions for inquiry learning. These vignettes were chosen to be representative of conversations analyzed in our larger inter-

Figure 3. (a) The interviewer pointing out the part of *Tornado* visibly moved by a child's breath. (b) Two adult visitors returning from the booth to the exhibit to discover the silent tubes that move air around the chamber.

view corpus, but also to contrast children and adults under circumstances where they returned to the exhibit with new questions.

Vignette 1: Guided Discovery of Air As an Invisible Natural Force. Vignette 1 involves a father and his two children, a girl (8 years old) and a boy (5 years old). When their group, including the children's mother and a male friend, initially visited the exhibit, the children pleaded with their parents to get into *Tornado.* After some discussion, the adults allowed them to enter the exhibit, remarking that the Exploratorium is supposed to be a "hands-on kind of place." After the children were inside the chamber for a few moments the father stopped the phenomenon by pushing the button at the front of the exhibit. As the vortex died down, the children urged their father to "Start it, Pop," which he eventually did, and the vortex reformed. As the family left the exhibit, we invited them to participate in our experiment.

Inside the booth, we used the video record of their visit to discuss a number of *Tornado's* features, and when the interviewer asked the girl, "Do you need to touch it to mess it up?" she said she was unsure but thought so. This led her father to suggest they "go and try it." They returned to the exhibit and, as we again recorded their activity, the father guided the children through an experiment in which they were to try to "do anything you can to mess it up without touching it." As the children stood beside each other, the older girl first led them to wave their hands toward the vortex and then to lean in and blow on it. The children and their father then returned to the *Video Traces* booth.

As the conversation resumed about whether you need to touch the vortex to "mess it up," the interviewer serendipitously froze the video image just as the girl blew a chunk out of the vortex (see Fig. 3a). With this striking image in view, the interviewer again asked if they could mess it up without touching the vortex.[1]

Int: Ooo[1], look right the[re.][2]

1 (pauses videotape to display still image)

2 (points to part of still tornado that is blown out)

[1] Transcripts conventions include the following: action descriptions are indexed with italicized numbers at their onset within an utterance; the boundaries of overlapping talk are shown with leading and trailing brackets; elongated pronunciation is shown with repeated colons; and words spoken with emphasis are shown in all caps.

Father: [Ooo.]

Int: Let's look at that one. You're not touching it, are you?

Girl: No.

Int: But did you change it.

Girl: Yeah.

Father: What changed it?

Girl: That I was blowing on it, that messed it up.

Int: That's sort of like touching it?

Girl: Mm, hmm.

Father: What are you touching it with?

Girl: AIR.

Vignette 1 demonstrates how an initial puzzle, raised by the interviewer, is taken up by the girl and her father during a return trip to *Tornado.* Inside the exhibit, the girl leads her younger brother to try out alternative actions that might "mess up" the vortex without touching it, then they all return to the *Video Traces* booth. By stopping the video record of this experiment just as the girl's breath displaces part of the vortex, the interviewer and the girl's father are able to guide her to identify a previously invisible entity (i.e., "AIR") as the means of disrupting the vortex. We take this kind of conversation to be a form of inquiry and, when sustained, to lead to the kinds of conceptual change that science educators work to cultivate.

Vignette 2: Adults Return to* Tornado *Looking for Sociotechnical Forces. Vignette 2 involves an adult couple. After standing together outside *Tornado* and gazing silently at the moving vortex, they walked away and we invited them to participate in our experiment. In the *Video Traces* booth, the interviewer asked what makes *Tornado* spin, and they identified the fan at the top of the exhibit. Having already found that adults seldom notice the air tubes as a cause of the spinning vortex, the interviewer told the couple that it was not primarily the fan that produced spin and asked for other explanations.

Without being able to identify other visible mechanisms, the couple began appealing to natural forces. The man said that, because a circle is the simplest shape in nature, the vortex forms circularly. The woman first suggested that spin had something to do with the shape of the chamber, then that it had something to do with heat. The interview continued, and when the couple was asked if they had any questions, the woman said that she "just want[ed] to know all the secrets." The interviewer told them at least one more secret could be discovered—the source of the spinning air—and asked if they would like to return to figure it out. Because the couple was on their way out of the museum, and it was nearly closing time, the interviewer suggested they make only a brief stop at the exhibit. Figure 3b shows the couple finding the air tubes and, in the seconds that follow this discovery, turning back to the booth and signaling "okay" with their hands. As in the first vignette, puzzles encountered inside the *Video Traces* booth lead visitors back to the exhibit with new questions. In this case, the tension between designed and natural causes is resolved in favor of the former.

DISCUSSION AND CONCLUSION

Just as reflective, representational action is undersupported in the Exploratorium and science centers like it, so too is video technology underutilized as a resource for educational purposes more generally.[2] In both classrooms and science centers, information technologies have received extensive (sometimes exclusive) attention. While we advocate continued development of software and hardware designed to facilitate learning, video is a flexible technology with complementary attributes, and we think *Video Traces* is an exemplar of an activity system that takes advantage of many of these attributes. At a practical level, there are also obvious advantages to a system composed of low-cost, off-the-shelf recording and playback equipment.

There are several conceptual features of *Video Traces* that appear to support valued types of activity and learning. First, giving people access to images of their own activity may allow them to speak more expansively and with more ownership about scientific phenomena than they would in more asymmetric interview situations (Harper, 1987). Second, the combination of video records and familiar device controllers (i.e., hand-held remotes) may tap sophisticated strategies for watching and inspecting visual images, because video records circulate widely in popular culture (Cubitt, 1991).

Third, under the premise that representational action is fundamental to scientific learning and doing, video records of one's own experience offer a unique type of bridging representation in the museum setting. Located between the naturally occurring forms of talk and gesture that occur during experiences at exhibits and conventional scientific representations that abstract experiences into specific forms like graphs or general principles, our records both retain a trace of the original experience at the same time as making that trace available to new forms of scrutiny. Investigations of the microstructure of the phenomena, through replay, freeze frame, and slow motion, are transformative representational practices we observed to be usable resources for visitors, resources that led to questions and subsequent investigations.[3]

Fourth, *Video Traces* was a flexible activity system for investigating different kinds of scientific puzzles. On one hand, it became a site for pursuing conventional pedagogical goals in an inquiry mode, as in Vignette 1, where adults guided a child to identify air as a mechanism for "touching the tornado." On the other hand, when we realized that adults were recurrently failing to account for an invisible sociotechnical mechanism (the quiet air tubes) rather than a natural one, we were able to explore this as a puzzle and send these adults back to the exhibit to plumb these kinds of "secrets," as in Vignette 2. More systematic studies with *Video Traces* should be conducted to determine whether the type of guided discovery in Vignette 1 would be rare or frequent, but each of the other three adult–child interactions also involved lengthy, interesting conversations between adults and child about the phenomena. By interesting we mean they were predominantly: (a) about visually available phenomena; and (b) how these phenomena reflect the activities of visitors in the record. This makes the *Video Traces* booth an environment that is strongly structured for eliciting talk about how phenomena work, which compares favorably with our participants' initial visits and the existing literature on exhibit visits.

The finding that adults miss certain crafted features of the exhibit and thereby appeal to natural causes from some sort of lay-science catalog appears quite robust, at least at this exhibit. It remains to be seen whether using *Video Traces* at other exhibits at the Exploratorium or

[2]Video continues to grow in prominence as a tool for doing research about learning, but remains little used in activity systems designed for learning itself. (For an exception, see Rubin, 1993.) It is this latter sense we focus on here.

[3]Other representational resources were provided that, although barely explored in this pilot study, could function as further stepping stones on a path from spontaneous to scientific (or artistic) representations. For example, we taped a piece of clear plastic over the screen and invited one visitor to draw directly on top of the stilled image of the vortex.

elsewhere would show a general pattern of visitors making such appeals despite discoverable, crafted features of the exhibit that would challenge the attributions of these kinds of natural causes. Regardless, these initial findings lead us to believe that science centers may be especially promising places for people to investigate the boundary between what is real and what is a model, between what is natural and what is crafted.

Contemporary educational research operates in two, sometimes contradictory modes. In one mode, we study what people understand and how they learn in the course of their activities. In another mode, we intervene to create environments in which thinking or learning may be facilitated. *Video Traces* appears to be a flexible system in this sense as well. We can either use this technical arrangement as a form of elicited interview in studies of thinking and learning (Frankel, 1984; Harper, 1987; Jordan & Henderson, 1995) or we can use the technology to create more systematic forms of intervention. In this latter mode, we still have much to learn about how new representational resources can be used to reorganize visitors' experiences in interactive science museums.

We end this article by looking forward to variations in how the *Video Traces* idea could be extended. A first variation, already suggested here, is to try *Video Traces* at different exhibits both in the Exploratorium and elsewhere. This could be a potentially useful investigative paradigm for assembling a comparative corpus that could vary across many dimensions: types of exhibits; types of museums; types of communities served by museums; and, of course, types of visitor groups.

A second variation would involve a stand-alone library of video trace records that would reside and accumulate next to an exhibit. In this variation, the traces would be produced without the mediating interview. Instead, we would arrange video equipment that could be controlled using a simple interface. Visitors who wanted to capture their activity could use this interface to start and stop a video recording of their interaction with the exhibit. They could then return to the interface to review this record, possibly recording an audio annotation over the video trace. In this variation, visitors could comment on what they did, what they could not do, and what they figured out; they could pose questions, suggest experiments, or make analogies to other experiences. Using little more than the kind of interface already present on most consumer camcorders, it would be possible to extend the well-documented observation that visitors learn by watching other people do things in interactive exhibits (Diamond, 1980).

A third variation would be to move video trace records, produced in either the interview or the stand-alone format, to settings outside the science center, like homes or schools. *Video Traces* have two generic features of scientific representations—mobility and immutability (Latour, 1990)—that are well suited to this task. Video trace records are immutable in that the record stays the same, regardless of who plays it and when; they are mobile in the sense that these records can be examined anyplace people have access to a video device with a standard set of controls (e.g., pause and playback at various speeds). This variant of *Video Traces* could allow teachers to design learning experiences that take advantage of complementary resources in the museum and the classroom. Science centers like the Exploratorium provide rich resources for having phenomenological experiences but fewer resources for extended conversation and collective inquiry. Classrooms could be characterized as having the opposite balance of resources. As immutable mobiles, *Video Traces* could be just the sort of representation needed to connect these settings. So, for example, a class trip to the Exploratorium could produce 15 independent video trace records from pairs of students in a class of 30; these documents could then travel to the classroom and serve as a corpus of concrete representations for comparative inquiry about a common phenomenon.

In this article we described a preliminary study of a novel technical arrangement designed to extend visitors' resources for representing and reflecting on their experiences with an interactive science exhibit. We presented evidence that conversations within the *Video Traces* booth support forms of visitor activity that resemble inquiry learning, at least when compared with their unmediated, initial visits to the *Tornado* exhibit. We think it is likely that both the interview situation and the novel technical arrangement contributed to qualitatively different visitor interactions with this popular exhibit. However, we have also shown that video capture and review provide resources and enable activity that would be difficult or impossible to achieve by interacting with the exhibit alone or in conversations without these resources. As such, we believe the *Video Traces* idea holds considerable promise for promoting sustained inquiry through representational action, both at interactive science centers and elsewhere.

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REFERENCES

Burgess, R. G. (1984). *In the field.* London: George Allen & Unwin.

Cubitt, S. (1991). *Timeshift: On video culture.* London: Routledge.

Dewey, J. (1938). *Logic: The theory of inquiry.* New York: Henry Holt.

Diamond, J. (1980). *The ethology of teaching: A perspective from observations in science centers.* Unpublished doctoral dissertation, University of California, Berkeley.

diSessa, A. A., Hammer, D., & Sherin, B. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior, 10*(2), 117–160.

Duensing, S. (1987). Science centres and exploratories: A look at active participation. In *Communicating science to the public* (*Ciba Foundation Conference*). Chichester: John Wiley & Sons.

Duensing, S. (1993). *Exhibit development as a way of thinking and communicating.* Paper presented at the DEA seminar series: Communicating Science, Paris.

Eagleman, J. R. (1983). *Severe and unusual weather.* New York: Van Nostrand Reinhold.

Falk, J. D., & Dierking, L. D. (1992). *The museum experience.* Washington, DC: Whalesback.

Frankel, R. M. (1984). From sentence to sequence: Understanding the medical encounter through microinteractional analysis. *Discourse Processes, 7*(2), 135–170.

Fraser, A. B. (1996). BadMeteorology. www.ems.psu.edu/~fraser/BadMeteorology.html

Garfinkel, H. (1967). *Studies in ethnomethodology*. Englewood Cliffs, NJ: Prentice-Hall.

Gilbert, G. N., & Mulkay, M. (1984). *Opening Pandora's box: A sociological analysis of scientists' discourse.* Cambridge: Cambridge University Press.

Goodwin, C. (1993, November). *The blackness of black: Color categories as situated practice.* Paper presented at the *Discourse, tools and reasoning: Situated Cognition and Technologically Supported Environments Conference,* Lucca, Italy.

Goodwin, C. (1994). Professional vision. *American Anthropologist, 96*(3), 606–633.

Goodwin, C. (1995). Seeing in depth. *Social Studies of Science, 25*(2), 237–274.

Gordin, D. N., & Pea, R. D. (1995). Prospects for scientific visualization as an educational technology. *Journal of the Learning Sciences, 4*(3), 249–279.

Grazulis, T. P. (1991). *Significant Tornadoes, 1880–1989.* St. Johnsbury, VT: Environmental Films.

Hall, R. P. (1996). Representation as shared activity: Situated cognition and Dewey's cartography of experience. *Journal of the Learning Sciences, 5*(3), 209–238.

Harper, D. (1987). *Working knowledge: Skill and community in a small shop.* Chicago: University of Chicago Press.

Jordan, B., & Henderson, A. (1995). Interaction analysis—foundations and practice. *Journal of the Learning Sciences, 4*(1), 39–103.
Knorr-Cetina, K. (1981). *The manufacture of knowledge: An essay on the constructivist and contextual nature of science*. New York: Pergamon Press.
Latour, B. (1987). *Science in action: How to follow scientists and engineers through society.* Cambridge, MA: Harvard University Press.
Latour, B. (1990). Drawing things together. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice*. Cambridge, MA: MIT Press.
Lynch, M. (1990). The externalized retina: Selection and mathematization in the visual documentation of objects in the life sciences. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice*. Cambridge, MA: MIT Press.
Miller, P. (1987). Tornado! *National Geographic, 171*(6), 690–715.
Oppenheimer, F., & the Staff of the Exploratorium (1986). *Working prototypes: Exhibit design at the exploratorium*. San Francisco: The Exploratorium.
Pickering, A. (1992). *Science as practice and culture*. Chicago: University of Chicago Press.
Roschelle, J. (1992). Learning by collaborating: Convergent conceptual change. *Journal of the Learning Sciences, 2*(3), 235–276.
Rubin, A. (1993). Video laboratories: Tools for scientific investigation. *Communications of the ACM, 36*(5), 64–65.
Semper, R. (1990). Science museums as environments for learning. *Physics Today,* November.
Star, S. L. (1983). Simplification in scientific work: An example from neuroscience research. *Social Studies of Science, 13,* 206–228.
Stevenson, J. (1991). The long-term impact of interactive exhibits. *International Journal of Science Education, 13*(5), 521–531.
Taylor, S. M. (1985). *Understanding processes of informal education: A naturalistic study of visitors to a public aquarium*. Unpublished doctoral dissertation, University of California, Berkeley.