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RESEARCH REPORT

Is it Live or is it Memorex? Students' Synchronous and Asynchronous Communication with Scientists

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This study compared students' investigations with an atomic force microscope and viruses in real-time synchronous and asynchronous learning environments. Student interactions with scientists (live videoconference versus email) were examined to see whether communication patterns were different for the different modes of instruction. Students' knowledge of viruses, microscopy, and nanoscale science was compared for asynchronous ($n = 44$) and synchronous treatments ($n = 41$). Eight teams of four students were video-recorded and student discourse was analyzed. Data sources included students' questions, pre-instruction and post-instruction knowledge assessments, and written descriptions of the investigations. Results showed that students in the asynchronous group asked significantly more inquiry and interpretation questions of scientists and fewer questions about the scientists than students in the synchronous group. Both groups showed significant gains in knowledge of virus types and morphology. Students in the asynchronous group made significantly more written notations about what they learned from the investigations than students in the synchronous group.

Overview and Perspectives

Over the past decade the Internet has shown a limitless capacity to advance research and learning in science and education. Readily available technology tools allow today's high school science students to engage in complex scientific investigations not possible until very recently. They can pose their own questions about science and can use Internet tools to pursue answers. For instance, students can

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engage telescopes to explore the vast reaches of our universe, while others use microscopes to investigate viruses millions of times smaller than what can be seen with the naked eye. Interactivity with these remote environments from anywhere, any place, and anytime can be highly motivating. Included among the possibilities is coupling remote microscopy with virtual-reality capacity and visualization, allowing scientists to engage with students to experiment at the nanoscale. This paper reports on a study of remote and virtual experimentation and the interactions students have with scientists. Specifically, the study compared synchronous and asynchronous student communication during inquiry with adenoviruses using atomic force microscopy.

Inquiry instruction continues to be a major goal of science education reform (American Association for the Advancement of Science, 1989, 1993; National Research Council [NRC], 1996). Teaching students science through inquiry involves engaging students in the processes used by scientists such as asking questions, making hypotheses, designing investigations, grappling with data, drawing inferences, redesigning investigations, and building and revising theories (American Association for the Advancement of Science, 1993). However, not all schools have access to the resources needed to do cutting-edge inquiry. The challenge for science educators is to find ways to provide inquiry experiences for all students, even those who have limited access to supplies and materials or are remotely located away from science laboratories.

What does it mean to engage students in the processes of science? Engagement to teachers often means involving students in hands-on science experiences. But can students construct meaning without being able to physically manipulate objects in science? Jones et al. (2004) argued that students may gain a *deeper, more effective type of knowledge* when touching and manipulating objects than they could from sight and sound alone. Many have argued that hands-on experience is an integral part of inquiry (Chiappetta, 1997; Crawford, 1999; Huber & Moore, 2001a; Jones et al., 2004). But Crawford warns there is a danger in equating inquiry-based instruction with only traditional forms of hands-on instruction. Conceptual development may never take place in a solely traditional hands-on experience. Crawford notes that during traditional science activities, students engage in an investigation and answer a predetermined question using the lens of the activity's designer. Students may implement the investigation and collect data from their observations, but what will the interpretations mean? The nature of science in this context is conveyed as a static and immutable truth instead of the tentative product of scientific research promoted in authentic inquiry-based activities. Contrast this with more authentic inquiry where students ask questions, design their own investigation and draw conclusions based on their data.

Advancements in technology allow us to investigate whether or not science inquiry can be replicated in a virtual world. The *National Science Education Standards* speak of a technological literacy paralleled with a scientific literacy through inquiry-based strategies. The NRC (1996) defines inquiry in instruction as providing students with opportunities to: "(1) identify questions and concepts that guide scientific investigations, (2) design and conduct scientific investigations, (3) use technology and mathematics to improve investigations and communications…" (p. 175). It is becoming increasingly difficult to differentiate science from technology and vice versa, and both are increasingly embedded within the other (Jones, Andre, Superfine, & Taylor, 2003).

To be scientifically literate, a student must be skilled and proficient in employing tools (computer, simulations, and microscopes) that best engage the pursuit of scientific knowledge, understanding and appreciation (American Association for the Advancement of Science, 1989, 1993; NRC, 1996). The National Science Education Standards state that "the relation of science to… technology and the nature of science should be part of (students') education" (NRC, 1996, p. 20). Scientists are increasingly reliant on technology to help them test their hypotheses, make observations, draw conclusions, and ask new questions. For example, a physicist's exploration and experimentation of the properties of carbon nanotubes depends mightily on computer scientists' ability to write visualization software that simulates phenomena experienced at a nanometer scale.

Learning Science Online

Learning science online involves students using a computer connected to the World Wide Web through an Internet connection to explore physical phenomena related to their discipline of study. Online learning can provide students with authentic opportunities for content knowledge development and practical skill development. Simulations, interfacing opportunities, and esthetically motivating images all assist learners in constructing understanding of science content knowledge. There is evidence that students learning online perform as well, even better sometimes, than those in traditional classrooms (Bates, 1997). But teaching science online challenges the instructor to find ways to develop the practical skills that are typically gained through the physical, hands-on exploration with natural phenomena. Some online courses and web-based activities support textual representations with visual and interactive experiences (i.e., virtual zoo tours, virtual museums, and synchronous visits with experts). In these contexts the hands-on experiences are limited and social interactions that can scaffold learning are often missing.

Social interactions, both teacher–student and student–student, provide students with critical tools for learning. This social constructivist view of learning maintains that learning is a social activity, mediated by language and social discourse (Vygotksy, 1978). Within this perspective of learning, peers and teachers play critical roles in scaffolding learning in collaborative educational environments (Saba & Shearer, 1994). One of the early criticisms of online learning was its distance from the rich discourse that typically occurs in classrooms. Now students can learn online with the assistance of synchronous and asynchronous chat rooms, email, and video conferencing. Rueter and Perrin (1999) reported that peer interactions had a significant influence in the effectiveness of instructional technology with the computer simulation STELLA II. This study was conducted with non-biology university students during instruction on food webs. Rueter and Perrin reported that "group discussions enhanced the students' learning as much as the technology" (1999, p. 121).

But even with tools such as discussion boards, the lack of face-to-face interactions leaves one or more dimensions either missing or distinctively different (visual cues, auditory cues, non-verbal behaviors, etc.). Unfortunately there is little research that examines the social dimensions of learning in Internet-based instruction (Moallem, 2003).

Students Exploring Science Content Using the Internet

Can Internet science education websites facilitate and promote reform models as outlined by the National Science Education Standards? Huber and Moore (2001b) propose that "two types of Internet sites appear especially promising, those that offer simulations of research equipment or settings and those that allow students to interact with large data sets" (p. 12). Online learning models can be placed on a spectrum of instructional complexity. At one end of the spectrum are ongoing scientific research projects that allow students to connect to the Internet and partner with scientists asking unique questions, collecting data, and making interpretations of the research findings. At the other end of the spectrum are sites where students are mere recipients of information about scientific research.

Examples of more-inquiry based online instruction include the following: (1) the MIT Haystack Observatory Project, where students conduct research by remotely controlling a telescope (Pratap & Salah, 2004) to monitor the polarization of the maser emission from silicon monoxide around red giant stars; (2) the Journey North Program (Annenberg/CPB, Journey North, 2004), which promotes the collection of student data through the tracking of a dozen migratory species every spring, including the monarch butterfly and the whooping crane; and (3) the Center for Biological Timing (Block, 2001), a project funded by the National Science Foundation that researches the ability of organisms "to generate and regulate biological oscillations."

The intermediate level of online learning complexity involves students collecting and analyzing data, interacting with scientists and other students, and reporting that information to the Internet for public critique. Instances demonstrating this complexity include the GLOBE Program (GLOBE Program, 2004), which provides students with opportunities to conduct research on the Earth's environment to understand how it forms an integrated system; the JASON Project (Jason Foundation for Education, 2004; Moss, 2003), an interactive, online-learning project that offers teachers and students multi-media experiences to enhance the teaching and learning of science, mathematics, technology, and associated disciplines; and the CoVis Project (Center for Learning Technologies in Urban Schools, 2004), which employs a diverse range of communication and collaboration tools that approach the learning of atmospheric and environmental science by doing inquiry-based activities.

The most advanced levels of technology-enabled science inquiry are only beginning to be realized; that is, students having the opportunities to collect data through the remote manipulation of actual scientific equipment and tools. The power in these investigations is that students have contextualized experiences in science using authentic tools in science (Francis, 2000; Jones et al. 2001). In remote experimentation students can compare and analyze their data and findings with other investigators in different laboratories. Effective online learning models grounded in inquiry-based experiences incorporate opportunities for students to collaborate and communicate with experts, use remote tools to collect and analyze data (in many contexts creating powerful visualizations), and situate these experiences in prior knowledge and local educational environments.

Internet-mediated Discussions

Computer-mediated communication technologies and information accessibility is not limited to content transmission. While content is vital to learning, it is often the only facet that is conveyed when the "power of the Internet" is described in the literature. Learning also involves the collaboration and construction of knowledge through discourse. Extending that discourse with other students, scientists, and educators through passive and active media promotes learning to enrich a student's perspectives. The interaction between using technology in a classroom for the purpose of accessing information and creating an educational experience has created many pedagogical questions and very few answers (Mitchell, DiPetta, & Kerr, 2001; Windschitl, 1998).

Tele-learning, more specific than online learning, is a term that some researchers have used to define the making of connections among persons and resources for learning-related purposes (Collis, 1999). Tele-learning experiences are created through asynchronous and synchronous communication. Asynchronous methods are defined as passive experiences that do not require the learner and instructor (or novice and expert) to participate at the same time (Brewer, DeJonge, & Stout, 2001). Examples of this type of experience are threaded discussions, online web posting and email. Studies show that asynchronous methods are much more commonplace online than synchronous methods (Collis, 1999). Furthermore, asynchronous methods promote reflection (Hammond, 1999) and higher order thinking (Phillips & Luca, 2000) in students' responses, as well as include discussions to support collaboration activities (Phillips & Luca, 2000). Hammond (1999) asserts that students benefit through text-based asynchronous communication by having an opportunity to:

- articulate ideas on a topic and receive feedback on one's contribution;
- reflect on the ideas and perspectives of others, particularly one's peers;
- get help as and when it is needed; and
- participate in a social environment that increases motivation and supports learning.

Brewer et al. (2001) define synchronous learning as actively involving both the instructor and learner communicating at the same time, although not in the same location. For example, scientists who offer their expertise for students' inquiries via an audio conference call, video conference call, or instant message are communicating in synchronous, real-time fashion. Soong, Chan, Chua, & Loh (2001) argue that video conferencing promotes the social interaction of colleagues and peers without the need to be physically present. Location barriers are erased and distance education is facilitated by this synchronous medium. More recent synchronous technological innovations involve the remote manipulation of tools in science education (Jones et al., 2001). For instance, some secondary students can participate in outreach programs, assisting scientists in their data collection through the remote controlling of telescopes and microscopes (see, e.g., National Oceanic and Atmospheric Administration, Ocean Explorer, 2003).

Motteram (2001) argues that synchronous online learning tools promote the "social" aspect of education, and asynchronous tools support the "academic" aspects of learning as contextualized in her course. Motteram proposes two components of an educational context as being important to the process of educating students. They are building a community of learners within a group and the understanding of ideas and issues that are presented in a course. She found that different types of communication foster the development of both social and academic components of learning.

There are still many difficulties in the successful execution of synchronous learning environments. The exorbitant expense of videoconferencing, the inconvenience of having to be in a specified physical location to participate, and the continued technological difficulties are current limitations to the existing forms of synchronous online learning. The lack of research in this area adds to the growing need to understand its effects on future virtual learning environments. Gough (2000) argues:

> The arena of verbal communication is, and inevitably will continue to be, largely separated from the arena of non-verbal communication, no matter how closely we attempt to link the two, no matter how cleverly we blend the two in sophisticated electronic 'publications'. The convergence is going on, while leaving the initial forms also separate and active. And the convergence will never result in a unified single new form. (p. 142)

Instructional technology has progressed from the primitive computer software that was limited to serving as drill and practice for memorization, to synchronous opportunities for students to use the technology as a scientist would in conducting experiments, collecting and analyzing data, and collaborating with other investigators around the world. The social nature of learning that is critical for the negotiation of meaning by students is an important component to this last generation of technological designs (Hung & Chen, 1999).

Research Context

One of the purposes of this study was to investigate whether high school students' interactions with scientists using a real-time Internet connection were similar or different when compared with students who interacted with scientists via email. The study is situated within a social–constructivist framework designed to promote peer–peer and student–scientist interactions as the student constructs meaning during investigations of science phenomena. The research was part of an initiative that compared interactive, live learning experiences via the Internet in real time using an atomic force microscope (AFM) with experiences based on stored replays of AFM experiments with adenoviruses. The overarching goal was to see whether we could design cutting-edge science experiences for students in schools using replays of scientists' experiments that would be as effective as real-time, live experimentation.

The research sought to answer the following questions:

1. Are there differences between high school students' communication with scientists using synchronous (videoconference) versus asynchronous (email) communications tools?
2. Are there differences in students' understandings of viruses and science investigations based on their mode of experimentation (live vs. replay) and communication (synchronous vs. asynchronous)?

Participants

Four high school science classes participated in the study. The classes were taught by two experienced teachers. The school served 1,700 students and was located in a rural-suburban community in the mid-Atlantic region of the United States.

Eighty-five biology students participated in the study (44 males, 41 females; 64 Euro-American, 16 African-American, and five of other ethnicities). Two high school classes (41 total students) were randomly selected and administered the interactive, real-time (live) treatment. Two different classes (44 students) were randomly selected and administered the limited-interaction, experimental replay treatment.

Due to the limited mobility of the technical equipment used in the study, participants were selected through random cluster sampling. The entire class underwent either a live or replay experience. Students were randomly assigned to each of their classes by computer at the beginning of the school year. All students in the selected classes were given the opportunity to volunteer to participate in the study.

Students worked together in teams of four during the instruction in both treatments. Four teams from each treatment group were randomly selected for targeted observations and were videotaped during their investigations.

Methodology

The instructional activities and intervention took place during five science class periods (see Table 1). At the beginning of the instructional activity, students were told that the nanoproject would culminate in their writing a newspaper article of their experiences to be published in a Web newspaper. During the first class, students were given instruction on microscopy, virology, and nanotechnology by one of the

Table 1. Instructional sequence

Time frame for instruction	Activity
Day 1	Introduction to Nanotechnology
Day 2	NanoManipulator Training, Powers of Ten, Nanoscale I
Day 3	Station #1: NanoManipulator Experiments
	Station #2: Simulation of the AFM
Day 4	Station #3: Interview a Scientist I
	Station #4: Understanding Nanoscale II
Day 5	Station #5: Interview a Scientist II
	Station #6: Writing a Newspaper Article

participating scientists. On the second day, students moved through stations with a randomly assigned student team. Students were trained in use of the NanoManipulator (described further below) with a static image of a virus, provided instructions on a nanoscale, and shown a movie called the *Powers of Ten* (Eames & Eames, 1977) that detailed the relative size of objects both at the micro and macro scale. Over the next 3 days of instruction, all teams completed two additional stations a day with each station taking 20–25 min. The activities included the NanoManipulator, a mechanical simulator of an AFM (including creating a three-dimensional paper model of a virus), two interviews with scientists, a student writing station, and a nanoscale activity station.

Students in the study used a NanoManipulator, which combines an AFM with software, a desktop computer, and a haptic joystick—the Phantom (www.sensable.com). The AFM is a probing microscope that uses a nanometer-sized tip to image and manipulate objects at the nanoscale. The computer keeps track of the tip–surface interaction and displays three-dimensional real-time digital images of the scan that can be stored and reused. Additionally, the Phantom translates this tip movement and actively applies forces to the user's hand corresponding to the forces applied to the tip within the microscope.

The instruction was designed to promote student inquiry (students ask questions, design an experiment, collect data, and make interpretations). The AFM limits the types of questions that students can ask to those that can be carried out with the equipment (such as manipulating a virus, breaking the virus capsid, or rolling a virus). Students were encouraged to ask a question and conduct an experiment with the AFM.

Students in the interactive, real-time (live) condition controlled the AFM (located about 20 miles from the school at the university) through the Internet. The AFM at the university had live virus samples on which students experimented. Students worked in groups of four and were encouraged to select a general approach to exploring the structure and function of a virus through selecting one of the following actions: cutting a virus, pushing a virus with the AFM tip, or breaking the virus capsid. Each individual student had the opportunity to ask a question related to the group's inquiry. Individually students conducted their experiment with the AFM.

Students in the live treatment groups were also connected to the university microscopy laboratory with a video and audio connection using Microsoft NetMeeting software. Students could see and hear the scientist in the laboratory with the AFM at the university. Students were encouraged to discuss their investigations with the scientist at the time of the experiment as well as ask any questions related to their investigation. Students were allowed to interact freely with the scientist. The scientist's role was limited to answering the students' questions while monitoring the AFM.

Students in the replay condition had the opportunity to select an area of inquiry and to ask a scientist questions about the viruses through email, receiving a response the next day. Individually, students explored prerecorded experiments using the NanoManipulator system. These were the same types of experiments that students in the live condition could perform: cutting a virus, pushing a virus with the AFM tip, or breaking the virus capsid. Prior to the instructional intervention, computer scientists, physicists, and science educators worked together to record actual experiments using the AFM that represented three distinctly different investigations for the students to use.

Once the student described the experiment he or she wanted to perform, the student played a data file that showed the experiment being conducted on the computer screen. Within a category, stored experiments were randomly selected so that two or more students who were investigating the same question would see different experimental outcomes. Using the Phantom joystick (and the computer visualization), students could both see and feel before and after images of recorded data files of the virus samples, but they could not move the virus themselves since they had no live connection to actual virus samples.

Students in the replay condition had the same experience as the students in the live condition except that the experimental results were pre-recorded and their interactions with the scientists in the microscope laboratory were via asynchronous email. A scientist responded to each email within 24 h. In summary, the differences in the two treatments included real-time synchronous access to the scientist versus asynchronous email access to the scientist as well as differences in live experimentation versus pre-recorded experiments.

Data Sources

Student discourse—live treatment. Students' interactions with each other and with the scientists were video-recorded and the tapes were transcribed. Field notes were taken and the field notes were combined with the video transcripts to form a written transcript of the students' interactions during experimentation.

Student discourse—replay treatment. Students' teams were observed and video-recorded in the replay treatment and the combined transcripts were used for further analysis. In addition, the email communications that took place between the students and the scientists were captured and analyzed.

Knowledge assessments. One week before and after the instructional activity, participants completed a knowledge questionnaire—the Pre-Knowledge Questionnaire (PrKQ) and the Post-Knowledge Questionnaire (PoKQ). This assessment includes tasks where students were asked to represent their understanding of the morphology of a virus through drawings and the creation of a clay model. The knowledge questionnaire was piloted in a previous study (Jones et al., 2001). A panel of five science educators reviewed and critiqued each of the instruments. Before using these instruments again, a second panel reviewed each item for clarity and developmental appropriateness.

Newspaper articles. At the completion of the instruction, students were asked to write a newspaper story for an online school newspaper that described their experiences that had taken place that week.

Analysis

Qualitative and quantitative data were analyzed for differences in students' experiences across treatments. For most of the analyses, 10 teams of four students were included for each treatment (41 students in the live, real-time experimentation; 44 students in the replay experimentation). Field observations and videotapes were made of four randomly selected teams in each treatment (the targeted focus groups).

Student Discourse—Transcript

The transcripts of field notes and videotapes were read and re-read by two researchers for differences in students' interactions during experimentation. As patterns emerged during the readings, categories of analysis were defined and the transcripts were coded by category. All discourse was examined in the first round of analysis. Students' questions asked to each other and to scientists during experimentation emerged as significant categories for subsequent analysis.

An additional round of coding was conducted that examined specific categories of questions that emerged from students asking the scientists questions. These categories included *inquiry and interpretation questions* (questions about interpretations of the data), *scientist questions* (inquiries about the scientist), *technology questions* (questions about the microscope or NanoManipulator), *clarification questions* (asking for help understanding what they were seeing or what was done), or *equipment questions* (questions that were not directly about the technology used in the experiment but were more general in nature). Further descriptions of the categories of questions are presented in Table 2. Each question generated by students was considered as one

Table 2. Asynchronous and synchronous communication categories, descriptions, and examples

Category	Description	Examples
Inquiry and interpretation	These questions reflected students' interest in understanding observations and results	What happened to my virus when I cut it? Did the virus die, or is it still alive? Did it really "fuse" back together or did the stuff that came out just mound up beside the virus?
To and about the scientist	These questions exhibited general interest in communicating with the scientist, including inquiries about their personal qualities and characteristics	Can I talk to him first? Do you play basketball? Oh, how's your lab doing?
Technology	These questions identified student interest in the technology directly associated with the experience, including the NanoManipulator, the phantom and the AFM	What type of surface is the virus on? In your own definition, what is a NanoManipulator? And also does it matter about the surface?
Clarification	These questions reflected students' interest in understanding communication with the scientist	Can you see my picture? What did you say? Did you what?
Equipment	These questions were inquiries about any equipment that was tangential to the NanoManipulator experience	How much would one of these cost? Don't you want one of these? How do you obtain these viruses?

unit of analysis. Repeated questions by the same student used within the same context counted as only one entry. The transcript analysis of the field observations was conducted with four student teams in each of the treatment groups.

Student Discourse—Emails

The emails were initially read and reread for patterns. Subsequent analyses included coding student questions (as described above). The email analysis was conducted with the 10 student groups that were in the replay treatment.

Knowledge Questionnaire

The knowledge questionnaires (PrKQ and PoKQ) were examined to determine students' conceptions of viral dimensionality and viral shape. The pre-instruction and post-instruction drawings and clay models were analyzed for changes in students' understandings of virus dimensionality and characteristics. The category types for viral dimensionality were *two dimensions* or *three dimensions*, depending on whether or not the drawing indicated a significant sense of depth to the virus. Paired-sample t-test procedures were conducted to evaluate whether the mean differences between pre-knowledge and post-knowledge responses differed significantly in order to evaluate growth within treatment groups. An independent-sample t-test was used between the *replay* and the *live* treatments to investigate whether there were differences across treatment groups.

Drawings and clay models were coded for knowledge of viral shape. The category types for viral shape were *non-virus* and *virus*. Viral shapes included icosahedral (the adenovirus), rod-shaped (tobacco mosaic virus), and phage-like with legs. Non-viral shapes included amoeba shapes, paramecium shaped, stereotypical cell-like morphology, or irregular shapes not classifiable into any of the other categories.

Newspaper Articles

Student newspaper stories were analyzed for the frequency of students' use of "learned" and "know" statements. These statements were selected because they were evidence of how students perceived the experience as well as statements that provided information about students' perception of what they had learned from the instruction. Students' descriptions of the experience and their affective comments about the instruction were not analyzed in subsequent analyses.

Results

Experiential Differences

In this study a random sample consisting of eight teams out of 20 was observed and analyzed (four teams for each treatment). The 33 students on these eight teams asked a total of 252 questions to the scientists or to their peers. There were no statistically significant differences in the frequencies of questions asked between the two treatment groups, $t(31) = -0.976$, $p = .337$.

Synchronous and asynchronous questions to scientists. The most frequent type of question asked over email (see Table 3) concerned understanding the manipulation of the student's virus (inquiry/interpretation). For example, one student stated "When it was cut, it looked like it fused back together. Did it really 'fuse' back together or did the stuff that came out just mound up beside the virus?" Students were earnest about typing appropriate questions into the text box of an email. An examination of the messages showed that students maintained a degree of formality (e.g., students' written discussions stayed on topic and students did not inquire about scientists' personal lives). When writing, students would take time to reflect on the question and its message prior to sending the email.

The nature of the communication through email (asynchronous) with scientists was distinctly different from the students' conversations with the scientist in the live treatment (synchronous). Only 3% or one question asked by students in the live group was coded as being either inquiry/interpretation or technology. The vast majority of students' *synchronous* questions were informal in nature: "Oh, how's your lab doing?" and "Who is the person beside you?" Sixty-two percent of the questions

Table 3. Mean frequencies of synchronous and asynchronous question types to scientists

	Number of questions per team, *M* (*SD*)	
Category	Replay[a] (asynchronous)	Live[b] (synchronous)
Technology	0.60 (0.97)	0.00 (0.00)
Inquiry/interpretation[c]	1.10 (0.57)	0.25 (0.50)
About the scientist[d]	0.20 (0.42)	5.25 (5.32)
Equipment	0.10 (0.32)	0.50 (1.00)
Clarification in communication[e]	0.00 (0.00)	2.50 (3.00)

Note: [a]Replay data were collected through the analysis of emails from all 10 teams that participated in the study. [b]Live data were collected from observations and video recordings of a random sample that included four teams. [c]$t(12) = 2.605, p < .023$. [d]$t(12) = -3.182, p < .008$, [e]$t(12) = -2.817, p < .016$.

were directed to the scientist about the scientist and 39% were questions that clarified communication with him. Students' questions reflected their interest in investigating his personal qualities and characteristics. In stark comparison, only 10% of the students' questions asked asynchronously (via email) were about the characteristics of the scientist.

Students' Understandings of Viruses and Science Investigations

In both replay and live treatment groups, there was a significant shift from two-dimensional to three-dimensional representations of viruses on the drawings and clay model tasks from the PrKQ and PoKQ (see Table 4). An independent-samples *t*-test found no significant post-test differences by treatment for the dimensionality of viruses depicted in drawings, $t(72) = 0.53$, $p = .600$, or in the clay models, $t(79) = 0.23$, $p = .816$.

Table 4. Viral dimensionality

Representation mode		Two dimensions	Three dimensions	*t*
Drawings				
Replay (*n* = 35)	Pre	32	3	–4.41***
	Post	14	21	
Live (*n* = 38)	Pre	30	8	–5.41***
	Post	17	21	
Clay models				
Replay (*n* = 38)	Pre	20	18	–5.70***
	Post	4	34	
Live (*n* = 40)	Pre	25	15	–2.98**
	Post	5	35	

Note: The values represent frequencies of student responses. **$p < .01$, ***$p < .001$.

Table 5. Viral shapes

Representation mode		Virus	Non-virus	*t*
Drawings				
Replay ($n = 40$)	Pre	18	32	–7.85***
	Post	34	15	
Live ($n = 42$)	Pre	14	28	–6.57***
	Post	35	15	
Clay models				
Replay ($n = 39$)	Pre	16	33	–9.25***
	Post	33	16	
Live ($n = 39$)	Pre	19	30	–9.84***
	Post	37	12	

Note: The values represent frequencies of students who represented a virus shape (icosahedral-like as the adenovirus, phage-like or tube-like as the tobacco mosaic virus) in one column, or some other non-virus shape in the other column. ***$p < .001$.

Viral shape. An independent-samples *t*-test showed there were no significant differences by treatment for the shape of the viral drawings, $t(82) = –0.38$, $p = .709$, or the clay models, $t(79) = –1.53$, $p = .130$, made after instruction (see Table 5). The majority of students began the experience with incorrect or incomplete conceptions of what a virus looked like. Students often visualized viruses as being shaped similar to an amoeba, a cell, a paramecium, or else an amorphous shape without any specific characteristics. After the experiences investigating viruses, the majority shifted their thinking to hold a more scientific conception of a viral shape, icosahedral-like as the adenovirus, tube-like as the tobacco mosaic virus, or phage-like.

Student Newspaper Articles

Eighty-four students made a total of 237 references in the newspaper stories to what they learned or knew from the educational intervention. Each claim offered by students was considered as one unit of analysis. Results indicate 12 students made no mention of what they *learned* or *knew* about the experience. In comparison, three students made 10 or more references in their story, including one making 14 claims and another making 13 claims. A word count was conducted on all student newspaper stories ($n = 84$) for the purpose of describing the overall population ($M = 200.49$; $SD = 100.63$; range = 31–559).

A second word count was explored. The student population was split by treatment (replay, $n = 40$; live, $n = 44$) and an independent *t*-test was conducted to determine whether the number of words used in the student newspaper stories was different by treatment. Replay students' stories ($M = 247.98$; $SD = 116.48$) were significantly longer, $t(82) = 4.60$, $p < .001$, than students' stories in the live treatment group ($M = 157.32$; $SD = 56.91$).

Table 6. "Learned" and "know" statements in student newspaper stories by treatment

Treatment condition	*n*	*M*	*SD*	*t*
Replay	40	3.95	3.42	3.70***
Live	44	1.80	1.44	

Note: Means and standard deviations are calculated from frequencies of comments in student newspaper stories. ***$p < .001$.

The content of the stories was analyzed to determine how and on what students were focusing their discussion. Students in the replay group made a total of 158 comments in the newspaper stories in reference to what they *learned* or *knew* from the experience, while students in the live group made a total of 79 comments. Means and standard deviations are presented in Table 6.

Students in the live treatment group made significantly fewer *learned* and *know* declarations in their student newspaper stories (see Table 6).

Discussion

Some years ago there was an advertising campaign for audiotapes and the question to the consumer was "is it live or is it Memorex?" The premise of the commercial was that the taped recording of music experience was indistinguishable from hearing the live music. This question lies at the heart of the present study. How does a set of recorded experiments (replays of data files) compare with live experimentation? The question is not trivial. A live connection between a classroom and an AFM is expensive to set-up and maintain. If a replay experimentation experience can be used effectively without a live connection, the costs drop dramatically.

The differences in metacognitive verbalizations made by students in the replay group suggest that there may be ways to enhance inquiry with technology. The metacognition that students showed when writing their email correspondence suggested that they were engaging in making connections and interpreting their data. Strategies that promote meaningful learning include (a) writing or summarizing what it is you know about a concept, (b) explaining what you know about a concept to someone else, and (c) monitoring understanding (Ausubel, 1968; Motteram, 2001; Ward & Wandersee, 2002).

Overall, there were no significant differences between the two treatment groups in the *number* of questions students made during experimentation. However, there were differences in the *type of* student questions posed to scientists in synchronous videoconferencing compared with questions posed via asynchronous email. Whereas most of the questions in the live, synchronous treatment group were focused on personal questions about the scientist, more than four out of five students' questions and statements in the *replay* condition (asynchronous communication) were directly related to their scientific investigation. These asynchronous communications were about students' inquiry and interpretations of their data and the technology used to investigate their question. The intent of students' questions appeared to be designed to increase their understanding of the data and to verify their interpretations.

Observations of students as they typed their email communication showed they would reflect on their experiments and their findings before typing their questions and comments into the textbox. Students assumed a degree of formality with the asynchronous form of communication as evidenced by the lack of personal questions asked of scientists and the focused nature of the email communication. The email context contributed to students clearly formulating questions that focused on the inquiry, the prediction, the observations, the analysis, and the interpretations of what happened.

In a study comparing students' email communications with instructors in active (student-centered) classrooms with traditional lecture-style classrooms, Marbach-Ad and Sokolove (2002) found that the students tended to email more in the active learning classes. Furthermore, these students sent content-related questions and comments four times more often than students in traditional classes. In addition, students who earned higher final grades (As and Bs) tended to send more content-related emails whereas students with lower grades tended to send emails with questions about procedures. Like students in the current study, Marbach-Ad and Sokolove's students used email communication as a way to clarify their learning and to ask questions that arose during instruction.

The virtual presence of a scientist through telecommunication software changed the nature of the experience for students. Their questions were directed in different ways. When students were made aware of the scientist's virtual presence on the computer screen, they became quickly intrigued. Because the scientist in the university laboratory was in clear view from the students' seats around the NanoManipulator, many students stopped what they were doing at the NanoManipulator and watched as contact was established with the scientist. Students in the live treatment became enchanted with what we call the "Actor Phenomenon." The scientist that appeared on the computer screen was at times more interesting and engaging for some students than the manipulation of viruses. Some students were hesitant or shy to communicate with the virtual scientist, analogous to meeting a celebrity. Other students literally jumped at the chance to engage the virtual scientist in conversation. Few students seemed to find the opportunity uninteresting or not useful. Casual questions about who he was, what he did, or even, if he liked basketball dominated the large majority of conversations.

The number of the "learned" and "know" statements in the newspaper stories of the replay treatment group was significantly more frequent than those in the live group. This result corroborates the outcome that the replay group may have been more focused on the core science content in comparison with the live group. Not only were the questions posed by the replay group more focused on the science of the situation, but also their writing summarizing the experience conveyed that they took away more science from the experience than the live group.

Students in both groups showed significant gains in understanding virus dimensionality and shape. Students in both the replay and live treatment groups shifted their conceptualization of viruses from two dimensions to three dimensions. One reason students may have tended to begin this instruction with two-dimensional concepts of viruses could be that students' prior exposure to virus information in schools was typically through two-dimensional textual representations found in textbooks and workbooks. However, the experience, whether live or replay, of exploring the morphology of viruses through a haptic device such as the Phantom seemed effective in altering this perception.

Students in both treatment groups also significantly changed their conceptions of virus shapes from cell-like (ameba, paramecium, bacteria) to virus-like (adenovirus, phage-like, or tobacco mosaic virus). By engaging both haptically and visually in the three-dimensional NanoManipulator system display, students shifted toward more accurate understandings of the shapes of viruses.

The use of technology in conducting experiments is always constrained by the functioning of the equipment. Although care was taken to ensure backups to equipment delays or failure, there were times when the Internet connection between the NanoManipulator system at the high school classroom and the AFM at the university "crashed" and some students would have to wait short periods of time for the system to be "rebooted." A second variation associated with the technology was the microscopic "drift" that occurred in the sample under the microscope. But the unexpected variability of equipment functioning is part of doing live experiments. We were able to control for this type of delay with the replay experiments that used previously recorded experimental data. The benefit of prerecorded experimentation is that there is no loss of time due to equipment; the drawback is that students do not experience the variability that naturally occurs in scientific experimentation.

Implications

The findings of this study have implications for changing the ways and means through which technology is integrated and utilized in the science classroom. Our ability to enable students to become collaborators in scientists' laboratories through technology is constrained to a large part only by our imagination. The result that the replay condition produced stronger content learning outcomes is encouraging since this type of experience is easiest and least costly to replicate in other settings (Campbell et al., 2004). This study provides evidence that replays of live experiments can be of value to student learning.

Results from this study show that students' questions are more focused in nature when employing asynchronous communication models like email. Students in the live experience had very different experiences with communication software, as students used the opportunity to investigate the scientist. Synchronous communication models like NetMeeting are typically novel to pre-college science classes and the types of discourse that students' employ is not well understood. Future research is needed to document how students can benefit most from communicating with scientists. What aspects of communication with scientists impact knowledge of science content versus other variables such as attitudes, knowledge science processes, knowledge of science careers, or images of scientists?

Conclusions

This study described differences and similarities in experiments for high school students using a real-time, live Internet connection to an AFM compared with a stored replay of AFM experiments without Internet connections. Students in the live treatment engaged in conversation with a scientist differently than did students in the replay treatment. Results found that an "actor phenomenon" existed for students in the live treatment: That is, interactions with the scientist were informal in nature and the dialogue was directed at learning about the scientist and the context of the learning experience. Students in the replay treatment had more structured communications with scientists and tended to seek information about their manipulations and the analysis of their experience. The students in the replay condition also self-reported more learning that resulted from the experience.

The models for using the Internet in science instruction are changing dramatically from the use of text-based resources with increased multimedia representation to one of remote experimentation and student-controlled experiences. Through conscious reflection and discussion, technology can assist students to take part in doing real science in ways never before conceptualized. Remote manipulation of microscopes and the simulation of such an experience can be effective and realistic ways to implement online inquiry.

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