# Evaluation of a Scientific Collaboratory System: Investigating Utility Before Deployment

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## 1. INTRODUCTION

The evaluation of scientific collaboratories has lagged behind their development, and fundamental questions have yet to be answered: Can distributed scientific research produce high quality results? Do the capabilities afforded by collaboratories outweigh their disadvantages from scientists' perspectives? Are there system features and performance characteristics that are common to successful collaboratory systems? Our goal is to help answer such fundamental questions by evaluating a specific scientific collaboratory system called the nanoManipulator Collaboratory System. The system is a set of tools that provide collaborative interactive access to a specialized scientific instrument and office applications.

To evaluate the system, we conducted a repeated-measures controlled experiment that compared the outcomes and process of scientific work completed by 20 pairs of participants (upper level undergraduate science students) working face-to-face and remotely. We collected scientific outcomes (graded lab reports) to investigate the quality of scientific work, post-questionnaire data to measure intentions to adopt the system, and post-interviews to understand the participants' views of doing science under both conditions. We hypothesized that study participants would be less effective, report more difficulty, and be less favorably inclined to adopt the system when collaborating remotely. However, the quantitative data showed no statistically significant differences with respect to effectiveness and adoption. Furthermore, in post-interviews participants reported advantages and disadvantages working under both conditions but developed work-arounds to cope with the perceived disadvantages of collaborating remotely. A theoretical explanation for the results can be found in the theory of the life-world (Schutz & Luckman, 1973, 1989). Considered as a whole, the analysis leads us to conclude there is positive potential for the development and adoption of scientific collaboratory systems.

## 2. EVALUATING SCIENTIFIC COLLABORATORIES

### 2.1 Designing an evaluation

Evaluating scientific collaboratories has unique challenges, many of which can be attributed to the context in which science occurs and the substantial resources required to perform the studies. Evaluation purpose, the scientific context and available resources were all factors in the overall evaluation design for our study.

Collaboratory evaluation can have multiple purposes and goals. Examples include: increasing our understanding of individual behavior in geographically distributed collaboration, discovering new knowledge about collaborative scientific work processes as mediated by technology, informing the design of collaboratory technology, and providing insights regarding the efficacy of scientific collaboratories. These purposes are complex and multi-faceted, often requiring multiple comprehensive studies that employ qualitative and quantitative research methods.

Scientific research often occurs in contexts where expertise, instrumentation and laboratory resources are scarce, costly and in high demand, and where work processes are rapidly evolving. Using resources to perform evaluation studies often competes with resources used for natural science research. Furthermore the population of potential study participants may be in flux and coping with multiple demands on their time. A typical population includes undergraduate and graduate students, post-doctoral fellows, faculty and corporate scientists who have the required specialized scientific knowledge. Students and post-doctoral fellow have naturally high turnover rates, and faculty and corporate scientists may face severe time constraints. Another difficulty is that scientific research is dynamic; processes are evolving, sometimes very rapidly, and tasks may change over the course of an evaluation study. It is a challenge for evaluators to capture and understand the changing activities in order to determine methods and measures to evaluate them.

Other resources required to conduct an evaluation include personnel knowledgeable about evaluation methods and about the collaboratory system and its role in scientific investigations, as well as the equipment, supplies, travel funds, and time to collect and analyze evaluation data. The mere fact of a collaboratory's geographic distribution may make a comprehensive on-site field study incorporating in-depth interviews and observations prohibitively expensive. It can also be challenging to capture system usage data because many collaboration technologies do not have automatic logging capabilities or documented application programming interfaces to facilitate adding automatic logging capabilities.

Given these challenges we choose a controlled experiment approach to evaluation. However, the tasks used in the controlled experiment were not abstract representations of scientific tasks but replications of actual experiments performed by scientists. This reduces the gap between real world, intended use of the collaboratory system and its evaluated use to increase the validity of the evaluation results.

There are several advantages to an experimental approach. One advantage is that the evaluation can take place before all necessary infrastructure components are developed and deployed. For example, many emerging collaboration systems, including the system we evaluated, require very high speed, robust and secure internet connections that are only now emerging. In an experiment the actual geographical distance between collaborators can be small and evaluation can occur without waiting for new networking technology to be developed and deployed.

A second advantage is that the time before results are available is shorter compared to other evaluation methods, such as field studies. Field studies to evaluate collaboratory systems can take longer to perform than experiments due to the rhythm of science. There can be long periods of time when scientists do not actively collaborate due to differences in their schedules and available resources. An experiment is not dependent on these cycles of inactivity and activity, enabling us to provide feedback to system developers and funders in a timely fashion.

A third advantage is that there is the risk of having no results is reduced. Science is a dynamic and highly specialized. It can happen that scientists are enthusiastic about using a collaboratory system during the initial research funding and system design process, but by the time the system is developed and ready for use their work may have gone in a different direction reducing their need for the system, or they may have moved to a different institution imposing limitations on their participation in the evaluation. Finding additional scientists to participate in the evaluation can increase the time to results and costs, especially when new technical infrastructure is needed to support the system.

### 2.2 Evaluation hypotheses

Previous research in computer supported cooperative work (e.g., Dourish, Adler, Bellotti, & Henderson, 1996; Olson & Olson, 2000) and theory of language (Clark, 1996) would predict that working remotely would lack the richness of collocation and face-to-face interaction, e.g., multiple and redundant communication channels, implicit cues, spatial co-references, that are difficult to support via computer-mediated communications. This lack of richness is thought to impair performance because it is more difficult to establish the common ground that enables individuals to understand the meaning of each other's utterances. Other research (e.g., Starr & Ruhleder, 1996; Orlikowski, 1993; Olson & Teasley, 1996) would predict that working remotely may not be compatible with many structural elements of work, such as existing reward systems and common work practices. As a result a collaboratory system is not likely to be adopted by individuals especially when individuals can themselves decide whether they work face-to-face or remotely. Thus, our evaluation hypotheses were:

H1: *Study participants will be less effective collaborating remotely than collaborating face-to-face.*

H2: *Study participants will report more difficulty collaborating remotely than collaborating face-to-face.*

H3: *Study participants will report they are more likely to adopt the system after using it face-to-face than remotely*.

In the following sections we report on the controlled lab study conducted to test these hypotheses, including discussions of the context of the evaluation, the lab study design, data collection and analysis, and the results of the controlled lab study and their implications.

## 3. EVALUATION CONTEXT: THE nanoMANIPULATOR COLLABORATORY

The collaboratory system we are evaluating provides distributed, collaborative access to a specialized scientific instrument called a nanoManipulator (nM). The single-user nM provides haptic and 3D visualization interfaces to a local (co-located) atomic force microscope (AFM), providing a natural scientist with the ability to interact directly with physical samples ranging in size from DNA to single cells. An nM can be used in live and replay modes. In live mode, an nM is used both to display and record data from an atomic force microscope and to control the microscope. The recorded data, including all data produced by the microscope, is saved in a “stream file” so that it can be replayed later for analysis. In replay mode, the nM is a display device where the stream file, instead of the live microscope, provides the data for the visual and haptic displays. Approximately 80% of nM use is in replay mode where scientists move forward and backward through the data, stopping at critical points to perform visualization and analysis. Details regarding the nM and its uses are described in (Finch, Chi, Taylor II, Falvo, et al., 1995; Taylor II & Superfine, 1999; Guthold, 2000; Guthold, Matthews & Negishi, 1999).

The collaboratory version of the nM was designed based on results of an ethnographic study from which we developed an understanding of scientific collaborative work practices, the role of an nM as a scientific instrument, and scientists’ expectations regarding technology to support scientific collaborations across distances (Sonnenwald, Bergquist, Maglaughlin, Kupstas-Soo & Whitton, 2001; Sonnenwald, 2003; Sonnenwald, Whitton & Maglaughlin, 2004).

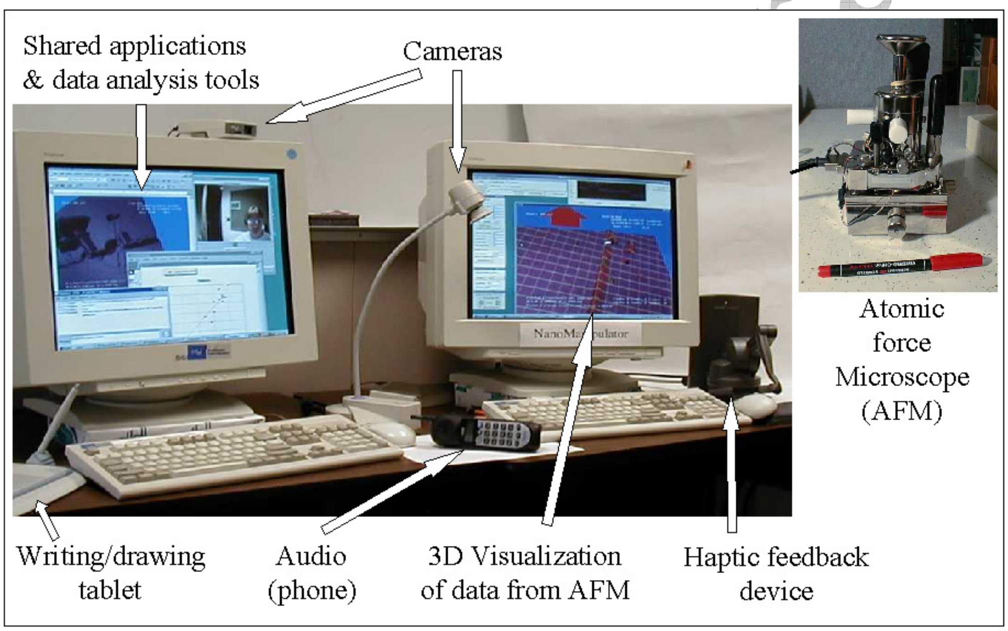


Figure 1. nanoManipulator Collaboratory System

The collaboratory system (Figure 1) is based on two PCs. One PC is equipped with a Sensable Devices Phantom™ force-feedback device. This PC and its associated software provide haptic and 3D visualization interfaces to a local or remote atomic force microscope (AFM) and support collaborative manipulation and exploration of scientific data in live and replay modes.

The collaboratory system allows scientists to dynamically switch between working together in *shared* mode and working independently in *private* mode via a menu option (see Figure 2). In shared mode, remote, i.e., non-collocated, collaborators view and analyze the same (scientific) data. Mutual awareness is supported via multiple pointers, each showing the focus of attention and interaction state for one collaborator. As illustrated in Figure 2, the red cone is the remote scientist’s pointer and the text label on the cone indicates the function the remote scientist is performing. In this example, the remote scientist is positioning measure points that are displayed as red, green and blue lines. The double green arrows indicate that the local scientist is zooming out, or enlarging the magnification of the sample.

We use optimistic concurrency techniques in shared mode (Hudson, Helser, Sonnenwald, & Whitton, 2003), eliminating explicit floor control and allowing collaborators to perform almost all operations synchronously. Because of the risk of damage to an AFM, control of the microscope tip is explicitly passed between collaborators. In private mode, each collaborator can independently analyze the same or different data from stream files previously generated. When switching back to private from shared mode, collaborators return to the exact data and setting they were using previously.

The second PC supports shared application functionality and video conferencing (via Microsoft NetMeeting™) and an electronic writing/drawing tablet. This PC allows users to collaborate using a variety of domain-specific and off-the-shelf applications, including specialized data analysis, word processing and whiteboard applications. Video conferencing is supported by two cameras. One camera is mounted on a gooseneck stand so it can be pointed at the scientist's hands, sketches, or other physical artifacts scientists may use during experiments; the other is generally positioned to capture a head and shoulders view of the user. Collaborators have software control of which camera view is broadcast from their site. Previous research (e.g., Bellotti & Dourish, 1997; Harrison, Bly, & Anderson, 1997) has illustrated the importance of providing the ability to switch between multiple camera views, as well as repositioning and refocusing cameras.

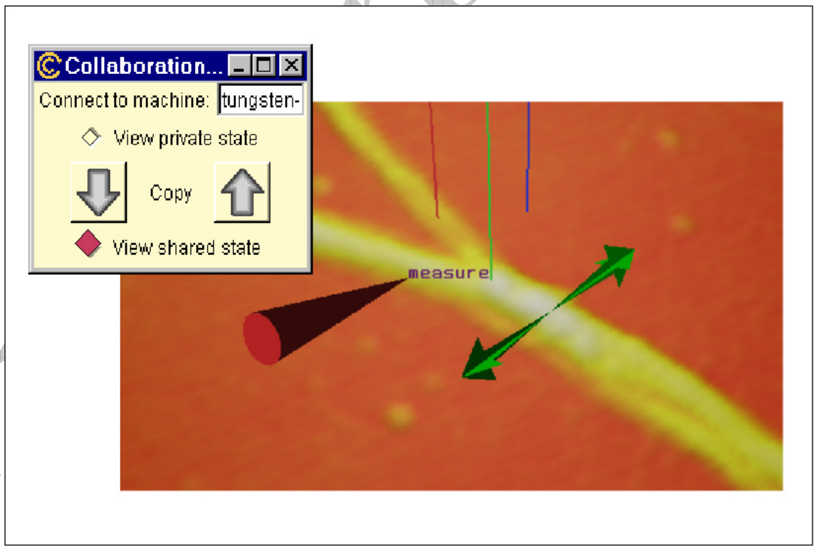


Figure 2. Shared menu and screen view

A wireless telephone connected to a commercial telephone network provides high quality audio communications for collaborators. A telephone headset and speakerphone options are also included to allow users mobility and provide the option of having others in the room participate in a conversation with a remote collaborator.

## 4. THE CONTROLLED EXPERIMENT STUDY

The controlled experiment study was a repeated measures design comparing working face-to-face and working remotely with the order of conditions counterbalanced. This type of experiment is also referred to as a "mixed design" because it allows both within-group and between-group comparisons.

Twenty pairs of study participants conducted two realistic scientific research activities each requiring 2 to 3 hours to complete. Participants worked face-to-face on one occasion and, on a different day, collaborated remotely (in different locations). When face-to-face, the participants shared a single collaboratory system; when collaborating remotely, each location was equipped with a complete collaboratory system. We collected a variety of quantitative and qualitative evaluation data, including task performance measures to compare the quality of scientific work produced in the two collaboration conditions, post-interviews to gain, from participants' perspectives, a more in-depth understanding of the scientific process in both conditions, and post-questionnaire data.

### 4.1 Study Participants

The study participants were upper-level undergraduate natural science students from local Research I universities. We chose this population because it is relatively large and representative of individuals who perform scientific research, most often under the direction of faculty or postdoctoral fellows. The science and math skills of this pool are somewhat consistent, as they have taken a similar set of core science and math courses as freshman and sophomores. Study participants were recruited through announcements in class, student newspaper advertisements, posters, and e-mail announcements.

The majority of the 40 participants reported they were majoring in biology and reported A/B grade point averages; no participant reported a GPA lower than a C. Thirty-six participants were Caucasian, 2 were African American and 2 were Asian/Indian. All were fluent in English and all but one appeared to be a native English speaker. Participants were randomly assigned to pairs without respect to their undergraduate major, self-reported GPA and ethnicity, and pair assignments did not change over the course of the experiment. We strove for a mix of gender composition in the pairs; 9 pairs were of mixed gender, 6 pairs were female only and 5 pairs were male only. To avoid bias or confounding results, we selected participants who had no experience collaborating across distances or using the nanoManipulator. In particular, no participant had any substantive knowledge of fibrin, the biological material under investigation in the collaborative activities.

All study participants had previous experience collaborating face-to-face with others while conducting scientific experiments and working on class projects. Twenty-five percent of the study participants (5 pairs out of 20) knew their partner before participating in the experiment, a situation that mirrors scientific and teaching practice. Scientists who collaborate may know each other, however, they frequently have their students or postdoctoral fellows, who do not know each other, work together to design and conduct the actual experiments and data analysis for their collaborative project. Collaboratories, in particular, bring together scientists who are from different disciplines and locations, and who do not know each other. One scientist may have knowledge of the scientific tool and methodology, and the other scientist has knowledge of the sample to be investigated. Due to the small number of previously acquainted pairs in our study, it was not possible to determine if the previous acquaintance statistically affected the experimental outcome measures. However, the outcome measures of participants who knew each other previously follow the same trends as the measures from the participants who had not known each other previously.

## 4.2 Experiment Design

The controlled experiment consisted of three sessions: an introduction and two task sessions. The *introduction* consisted of a presentation providing background information on the controlled experiment, a thorough introduction to the natural science used in the controlled experiment, and a brief hands-on demonstration of the collaboratory system. During the presentation and demonstration participants were encouraged to ask questions. Study participants signed an informed consent document and completed a demographic questionnaire. This session typically lasted 45 minutes.

Table 2. Conceptual Experiment Design: Repeated Measures with the Order of Conditions Counterbalanced

| Condition: Type of Interaction | Order of Conditions | |
|---|---|---|
| | Task Session 1 | Task Session 2 |
| Face-to-Face (FtF) | Pairs 1-10 | Pairs 11-20 |
| Remote | Pairs 11-20 | Pairs 1-10 |

*Task sessions 1 and 2* were performed on different days and under different conditions: face-to-face (FtF) and remote. The order of the conditions was counterbalanced (see Table 2), and pairs were randomly assigned to the two order conditions. Each task session had three parts: a tutorial, scientific research lab, a post-questionnaire and a post-interview.

The hands-on *tutorial* led participants through instructions on how to use the features of the collaboratory system required for that day's lab. The tutorial before the remote collaboration session also included instructions on the video conferencing system, shared applications, and the collaboration-specific features of the system. Each participant completed the tutorial in a separate location and was accompanied by a researcher/observer who was available to assist and answer questions. Participants were allowed to spend as much time as they wanted on the tutorial; typically they spent 45 minutes.

The *scientific research labs* in both task sessions were designed in collaboration with natural scientists who regularly use the nanoManipulator to conduct their scientific research. The tasks were actual activities the scientists completed and documented during the course of their investigations. The labs were designed to be similar in difficulty as judged by the natural scientists and pilot study participants. To complete the labs participants had to engage in the following activities typical of scientific research: operate the scientific equipment properly; capture and record data in their (electronic) notebook; perform analysis using scientific data analysis software applications and include the results of that analysis in their notebooks; draw conclusions, create hypotheses and support those hypotheses based on their data and analysis; and prepare a formal report of their work. We did not require the study participants to design a natural science experiment or write a paper describing the experiment because the collaboratory system under evaluation was not designed to explicitly support these components of the scientific research cycle.

During each scientific research lab, study participants were asked to work together, using the collaboratory system in replay mode to manipulate and analyze data recorded previously during an experiment conducted by a physicist (Guthold, 2000). As discussed above, the pre-recorded stream file contained an exact and complete record of all data collected from an AFM when the experiment was originally performed. All visualization options and controls on the system, except “live” microscope control, were available to the study participants in replay mode.

The subject of the scientific research labs was the structure of fibrin, a substance critical for blood clotting. In the first lab, participants were asked to measure distances between branch points of fibrin fibers and to discuss the possible relationship between these distances and the blood clotting process. In the second lab, participants were asked to measure additional structural properties of fibrin, and based on these measurements, discuss its possible interior structure.



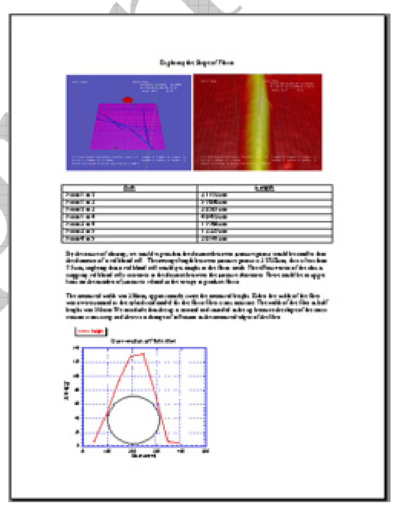

Figure 4. Sample lab report page including microscope data capture, measurement data recording, and data analysis

Study participants were asked to document their results, recording data they collected and their analysis of that data, in a lab report. The lab report mirrored lab notes created by the scientists when they originally conducted their fibrin investigation. Lab reports created by participants contain data images, tables of data values, explanatory text and annotated graphs illustrating their analysis of their data (Figure 4). A single report was requested from each pair of study participants for each task session.

After each lab, each study participant was asked to complete a post-questionnaire and to participate in a one-on-one interview with a researcher. The post-questionnaire took approximately 20 minutes to complete, and post-interviews lasted between 30 and 60 minutes. The questionnaires and interviews provided data regarding participants' perceptions of the lab activities, of the technology in the collaboration system, and of the collaborative process as discussed below. The sessions and data collection instruments were tested and refined in a pilot study.

Figure 5. Overhead view of participants working remotely

Figure 6. Overhead view of participants working face-to-face

## 4.3 Evaluation Measures

4.3.1 *Task Performance (Outcome) Measure: Lab Reports*. A primary goal of our overall evaluation study is to compare the quality of science produced in face-to-face collaborations and to that produced in remote collaborations. Typically statistics such as number of publications, citation counts, number of grants and patents awarded, and peer reviews, are used to measure science quality. These measures, however, require years of performance and data collection that are not possible in evaluation studies with a limited timeframe. Therefore, we chose to have study participants create laboratory reports that are modeled on scientists' lab notes that document their data collection and analysis progress. We graded the reports and used the grades as a task performance measure, i.e. as a measure of the quality of science conducted face-to-face and remotely.

The instructions for the lab activities and for what should be included in the laboratory reports were designed in collaboration with natural scientists. As is typical in controlled experiments, the instructions were specific and guided participants' actions. The information participants were asked to provide in the reports mirrored the information found in the scientists' lab notes created when they conducted their original research on fibrin. Each pair of study participants collaboratively created a lab report under each condition, generating a total of 40 lab reports; 20 created working remotely and 20 created working face-to-face.

The lab reports were graded blindly; the graders had no knowledge of the lab report authors or under which condition the report was created. An additional subset of reports (6) was graded using the updated template. Intercoder reliability was calculated for these assigned grades using Cohen's Kappa (Robson, 1993). Values of .75 and .79 were calculated for graded lab reports from the first and second task sessions respectively. Values above .70 are considered excellent (Robson, 1993).

4.3.2 *Participants' Perceptions: Post-interviews*. To further our understanding of participants' perceptions of the system, we conducted semi-structured interviews with each participant after each task session. Study participants were asked what they thought about their experience, including the most satisfying and dissatisfying aspects of their experience (Flanagan, 1954). In addition, we inquired about specific incidents that were noted by the observer, work patterns that emerged during the experience, and the impact technology may have had on their interactions with their research collaborator. After Task Session 2, participants were also asked to compare working face-to-face and working remotely. To better learn each participant's perspective, participants were interviewed individually, for a total of 80 interviews, each lasting from 30 to 60 minutes. Each interview was audio-recorded and transcribed.

The interviews were analyzed using both open coding and axial coding (Berg, 1989). During open coding a subset of the interviews were read thoroughly and carefully by two researchers, and the researchers identified coding categories, or coding frames. For example, a category that emerged was negative references to aspects of the technology. During axial coding, we looked for relationships among categories. After the initial set of categories and their relationships were discussed among the research team, three team members analyzed another subset of interviews. Definitions of coding categories and relationships among the categories were further refined during this analysis. All three researchers analyzed an additional subset of interviews. No new coding categories or relationships emerged, and researchers were in agreement regarding the application of the codes. Intercoder reliability, calculated using Cohen's Kappa, yielded values of .86 and .81. Values above .70 are considered excellent (Robeson, 1993). In the final step, all interviews were re-read and analyzed using the coding categories. For the purposes of this paper, we analyzed the following codes: references to working face-to-face; references to working remotely; comparison between working face-to-face and remotely; positive aspects of the technology; and negative aspects of the technology.

Table 4. Innovation Attributes Correlated with Adoption (Rogers, 1995)

| Attribute | Description |
|---|---|
| Relative advantage | Improvement over current practice |
| Compatibility | Consistency with adopters' values, past experiences & needs |
| Complexity | Perceived difficulty of learning to use the innovation |
| Trialability | Ease of experimenting with the innovation |
| Observability | Results of innovation easily seen and understood |

4.3.3 *Innovation Adoption Measure: Questionnaire*. Innovation adoption and diffusion theory provided us a foundation for investigating the potential of the collaborative system for adoption by scientists. Synthesizing over five decades of innovation adoption and diffusion research, Rogers (1995) identifies five attributes of innovations that are correlated with the adoption of innovations. The five innovation attributes are: relative advantage, compatibility, complexity, trialability and observability (Table 4.)

*Relative advantage* is the degree to which potential adopters perceive that an innovation surpasses current practices. *Compatibility* is the degree to which an innovation is perceived to be consistent with adopters' existing values, past experiences and needs. It includes individual, group and organizational goals, needs, and culture, and is concerned with the level of congruence between a group's traditional work patterns and the work patterns required by the innovation. *Complexity* refers to the perceived difficulty of learning to use and understand a new system or technology. When a system is perceived as complex, it is less likely to be adopted. *Trialability* refers to the ease of experimenting with an innovation. It includes the level of effort needed and the risk involved in observing and participating in small scale demonstrations of the system, including the ease with which you can recover from (or "undo") an action taken using the system and the cost of reversing the decision to adopt. *Observability* is the degree to which the results of the innovation are easily seen and understood.

Numerous researchers have validated these attributes in a variety of domains including medicine, engineering, and airline reservation information systems (Rogers, 1995; Tornatsky & Fleischer, 1990). Researchers, e.g., Grudin (1994), Shniederman (1997), Olson and Teasley (1996) and Orlikowski (1993), have also identified the importance of the attributes in computer supported cooperative work (CSCW) contexts. Rogers' theory and the five attributes guided the construction of our post-questionnaire.

We used the same questionnaire under both collaboration conditions to enable a comparison of results. As upper-level undergraduate natural science students, the participants had many previous experiences conducting scientific experiments using a variety of scientific instruments and could assess the innovation attributes, including relative advantage and compatibility, based on these previous experiences. Details regarding the construction and validation of the questionnaire instrument can be found in Sonnenwald, Maglaughlin and Whitton (2001).

## 5. RESULTS and DISCUSSION

The quantitative data analysis did not support the hypotheses. No statistically significant negative differences in the measures of scientific outcomes and intentions to adopt the system that are attributable to condition emerged. The analysis of the qualitative interview data helped explain this null result. Participants reported advantages and disadvantages working under both conditions and developed work-arounds to cope with the perceived disadvantages of collaborating remotely.

We present the detailed results in several parts. We examine data from each measure, examining similarities and differences that arise when working face-to-face and remotely, with respect to our hypotheses regarding scientific outcomes, participants' perceptions of the scientific work process and technology, and collaboratory adoption.

### 5.2 Task Performance (Scientific Outcomes): Analysis of Graded Lab Reports

Table 6. Graded Lab Report Statistics

| | Graded Lab Report Scores (max. score = 100) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lab A | | | | | Lab B | | | | |
| | Mean | SD | Max | Min | Range | Mean | SD | Max | Min | Range |
| FtF | 70.0 | 16.75 | 88 | 42 | 46 | 86.4 | 10.52 | 98 | 70 | 28 |
| Remote | 70.0 | 8.89 | 80 | 55 | 25 | 75.1 | 10.49 | 89 | 56 | 33 |

Hypothesis H1 suggests that collaborating remotely would have a negative impact on scientific task performance outcome measures. Only minimal support was found for this hypothesis. The average lab report scores for the first task session were identical (70/100) for both the face-to-face and remote condition (Table 6). Furthermore, using a multivariate analysis of variance (MANOVA) test (row 1, Table 7), the differences in scores for the face-to-face and remote conditions are not statistically significant.[1]

However, the data suggest that collaborating remotely first may have a positive effect on scientific outcomes in this context. When order is taken into account using a multivariate analysis of variance (MANOVA) test (row 2, Table 7), participants who collaborated remotely first scored significantly higher on the second task than did those who collaborated face-to-face first ($p<0.01$). Furthermore, there is no statistically significant difference between FtF and remote lab scores for participants who collaborated face-to-face first (row 3, Table 6). However, there is a statistically significant difference ($p<0.01$) between the FtF and remote lab scores for participants who collaborated remotely first (row 4, Table 7).



[1] The average lab report scores were greater in the second task session for both conditions, indicating a possible learning effect. This difference is accounted for in the analysis of variance computation.

Table 7. Multivariate Analysis of Variance (MANOVA) of Differences between Lab Report Scores

| | | MANOVA Results | | |
|---|---|---|---|---|
| | Type of Comparison | df | F | *p* |
| Between Group | Condition: FtF vs. Remote | 1 | 2.67 | 0.1198 |
| Between Group | Condition & Order: FtF first & Remote second vs. Remote first & FtF second | 1 | 9.66 | **0.0061** |
| Within Group | FtF first vs. Remote second | 1 | 1.09 | 0.3110 |
| Within Group | Remote first vs. FtF second | 1 | 11.24 | **0.0035** |

The only statistically significant correlation (at the .05 level) between scores across conditions and order occurs among scores within the group who collaborated remotely first. Using a Pearson correlation test the value of the correlation between scores is .698, $p=0.025$. That is, if participants received a high grade on their first lab report created when collaborating remotely, then they were likely to receive a high grade when collaborating face-to-face. The converse is not supported, i.e., the score participants received when collaborating face-to-face did not predict their score when collaborating remotely.

Previous research (e.g., Olson & Olson, 2000) would predict that scores from a remote first session would be lower because the remote session would lack the richness of collocation and face-to-face interaction, including multiple and redundant communication channels, implicit cues, and spatial co-references that are difficult to support via computer-mediated communications. This lack of richness is often thought to impair performance. Perhaps technical features such as seeing your partner’s pointer and functions, optimistic shared control of scientific instrumentation and applications, improved video that provides multiple views, and high quality audio communications may be “good enough” for scientific tasks focusing on collecting, analyzing and interpreting data.

Further, the literature would predict that participants would learn more working together face-to-face and thus have higher scores after working face-to-face, whereas our data indicate participants performed better in a second, face-to-face collaboration after first collaborating remotely. One alternate explanation for the difference in scores is that the activities in the second task were inherently more difficult to perform remotely than face-to-face. Replication of the study using a Solomon four-group design to obtain data from two consecutive face-to-face and remote sessions is needed to provide additional insights regarding any possible task effect. We looked to the post-interview data for further insights regarding these results.

## 5.3 Participants' Perceptions of the Scientific Process: Post-Interview Analysis

Hypothesis H2 proposes that participants would find working remotely more difficult than working face-to-face. Analysis of the interviews provided only partial support for this hypothesis. As expected, participants reported disadvantages to collaborating remotely. However, participants also reported that some of these disadvantages are not significant in scientific work contexts, and that coping strategies, or work-arounds, can reduce the impact of other disadvantages. Furthermore, participants reported that remote collaboration provided several relative advantages compared with face-to-face collaboration (Table 8).

Table 8. Interview Analysis: Participants' Comments on Remote Collaboration Compared to Face-to-Face Collaboration

| **Disadvantage** | **Significance, Coping strategy, or Relative advantage** |
|---|---|
| Interaction less personal | Doesn't matter for this work |
| Fewer cues from partner | Need to talk more frequently and descriptively |
| Some tasks are more difficult | Easier to explore system & ideas independently;<br>Having identical views of data visualization is better;<br>Working simultaneously on the data visualization increases productivity |

Similar to previous studies (e.g., Olson & Olson, 2000; Olson & Teasley, 1996), study participants reported face-to-face collaboration was more personal than remote collaboration. They said that when working face-to-face it was:

> *more personal*
>
> *easier to express yourself*
>
> *[we] did more chatting [face to face]*

Of course, problems can also arise when working face-to-face difficult. As one participant reported after working face-to-face:

> *It was a little difficult at times to determine if…[my partner] had something to say and she just wasn't saying it or she just wasn't sure…I found it a little hard to communicate.*

Many participants reported that a lack of personal interaction when working remotely did not have a negative impact on their work. The impersonal nature of remote collaboration increased their productivity and facilitated collaborative intellectual contributions. As participants explained:

> *If we were…working side by side, we might tell more stories or something like that….[However] if you're trying to get something done, sometimes the stories and stuff can get in your way.*

*It does make for a less interpersonal experience if you're not working right beside someone…but [when working remotely] I had time to figure things out for myself instead of [my partner] just doing it and me just accepting what he was doing, or me doing it and him accepting what I did. This time [working remotely], we both got to figure it out and say 'hey, look at this' in collaboration.*

*I think that being in separate rooms helps a little bit because it's more impersonal…[You] just throw stuff back and forth more easily.*

Participants also reported that when working remotely they received fewer implicit cues about what their partner was doing and thinking. Similar to previous research (e.g., Clark, 1996), the study participants explained that without these cues, it can be difficult to follow social interaction norms and assist your collaborator:

*[when collaborating face to face] it was a lot easier to ask questions of each other…since you have a feeling [about] when to interrupt them…if you're in the same room…you'll wait [to ask a question] until the other person is not doing as much or not doing something very specific*

*It is hard to get the context of any question that's asked because you're not paying attention to what the other person is doing because they're in a little [video-conferencing] screen.*

To compensate for this lack of cues, several participants reported they needed to talk more frequently and descriptively when collaborating remotely. Participants reported:

*Even though we were in separate rooms, it kind of seemed like there was more interaction compared to being face-to-face, which seems kind of strange… It just seemed more interaction was expected…Maybe needed.*

*We had a really good interaction [when collaborating remotely]… You're conscious that you're not together and you can't see [some things, and] so you think more about [interacting. For example, you think] 'I need to let this person know that I'm about to do this' or 'this is what I'm seeing and I'm trying to let you know so, and you're like doing the same to me'. Yeah, so [our interaction] was probably more. Interaction was really easier. It made [working together] better.*

*You have to be more descriptive with your words.*

Thus to compensate for the absence of implicit cues in the remote condition many participants provided explicit cues for their partner. When working remotely, it appears that some individuals recognize they do not have a common shared physical reality and subsequently may not have a shared cognitive reality. However, humans are intrinsically motivated to develop a shared reality (Schutz & Luckman, 1973, 1989). Subsequently, study participants developed and adopted a strategy of providing explicit cues to their partner, to develop a shared reality. These explicit cues appear to be joint actions (Clark, 1996) that help coordinate activities between participants. The cues may contribute to faster and more accurate formation of common ground and mutual understanding.

It is interesting to note that even with the disadvantages of remote collaboration and the need for coping strategies, many participants reported they could work and assume the roles similar to those they typically assume when collaborating face-to-face. Participants commented:

> *[collaborating remotely] was just like if we had to sit down and do a group project and we were sitting right next to each other.*
>
> *I tend to naturally take on the role of coordinator. So if anything seems like it's not getting done fast enough, I'll go and say, 'Well, you need to do this' or 'I need to do that.' So I think I …did this [collaborating remotely] because I do that with everything I do.*

Schutz and Luckman (1973, 1989) suggest that when developing a shared reality or acting within the context of different realities, individuals assume that differences will not keep them from achieving their goals. In Schutz and Luckmann's terms, individuals assume there is a congruence of relevance systems. This assumption may explain why participants assumed similar roles as if working face-to-face and could be successful working remotely.

In addition to receiving fewer cues from a partner when collaborating remotely, participants also reported that some physical tasks are more difficult. These tasks include drawing, e.g., creating and sharing sketches of scientific structures, manipulating mathematical equations, and jointly using shared applications in NetMeeting. Some of these problems may be remedied by including more tools in the systems, such as MATLAB®. Others may be remedied by advances in technology, such as shared applications that support multiple pointers and use optimistic concurrency for floor control. Participants explained:

> *[when collaborating face to face] you could draw more easily, communicate diagrams more easily, and you could look at the other person and see their level of understanding more easily.*
>
> *The thing that frustrated me the most [collaborating remotely] was the shared applications [NetMeeting]…you could see the other person doing things but you couldn't do anything [simultaneously.]*
>
> *I caught myself pointing at my screen sometimes but [my partner] couldn't see my finger pointing at the screen.*

Although technology made some tasks more difficult, study participants also reported that the collaboratory system provides advantages over collaborating face-to-face. These advantages include the ability to work independently as well as collaboratively, having identical and unconstrained views of the data visualization, and working simultaneously with the data visualization.

> *I liked that we were separate. I think it gave a whole new twist on*

*the interactions, and if one of us got snagged up with something the other could independently work and get it done rather than both of us being bogged down by having to work on it simultaneously.*

*I think the technology helped the interaction…because...one person could do a task and then the other…has the chance to say, 'OK, well maybe we can do it this way.'*

*Sometimes when you're working side by side with somebody, you have to deal with 'Well, you're looking at [the data] from a different angle than I am, and so you're seeing a different perspective there.' Now [working remotely] we could both of us be straight on, having the exact same perspective from where we're sitting. It made it easier.*

*[My partner] could be changing the light focusing somewhere, while I could be zooming or moving [the plane] around. And that was really helpful because you're thinking, 'OK, as soon as I'm done moving the light I want to go ahead and shift [the plane]…[to be able to] say to [my partner], 'Why don't you [shift the plane] while I'm shining the light,' was really cool. It was really helpful.*

The participants in this study reported experiencing disadvantages of remote collaboration and the system that are similar to those that have been previously reported in the literature. However, the study participants also reported that some disadvantages had minimal impact on their scientific work, and that they developed and used coping strategies to compensate for disadvantages. In addition, they perceived remote collaboration to provide some advantages relative to face-to-face collaboration. They also reported that collaborating remotely was compatible with their previous ways of collaborating face-to-face. These findings elucidate our null result regarding scientific outcomes. Next we look at our data on innovation adoption.

## 5.4 Collaboratory Adoption: Post-Questionnaire Data Analysis

Analysis of the collaboratory adoption post-questionnaire data (Table 9) yielded no support for hypothesis H3. We performed a multivariate analysis of variance (MANOVA) using a general linear model to investigate whether differences in the adoption questionnaire responses can be attributed to condition, that is, working face-to-face or working remotely, or to any interaction effect between condition and order, i.e., working face-to-face first or remotely first.

The results indicate another null result. The differences in questionnaire responses due to condition are not statistically significant (at the $p<.05$ level). That is, participants' perceptions of the system's relative advantage, compatibility, complexity, trialability and observability were not significantly different from their perceptions after using the system face-to-face.

Table 9. Mean Questionnaire Reponses for Collaboratory System Attributes

| *Adoption Attribute* | Mean (and S.D.) Questionnaire Responses Scale: 1 (low) to 5 (high) | | | | | |
|---|---|---|---|---|---|---|
| | FtF (n=40) | Remote (n=40) | FtF Session 1 (n=20) | Remote Session 1 (n=20) | FtF Session 2 (n=20) | Remote Session 2 (n=20) |
| Relative advantage | 4.13 (0.60) | 4.05 (0.72) | 3.94 (0.54) | 3.83 (0.87) | 4.31 (0.61) | 4.27 (0.45) |
| Compatibility | 4.15 (0.64) | 4.20 (0.60) | 3.97 (0.60) | 4.20 (0.66) | 4.33 (0.64) | 4.19 (0.55) |
| Complexity | 1.26 (0.62) | 1.30 (0.75) | 1.41 (0.61) | 1.25 (0.78) | 1.10 (0.62) | 1.35 (0.73) |
| Trialability | 4.10 (0.80) | 3.89 (0.82) | 4.30 (0.49) | 3.78 (0.96) | 3.90 (1.00) | 4.00 (0.65) |
| Observability | 3.42 (0.85) | 3.50 (0.72) | 3.38 (0.83) | 3.45 (0.77) | 3.47 (0.89) | 3.55 (0.68) |



The data analysis indicates there is only one statistically significant difference in questionnaire responses due to the interaction between condition and order. This difference is for relative advantage ($p<.01$). Participants' mean score for relative advantage was always greater after their second lab session, irrespective of the order of conditions.

The null results are surprising because intuition would suggest that participants would perceive that the system provides fewer relative advantages when working remotely and that using the system face-to-face would be more compatible with participants' existing work patterns, norms and values primarily developed from face-to-face experiences. Furthermore, we expected the system would be perceived as less complex when working face-to-face because a partner who could provide assistance was collocated, and that participants would not be able to observe their partner as well remotely as face-to-face. However, even when working remotely there was always a remote partner who could provide help and be observed to some extent, and there may account for no statistically significant differences in perceptions of complexity and observability between conditions. These results are consistent with the interview data.

The null results also help to eliminate some possible explanations for the other results. For example, one possible explanation for the task performance results described earlier is that collaborating remotely first provided more time for participants to independently learn to operate the system. Therefore, when subsequently working face-to-face, they understood the system better and could perform tasks more effectively. However, there were no significant differences reported regarding trialability, observability or complexity between the conditions, which one would expect if working remotely first let participants learn more about the system. Indeed, there is a slight trend for trialability to be perceived as higher when working face-to-face in general (4.10 vs. 3.89) and after working face-to-face second (3.78 vs. 3.90). In sum, these results help eliminate this possible explanation for the task performance results.

### 5.5 Limitations

This study has several limitations. One limitation is the repeated measure design. A Solomon four-group design would have allowed additional comparisons among data from two consecutive face-to-face sessions and two consecutive remote sessions. These comparisons could potentially increase our understanding of the differences between working face-to-face and remotely, including differences caused by varying the order of working face-to-face and remotely, and the impact of any differences between the first and second task. However, a Solomon four-group design would have required substantial additional resources.

A second limitation can be found in our population sample. We used upper level undergraduate science students, one segment of the overall population who conduct scientific research and are potential collaboratory users. Graduate and undergraduate research assistants, postdoctoral fellows and faculty also comprise this population. However, due to the small number of individuals in these groups locally, to variance in their scientific knowledge, and to demands on their time, we did not include them in our population sample. The entire participant sample for the ongoing ethnographic study of the collaboratory system is taken from this working scientist population. In that study we will conduct interviews and make observations, gathering data similar to that collected during the controlled experiments. The presence or lack of correlation between these data will help confirm or refute the validity and reliability of the current study.

A third limitation focuses on the tasks. Although the tasks are representative of natural science data collection, analysis and interpretation, they do not encompass the entire life-cycle of the scientific process. For example, problem formulation, research design and research dissemination were not included in the tasks. Furthermore, the tasks in session 1 and 2 differed. Although designed to be similar in complexity, additional investigation may uncover aspects of the tasks that are inherently impacted by an interaction condition.



## 6. DISCUSSION

The data from the scientific task outcome measures, post-interviews and collaboratory adoption post-questionnaire do not support the hypotheses that working remotely would be less effective and more difficult than working face-to-face, or that working remotely would have a negative impact on participants' perceptions regarding innovation adoption. This leads us to conclude there is positive potential for the development and adoption of scientific collaboratory systems. Participants were able to adequately complete scientific work when collaborating remotely, readily developed and used strategies to compensate for system deficiencies, and developed positive attitudes toward adoption.

Schutz and Luckmann's theory of the life world (1973, 1989) may be used to explain some of the behaviors and responses we saw. Working remotely can be considered an example of a problematic situation in which an individual cannot assume his or her physical world is the same as the physical world of her or his collaborator's. However, humans have a desire to develop a shared reality. Although individuals may have different types and degrees of motivation in establishing a shared reality, we strive to assume a shared reality, an intersubjectivity, at least to the degree necessary for current purposes (Clark, 1996).

When developing a shared reality or acting within the context of different realities, Schutz and Luckmann propose that individuals assume that differences will not keep them from achieving their goals. That is, individuals assume there is a congruence of relevance systems. Schutz and Luckmann further propose that individuals assume that if you were with me, you would experience things the same way I do, i.e., individuals assume there is an interchangeability of standpoints.

When working remotely, participants' different physical locations and the system's limitations in fully and accurately representing the remote location may provide strong evidence that causes participants to believe they do not have a shared reality. However, as humans, they are motivated to develop a shared reality. Subsequently, they seem willing to proactively work to develop a shared reality, and appear to assume that the physical location differences will not keep them from completing their tasks (congruence of relevance systems). For example, no study participant reported that they could not do science when working with their partner remotely. This is especially interesting considering that 75% of the study participants had not worked with their partner previously. The participants appear to further assume there is an interchangeability of standpoints. They take explicit joint actions to develop a shared reality, using language to share their experiences and standpoint. For example, participants said that when collaborating remotely they discussed what they were currently doing with their partner more frequently and in greater detail than when working face-to-face. These explicit joint actions may help to create a shared reality and assist in task performance. The joint actions compensate for a lack of physical collocation and for limitations in the system's ability to represent the remote physical location fully and accurately.

In comparison, when working face-to-face, individuals may, perhaps erroneously, assume a shared reality already exists, or that it is more comprehensive than it really is, because there is a shared physical location. The shared physical location helps individuals believe there is also a shared reality. Knowledge about each other gained through the interpersonal interactions that commonly occur in face-to-face situations may also reinforce the perception of an existing shared reality. For example, the study participants reported they have more interpersonal interactions when collaborating face-to-face. Personal knowledge about a collaborator and a shared physical location may influence or strengthen an individual's assumptions about a shared reality, and subsequently reduce the type and number of joint actions whose purpose is to develop a shared reality.

More research is needed to explore whether the theory of the life world definitively explains our results, and if so, what the implications are for collaboratory system design. For example, the theory of the life world seems to imply that situation awareness is critical to collaboratory systems. However, are all system features, including multiple communication channels, synchronous task execution and haptics, equally important for situation awareness? In other work (Sonnenwald, et al, 2004) we begin to explore these issues proposing that contextual, task and process, and socio-emotional information is needed to create and maintain situation awareness when performing tasks collaboratively across distances. We further suggest that when designing collaboratory systems, control, sensory, distraction and realism attributes of technology should be considered with respect to their ability to facilitate access to these types of information. Continued evaluation of emerging collaboratory systems is required to explore these issues and enable us to realize the full potential of e-science and e-social science.

## ACKNOWLEDGEMENTS

Our thanks to the study participants; to Martin Guthold, Richard Superfine and Dorothy Erie who generously shared their natural science expertise and data in developing the scientific tasks and lab reports; to Kelly Maglaughlin, Leila Plummer, Ron Bergquist and Atsuko Negishi who helped run the experiment sessions; to Bin Li and Kelly Maglaughlin who helped code interviews; to the team who have and continue to build the nanoManipulator, including Frederick P. Brooks, Jr., Aron Helser, Tom Hudson, Kevin Jeffay, Don Smith, Russell M. Taylor II. This research was supported by the NIH National Center for Research Resources, NCRR 5-P41-RR02170. This chapter is based on a paper originally published in *ACM Transactions on Human-Computer Interaction*, volume 10, issue 2, pages150-176, 2003.

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