Patterns of Contact and Communication in Scientific Research Collaboration

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ABSTRACT

In this paper, we describe the influence of physical proximity on the development of collaborative relationships between scientific researchers and on the execution of their work. Our evidence is drawn from our own studies of scientific collaborators, as well as from observations of research and development activities collected by other investigators. These descriptions provide the foundation for a discussion of the actual and potential role of communications technology in professional work, especially for collaborations carried out at a distance.

1. Introduction

For many people, the word scientist conjures up an image of a white-coated figure, working alone in a laboratory with mysterious instruments and substances. But, as scientists know, science is a fundamentally social process. In most disciplines, the development of new ideas for scientific research, the execution of research tasks, and the preparation of formal research reports are all processes that involve extensive social interaction. We believe that scientific collaboration provides a model of the way professionals in many fields construct intellectual products, and that the study of research collaboration may help to specify the technological needs of cooperating work groups, as well as the limits on this technology. The premise of this report is that understanding the nature of collaborative work relationships can help to make efforts to test and implement technologies to support collaborative research a success.

Our analysis of what brings researchers together and leads them to have successful collaborations draws on data about the research and development process collected by us and by others, as well as extrapolations from relevant literature in social psychology and organizational behavior. Our own data are derived from three studies: 1) an interview study involving semi-structured, hour-long, telephone interviews with one member of each of 70 research collaborations in social psychology, computer science, and management science, in which the respondents provided detailed information about the unfolding of a single collaboration; 2) a survey study in which 66 psychologists described the production and their evaluations of a sample of their published articles; and 3) an archival study in which personal, organizational, and geographic variables were used to predict who would work with whom among 93 members of a large research and development organization. Our argument is that physical proximity makes it possible for scientists to find research partners and to carry out their research work in efficient ways. In the following section, we focus on the effect of proximity on scientists' selection of research partners and describe ways in which proximity aids the execution of research tasks.

2. Physical proximity: The framework for scientific collaboration

In an earlier paper (Kraut, Galegher, & Egido, 1988), we reported that physical proximity helps scientists avoid or minimize many of the problems that arise in the process of conducting research---meeting partners, defining problems, planning projects, supervising coworkers and subordinates---and may influence the probability of repeated collaboration. In this section we treat the role of physical proximity in more detail by examining its effects on the collaborative process and the mechanisms by which it has its effects.

As we have noted before, the process of selecting a research partner is in many ways analogous to the process of choosing a mate, with combinations of mutual benefit, personal and intellectual compatibility, and ease of contact all influencing whether a pair of potential partners decides to work together. In this process, simple proximity is especially important. As Hagstrom (1965) noted in his study of 96 university faculty and other scientists, "spatial propinquity often leads to collaboration since it is likely to lead to informal communication (p 122)." In our interview data, this general phenomenon is illustrated by a husband and wife pair who discussed research possibilities in the bathtub and a former pair of housemates whose research plans emerged over the breakfast table. More frequently, researchers in the same academic department decided to work together following informal discussions over lunch or coffee.

Interesting as they are, these stories do not permit us to assess the effect of propinquity on the likelihood of collaboration systematically. To do so requires a different type of data than either our own or Hagstrom's interview studies provide -- data that include information about pairs who did not collaborate as well as those who did. We obtained these data by looking at the relationship between propinquity and collaboration among research scientists and engineers in a large industrial, research and development laboratory. The research component of this company consists of approximately 500 PhD and MS-level researchers in the physical, engineering, computer, and behavioral sciences. The organizational structure consists of three hierarchical levels (laboratories, with approximately 125 members each; departments with approximately 30 members each; and groups with approximately 7 members each). The laboratories are located on two campuses approximately 40 miles apart. Each building consists of several floors, with several wings per floor. We selected a sample of 93 researchers, all those who had published at least two internal research reports in 1986 and 1987. At least one of these reports had a coauthor, and the other was either a solo-authored report or had a coauthor not included in the first report. For each of the 4278 unique pairings of the 93 researchers in the sample, we obtained data on four measures:

1. Collaboration: Data on whether each possible pair published at least one internal research report together were obtained from a company-maintained database of internal publications.
2. Organizational proximity: Proximity on the organizational chart was coded 1 if the pair were in the same group, 2 if they were in the same department, 3 if they were in the same laboratory, and 4 otherwise.
3. Physical proximity: Using the organizational phone book, which listed office addresses with codes for building, floor, and corridor, we computed a rough measure of physical proximity. Offices were coded 1 if they were on the same corridor of the same building, 2 if they were on same floor of the same building, but different corridor, 3 if they were on different floors of the same building, and 4 if they were in different buildings.
4. Research similarity: For each pair, we computed an index of the similarity between the publications of one member and those of the other member on which the first individual was not a coauthor. This index is based on the assumption that authors who share research interests will have written reports containing similar concepts and that abstracts of these reports contain sufficient detail to demonstrate this similarity. The research similarity index is based on information retrieval techniques developed to identify semantic similarity in large text sources (Deerwester, Dumais, Furnas, Landauer, & Harshman, under review). Basically, the similarity of a pair of abstracts is a function of the proximity of the concepts they contain in a semantic space.[1]

Table 1 shows the association of collaboration with distance between potential collaborators' offices, without controlling for any other variables.

Distance between offices and probability of research collaboration		
Office location	Total pairs	% collaborating
same corridor	243	10.3
same floor	1038	1.9
different floor	1736	.3
different buildings	1261	.4

TABLE 1

The data clearly show that pairs whose offices were close to each other were more likely to collaborate (Yule's Q for the 2x2 table comparing same corridor and floor to different floor or building = .82; $p < .001$).[2]

2.1 Mechanisms underlying the relationship between proximity and collaboration

To understand the association between proximity and the likelihood of research collaboration, we examine two general explanations---spatial segregation of similar others and the availability of frequent, high quality, low-cost communication as a mechanism to facilitate the development of ideas and the execution of collaborative tasks. After assessing the validity of the idea that this relationship is entirely a consequence of the fact that individuals with similar interests are co-located, we discuss the impact of informal communication on both social and mechanical aspects of collaboration.

2.1.1 The influence of spatial segregation

One explanation, bordering on artifact, is that researchers who are similar to each other in important ways also have their offices close to each other. It is true that both in academia and in industry researchers whose offices are close together are likely to share common organizational goals and to have research interests in common. In a university, for example, members of an academic department are likely to be co-located, and subspecialities within the same department often have offices on the same floor, corridor, or in the same wing of a building. It is possible that this similarity in research interests, not the fact of proximity, is sufficient to lead to research collaboration. Indeed, in our R&D sample, researcher pairs in the same department were more likely to work together than those in different departments (52% of 294 of the pairs in the same department versus Yule's Q = .88). Moreover, those with similar research interests as defined above were more likely to work together (3.3% of pairs in the top quartile of similarity versus .3% of those in the bottom quartile; Yule's Q based on a median split of similarity = .74).

But the effects of propinquity on research collaboration cannot completely be explained by organizational proximity and similarities in research interests among those who are close to each other. In a logit analysis holding constant organizational proximity and research similarity, physical proximity has an independent effect on research collaborations. Table 2 shows the association of collaboration and physical proximity, holding constant the organizational proximity between potential collaborators (i.e., whether they were in the same or different departments). Our sample did not include enough pairs of researchers who were in the same department but sufficiently far apart to analyze the effects of physical distance within a department. We did, however, have enough variation in physical distance among researchers in different departments to examine this relationship.

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1. Lynn Streeter and Susan Dumais suggested this approach, and Karen Lochbaum aided us by writing computer programs for this analysis. The analysis starts with a large matrix representing the number of times each of 7100 terms appears in each of the 4000 abstracts of research reports from the company. This matrix is reduced to a large number of orthogonal dimensions using singular value decomposition, so that terms which are similar in meaning appear as neighbors in the space. For each pair of researchers, we represent each member's work as a point in the 100 dimension space that is the centroid of the terms in the abstracts of his or her work. In comparing any two researchers, we use only those abstracts in which the other was not a co-author (i.e., solo authored work or collaborative work with other co-authors). The research similarity between two authors is the cosine or product moment correlation between the 100 dimensional vectors representing each author. A cosine of 1.0 (a 0 degree angle) would indicate that the two authors' papers are on top of each other in the space.

2. Yule's Q is a measure of association for 2 x 2 tables with unequal marginals. It is -1 if the least frequent variable never co-occurs with the more frequent variable, 1 if it always co-occurs, and 0 if there is no relationship between variables.

Numbers of research collaborations by organizational and physical proximity				
	Organization			
	Same Department		Different Department	
Office location	Pairs	% collaborating	Pairs	%collaborating
same floor	271	10.3	909	1.87
different floors	23	4.3	1708	.29
different buildings	0	NA	1261	.40

TABLE 2

Table 2 shows that among researchers in different departments, pairs of researchers who were on the same floor as each other were about six times more likely to enter into research collaboration than were pairs on different floors or in different buildings. Clearly, even among researchers in different departments, having offices on the same hallway increases the likelihood of research collaboration. What appears to be important in producing this relationship is the opportunity for unconstrained interaction that proximity provides. To illustrate the importance of these opportunities, we describe three properties of informal communication and show how these properties affect collaborative work and collaborative relationships.

2.1.2 The importance of informal communication

2.1.2.1 Communication frequency The major mechanism through which proximity has its impact on the likelihood and longevity of research collaborations is through its impact on frequency of communication. Even if we consider technologically mediated communication such as telephone and computer mail usage, the frequency of communication between any two people is a strong function of their geographical proximity. (See Figure 1a from Mayer, 1976 and 1b Eveland & Bikson, 1987). What holds true in the world of residential phone service and corporate mail networks holds true in the research world as well. As our interviews and those conducted by Hagstrom (1965) indicate, the informal contact that results from frequent opportunities for communication often leads to collaboration. In his sample of industrial research and development engineers, Allen (1977) showed a striking logarithmic decline in communication frequency with distance between potential communicators. (See Figure 1c). For example, in Allen's data, about 25% of engineers whose offices were next door to each other (less than 5 meters apart) talked to each other about technical topics at least once a week; if their offices were 10 meters apart, this figure drops below 10%. After this sharp decline, the curve asymptotes at approximately 30 meters, so that engineers 30 meters apart and those several miles apart had approximately the same low probability of talking to each other at least once a week.

Our own data show a similar phenomenon even among collaborators who are already working together. In our survey study of collaboration among psychologists, we asked our respondents to indicate the distance between their offices and those of the primary coauthor for each of their collaborative articles and to estimate the frequency of their communication with this coauthor when initially planning the project and when planning the journal article itself. In this analysis, physical proximity was strongly related to frequency of communication during both the planning stage and the writing stage of the research process, as shown in Figure 1d. It demonstrates, for example, that researchers who have offices next door to each other have approximately twice as much communication as those whose offices are simply on the same floor as their partners. One consequence of this frequent interaction is that researchers who are situated near each other are likely to come to like each other more (Zajonc, 1968). If, in turn, people are more likely to want to work with people they like, then the opportunity for frequent interaction is likely to have a strong influence on the likelihood of collaboration.

Relationship between distance and communication across different communication modalities

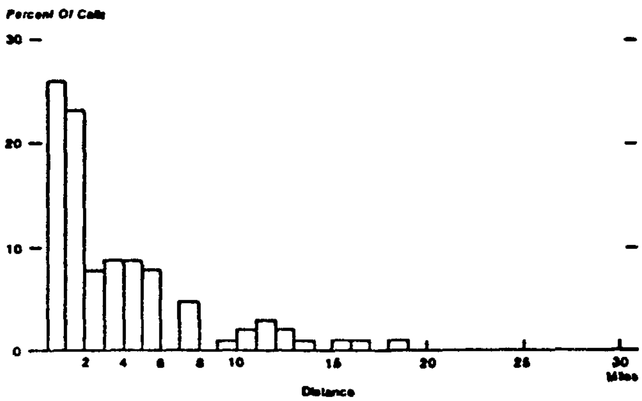

Figure 1a. Number of local phone calls by distance between parties. (Mayer, 1976)

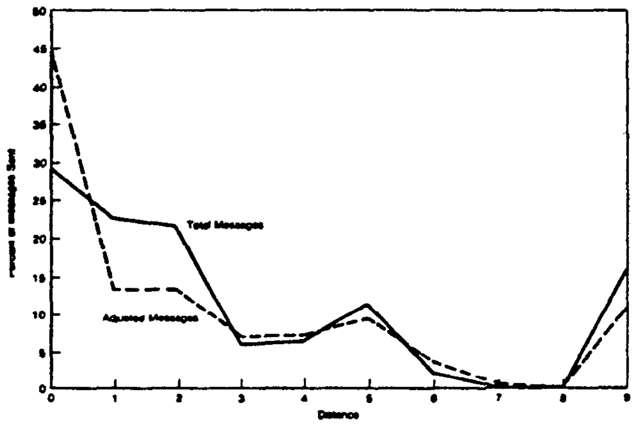

Figure 1b. Number of electronic messages by distance between parties. (Eveland and Bikson, 1987)

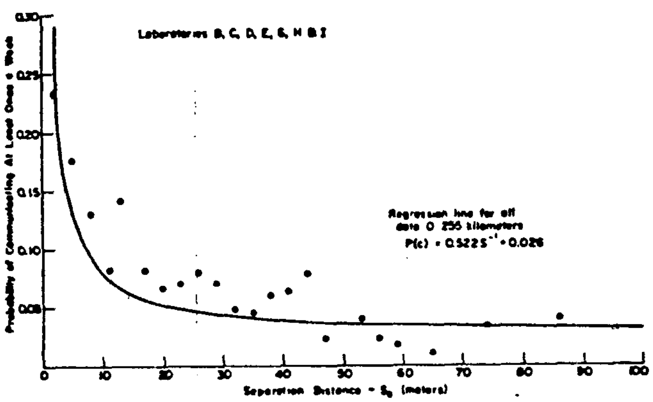

Figure 1c. Probaility of communication by distance between potential communicators. (Allen, 1977)

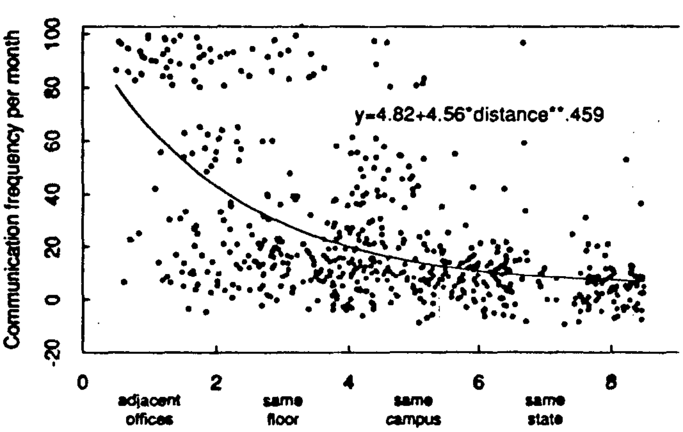

Figure 1d. Communication frequency by distance between collaborators.

2.1.2.2 Quality of communication In addition to increasing the likelihood of informal communication through increased contact, proximity increases the quality of communication. By high-quality communication, we mean two-way interactions involving more than one sensory channel. The opportunity for interactions of this type is especially important during the initiation and planning stages of a project, when the need for a rich communication modality is strongest. Typically, a common focus for collaborative projects is constructed from the pre-existing interests and expertise of the participants. One example of this sort of relationship is a social psychologist who sought a collaborative relationship with a cognitive psychologist to develop an ill-specified project in social cognition. He said, ". . . the idea was still very fuzzy. We often eat lunch together, so there are many informal opportunities to raise issues and discuss them . . . it was in one of those informal settings, at lunch, or after lunch sometime, I brought up the issue the broad outlines of things, little things meshed and she recommended I read a particular paper . . .". These informal conversations eventually grew into a collaborative project that joined the interests of these two researchers. It seems unlikely that one could have predicted the occurrence of a collaborative relationship between these two individuals, but, in this case, and in many others, the opportunity for high-quality, informal interaction led to a productive relationship. In sum, our data suggest that high-quality informal communication is important because it allows researchers to *develop* common interests with their neighbors.

Drawing again on our interviews, we learned that discussions of this type tend to merge into more focused conversations about specific projects. According to our respondents, the initial task-level activity in a collaborative relationship usually consists of multiple face-to-face discussions, occurring frequently over the course of days, or, more typically, weeks or even months. Our survey data support this observation; they indicate that when collaborators are most intensively planning their work, they meet almost daily ($M = 27$ times per month). These discussions are the most intensely interactive aspect of the entire research process and, according to the researchers, the most intellectually exciting and rewarding aspect as well. At a later stage of project development, when collaborators are planning the writing of their research reports, we observed a similar reliance on frequent face-to-face communication. Although actual writing is most often a solitary activity, our survey respondents report meeting 17.2 times per month while planning these documents. This is significantly less than during initial project planning ($p < .001$), but still frequent.

The intense, highly interactive meetings that characterize planning work generally take place in offices or conference rooms and, typically, the only technologies involved are paper, pencils, and blackboard. But current communication technology available to most researchers does not allow the intensity of interaction nor the spontaneous exchange of notes and documents that are typical of these face-to-face meetings. Thus, quality problems are likely to arise because research partners are unable to engage in rapid-fire conversation or are unable to obtain the feedback they need to adjust their communications to fit their partners' information needs (Krauss & Weinheimer, 1967; Kraut, Lewis, & Swezey, 1982).

2.1.3 Cost of communication

A third important feature of communication with one's research partner(s) is cost. Some costs are obvious; if one's research partners are not co-located, the costs of collaboration will have to include the expense of plane tickets and phone calls. More importantly, they are also likely to include the burden of having only intentional, structured interactions via a restricted modality within an already existing relationship. But proximity makes it possible to explore new relationships, and to supervise and sustain progress by providing the low-cost communication necessary to assess compatibility, to catalog what has been done, to alert partners to minor problems, and to enforce guilt.

Being situated near a pool of potential collaborators provides a low-cost opportunity for a researcher to discover the qualities of another that might make him or her a desirable collaborator. This increased awareness of the attributes of one's neighbors allows one to choose partners judiciously, lowering the risk of selecting an inappropriate collaborator. Later on, low cost communication and the opportunity for quick and easy access to a partner are crucial for collaborators' joint supervision of the project and each other's work. For most of our researchers, project management was extremely informal, with the supervision of subordinates and coordination with peers occurring during casual hallway and lunchroom conversation as often as through formal, scheduled meetings. These "on the fly" interactions are impossible in collaborations that occur over a distance.

Proximity also allows collaborators to consult with each other about the minor sticking points that crop up in all research projects, but distance raises the personal costs of communication so that short messages become uneconomical. Many interviewees reported frustration about the difficulty in conducting such consultations when working with collaborators who were in different locations and about the resulting slowness. For instance, one researcher said, "[This] was the first project that I had done long-distance and it certainly made it more time-consuming. I was used to being able to walk down the hallway from my office to [my collaborator's] office to talk to him about a problem . . . we either relied on the mail going back and forth or even phone conversations and that just wasn't as satisfactory as talking face-to-face . . . It took a long time, and I wasn't used to having that much of a lag for the turn-around . . . I was used to being able to make it much faster."

In sum, having multiple opportunities for high-quality, low-cost interactions makes it possible for potential collaborators to find each other and to manage their work efficiently. Without these opportunities, collaborations don't get started, and if the opportunity for informal communication declines, collaborative work typically slows down, becomes more burdensome and, sometimes, comes to an end.

3. Implications for technology for collaborative work

In the following discussion, we use our knowledge of the functions that proximity serves in research collaborations to define basic requirements that communication technologies must meet to support research collaboration, or for that matter, any cooperative intellectual work that spans months and is at least partially based on a sustained personal relationship among the members of a workgroup. Our view is that communications technologies that allow free-form interaction in real-time and time-shifted modes to substitute for, and even to augment, physical proximity are likely to yield great benefits.

To address the needs of multi-person work teams, particularly distributed work teams, at least three general classes of tools are needed: 1) communication tools to facilitate both planned and unplanned real-time and delayed interactions among collaborators, 2) coordination and management tools to minimize the overhead inherent in multi-person work, and 3) task-oriented tools designed to facilitate the completion and integration of specific work products, whether individually or jointly executed. Most of the research activity in technologies to support work groups has concentrated on a small part of this range, either on enhancements to formal face-to-face meetings with the explicit goal of structuring interaction or on highly task-specific applications. Thus, technologies such as teleconferencing, group decision support systems (e.g., Kraemer & King, 1986; Vogel & Nunamaker, 1988), group outlining systems (e.g., Cognoter, Foster, & Stefik, 1986), and group drawing programs (Lakin, 1986) are designed to facilitate formal meetings among coworkers. Moreover, they often fix on narrow, albeit important, aspects of these meetings. Tools like collaborative writing systems (EXPRESS, Thaler, 1988; Fish, Kraut, Leland, & Cohen, 1988) support specific tasks within the total work process. As such they support only a minor portion of the communicative activities that occur in the course of a cooperative work effort.

Instead, we believe that the aim should be specifically to increase the frequency and quality and to decrease the cost of interactions among potential collaborators who are working across barriers of place and time. A low-cost communications medium is one that is so ubiquitous that a potential user need make no planned effort to use it. That is, the behavioral cost to the actual user would be low, even though the financial cost to the user or the organization supporting him or her may be high. As we said earlier, high quality means that the communication system allows users to transmit all of the information they need to exchange rapidly. Typically, this will mean a two-way (or N-way) communication link involving more than one sensory channel. We expand on these requirements in the sections below.

3.1 Low-cost interactions

We believe that the lesson of the J-shaped relationship between distance and communication frequency is that much useful communication between actual and potential research partners is not planned and would not occur if it had to be planned. During the initiation of a collaboration, proximity allows low-cost contact that provides potential collaborators with the opportunity to make contact with each other and to discreetly assess their mutual compatibility before committing to work together. Once they become committed to working together, frequent communication holds together the threads of a collaborative relationship over time. During the execution of the work, the frequent, low-cost communication that proximity permits enables collaborators to provide each other with both subtle prods and status information through casual interactions. Also, quick and easy access to a partner permits sharing of major and minor decisions and, thus, creates the sense of ownership that keeps participants committed to a project. Finally, and perhaps most importantly, throughout the collaborative process as a whole, proximity supports a convivial personal and working relationship by building a consensus of views and interests and maintaining shared knowledge about the project and about the local culture in which it is embedded.

To maintain this level of communication in the absence of proximity requires technology that makes communication cheap, frequent, and spontaneous enough that collaborators can be in touch as easily as if their offices were next door to each other. The technology must allow not only frequent but informal and unplanned interactions as well; many of the interactions that make up this *feedback over time* are damaged by intentionality and simply would not occur if they must be willfully initiated. The recent attempt to provide an onmipresent video connection between two Xerox research facilities (Goodman & Abel, 1987) was based on this concept. This environment was designed to encourage unplanned interactions mediated by technology over considerable geographic distance. Usage data indicated that over 70 percent of the interpersonal communication between the two sites was casual, *drop-in* style interaction of less than 5 minutes in duration and that these interactions would likely not have occurred in the absence of continuous video link (Goodman & Abel, 1987). Participants' experiences suggest that having this video link was marginally adequate to promote a shared context and culture that supported joint work across the two locations.

Unfortunately, the communications technology in the Xerox experiment was limited, both by the state-of-the-art in commercial video equipment and by the high cost of transmitting the huge amount of information that comprises moving video images. As a result the two locations were linked only by a single channel for slow-scan video, two lines for audio connections, and an additional one for data. Participants felt that this was inadequate to support crucial aspects of cooperative work, such as project initiation, delicate negotiation, and detailed joint work that required shared graphics (Goodman and Abel, personal communication). The logistics of switching the limited video resource became burdensome, and in any case, was not sufficient to match the quality of the spontaneous interactions that physical proximity provided within a work site. We will deal with some aspects of these deficiencies in the technology in the section below, but can presage the discussion by noting that more sophisticated communications technology may more adequately solve some of the problems that proximity solves naturally for collaborators.

While the Xerox experiment attempted to use communications technology to duplicate the effects of physical proximity, one can go beyond mere duplication by using communications technology to create virtual environments that are impossible in the physical world. In the physical world an office can only be surrounded by a few others along a corridor. Even in a better, less linear office arrangement that minimizes average separation among co-workers we are still limited by the two-dimensionality of physical layouts. And in the real world, the inhabitants of those offices are as likely to be there because of accident, seniority, or bureaucratic inertia as because of careful planning.

To overcome the limitations of physical proximity, we can imagine video hallways or other communications technologies that would provide virtual proximity to a larger or more appropriate set of colleagues. Also, unlike physical office arrangements, which are not even as flexible as the organizational structures that support their inhabitants, such electronic hallways are potentially reconfigurable to accommodate organizational changes, changes in personal work interests, or other changes that might affect the collaborative compatibility of a particular set of people.

3.2 High quality real-time interactions

Just as proximity supports low-cost communication, it also supports high quality interaction. For example, during the idea generation stages that occur at the beginning of a project, when collaborators plan the execution of the work, and later when they plan the documentation of the project, proximity enables the intense, highly interactive, face-to-face sessions that are the cornerstone of the collaborative process. At a minimum, communication tools to support these meetings must allow participants to exchange whatever information they bring with them to the discussion or create during the course of a meeting itself. Some of this material might be text, on paper or in computer files. Other material might be graphical, ranging from hand-written notes, to figures, to photographs, to annotations of already exchanged documents. In addition, participants in these meetings must all be able to see, point to, and modify these text and graphics objects. Just as one participant in face-to-face meetings might point to headings on a blackboard or paragraphs on a page for the other participants, they must be able to do so in a technologically-mediated meeting. More importantly, however, the technology to support these intensely interactive meetings must support the backchannel and other feedback mechanisms that participants use to accommodate the informational needs and processing capacities of listeners as well as the dynamic evolution of speakers' conversational goals (Kraut & Higgins, 1984). When people communicate in ways that allow them to assess their partners' view of the world and of their own speech and to use this information to change their conversational tactics, their communication becomes more effective and efficient than it might be when this feedback is lacking (Krauss & Weinheimer, 1966; 1967; Krauss, Garlock, Bricker, & McMahon, 1977; Kraut, Lewis, & Swezey, 1982).

The role of dynamic feedback between communicators in facilitating smooth and efficient exchange of information may partially explain users' frustration with teleconferencing systems which provide inadequate half-duplex audio (i.e., to reduce audio feedback, only one person can talk at a time) in exchange for hands-free convenience. Similarly, the lack of real-time feedback may help to explain the dissatisfaction with some forms of asynchronous computer communication systems. In a computer conference, for instance, participants enter comments, perhaps about very complex topics, without knowing exactly who they are writing to and without being able to ascertain whether any listener has understood what they are saying. Without the capacity to obtain immediate feedback, authors may find it difficult to tailor their communications so that they are readily understandable to other readers. If readers do not understand a particular entry, they may be unlikely to follow it up or to respond in a way that seems directly relevant; this process of inadequate encoding and unresponsiveness may then produce the frustration about lack of responses that Tombaugh (1984) described. Given this dynamic, it is easy to see why it has proven to be difficult to get people to use computer conferences on a regular basis (Johansen, 1987).

3.3 Conclusions

We have not attempted to exhaustively catalogue technology that would support research collaborations nor even to list all of the communication technology of which we are aware. Rather we have focused our attention on the two major functions that physical proximity currently fulfills. We drew implications from these functions about two styles of communications technology that we believe could provide the foundation for technologies supporting cooperative work. Omnipresent video might provide the low-cost and therefore frequent and spontaneous interactions that are crucial to initiating collaborations, monitoring and coordinating the project, and maintaining a smooth personal relationship. Multimedia meeting tools might provide the high quality communication to support planning and review. While many other specific tools have been proposed and could be built to support particular tasks that occur frequently in a collaborative project, most are likely to build from these two foundations.

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