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Coordination costs and project outcomes in multi-university collaborations

Jonathon N. Cummings [a,*], Sara Kiesler [b,1]

[a] Duke University, 1 Towerview Drive, Box 90120, Durham, NC 27708, United States
[b] Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA 15213, United States

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Abstract

Multi-university collaborations draw on diverse resources and expertise, but they impose coordination costs for bridging institutional differences and geographic distance. We report a study of the coordination activities and project outcomes of 491 research collaborations funded by the US National Science Foundation. Coordination activities, especially division of responsibility for tasks and knowledge transfer among investigators, predicted project outcomes (e.g., producing new knowledge, creating new tools, and training students). However, more universities involved in a collaboration predicted fewer coordination activities and fewer project outcomes. A statistical mediation analysis showed that insufficient coordination explained the negative relationship between multi-university collaboration and project outcomes.

Keywords: Collaboration; Teamwork; Knowledge; Coordination; Geography

1. Introduction

Research is becoming increasingly distributed. R&D labs are spread across continents (Gassmann and von Zedtwitz, 1999), open source software projects have contributors from around the world (von Krogh and von Hippel, 2003), and scientific collaborations involve many institutions (Corley et al., 2006). Historians of science have traced the first surge in distributed research projects to the shift after World War II from little science to big science, whereby scientists collaborated to leverage the cost of expensive scientific equipment and trained specialists (Beaver, 2001; de Solla Price, 1963). With the advent of computer networking, scientists across institutions began to share data and networked instruments. The development of "collaboratories" allowed scientists in different geographic locations to share common resources (Kouzes et al., 1996). European, Asian, and US funding agencies such as the Department of Energy sponsored large-scale projects bringing researchers from different institutions together physically and virtually (Finholt, 2002).

Recent policy changes have encouraged scientists and engineers to form multiple-university collaborations in many fields (Katz and Martin, 1997). The EU framework program promotes collaboration across universities and businesses to help build new technologies and to establish connections among researchers in different member countries (Luukkonen, 1998). The US National Science Foundation created initiatives in interdisciplinary

* Corresponding author. Tel.: +1 919 660 7756; fax: +1 919 681 6244.
E-mail addresses: jonathon.cummings@duke.edu (J.N. Cummings), kiesler@cs.cmu.edu (S. Kiesler).
1 Tel.: +1 412 268 2848; fax: +1 412 268 1266.

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research such as Knowledge and Distributed Intelligence (KDI) and Information Technology Research (ITR). Large programs supported by the National Institutes of Health, such as the Human Genome Project (Collins et al., 1998) and AIDS research (Teasley and Wolinsky, 2001), also encourage research across disciplines and institutions.

We argue that despite the advantages of shared resources and expertise, as well as increased incentives through additional funding for multi-university work, research collaborations involving multiple universities impose significantly higher coordination costs than do single university projects. These coordination costs have institutional and geographic origins. In multi-university collaborations, for example, participating universities often have dissimilar institutional structures such as different pay scales for staff and graduate students and distinct requirements for joint appointments or student transfers. Other institutional differences are rooted in culture and norms. For instance, researchers may have to negotiate where to publish because of differing "A-list" journals and conferences where faculty members seeking tenure are expected to publish. Geography also increases the coordination costs for multi-university collaborations. Geographical distance can slow group communication and consensus making, and a problem at one location may go unnoticed by researchers at the other universities. The higher coordination costs of collaborating across universities are likely to complicate both disciplinary and multi-disciplinary research, potentially affecting the success of these collaborations (Cummings and Kiesler, 2005).

In this paper we examine project outcomes in single and multiple university research collaborations, and link coordination activities in these projects to their outcomes. Our arguments draw from organization theory on the knowledge-based view (e.g., Grant, 1996a; Kogut and Zander, 1992) and recent theoretical and empirical research on coordination in distributed work (e.g., Boh et al., 2007; Gibson and Gibbs, 2006; Hinds and Kiesler, 2002). We report a study in which we measured coordination activities and project outcomes in 491 research collaborations, over half of which had investigators at more than one university. Our findings suggest that coordination costs are a significant barrier to project success in multi-university collaborations.

1.1. Knowledge-based view applied to research collaborations

The goals of research collaborations are to achieve outcomes that include producing new knowledge, creating new research tools, training and educating students, and forming partnerships with institutions in the larger society, such as government agencies, museums, or schools. To achieve these goals, scientific policy increasingly encourages research collaboration across disciplines and institutions (Jeffrey, 2003). The US National Academy of Sciences has reported that important accomplishments, including discoveries in nanotechnology, bioinformatics, and neuroscience, have been achieved through research collaboration (National Academies, 1994). Research collaboration provides a mechanism for investigators with differing advanced training and skills to work together on projects that they could not do on their own. The involvement of multiple investigators can decrease the variability in output quality through feedback and the peer review of ideas (Rigby and Edler, 2005).

A body of organizational theory, called the knowledge-based view, provides a theoretical framework for thinking about the value of research collaborations that span multiple universities. The knowledge-based view originally came out of economic analyses of the so-called grow versus buy decisions by firms, that is, whether to develop resources within the organization or acquire these assets from external sources. Kogut and Zander (1992) and Grant (1996a,b) argued that specialized expertise embedded in people is the most important asset for organizations engaged in knowledge-intensive work. To innovate and gain competitive advantage, the organization may need to draw from a pool of many kinds of expertise. Applied to university research, for instance, a research endeavor may require various medical scientists, computer scientists, and neuroscientists. According to the knowledge-based view, growing specialized areas of expertise within a single university would be best advised when each form of expertise will be used frequently and is unlikely to be appropriated (copied) by others. Alternatively, a temporary alliance with other universities would be best advised when the area of expertise is expensive to develop internally, is not likely to be used frequently, or could be appropriated easily by other organizations. Thus, the knowledge-based view implies that collaboration in multi-university projects is not inherently superior to within-university projects but rather is best justified for bringing together infrequently used and unique forms of expertise.

1.2. Coordination in research collaborations

From the perspective of the knowledge-based view, organizations and project teams within organizations that are more effective at integrating their diverse expertise will be more successful (Grant, 1996a,b). Integrating diverse expertise for research requires creating a common language and shared meaning within the research team, and managing the dependencies of tasks and linking different pieces together into a collective whole (Malone and Crowston, 1994; Van de Ven et al., 1976).

Organization theorists have distinguished among several types of coordination activities that help project teams integrate and best utilize their expertise. One type involves dividing and assigning responsibilities for tasks to appropriate specialists. Tasks whose leadership is assigned to different individuals or groups may be loosely coupled and thus resistant to over-dependency and communication failures (Weick, 1979). Porac et al. (2004) described a scientific alliance across multiple universities, in which the loose coupling of investigators contributed to improved productivity due to lower costs of direct communication. A second type of coordination activity involves sharing resources such as a common website or intranet, a shared database, or shared remote instruments. Leveraging common resources not only reduces the costs of data and communication for each investigator but also can lead to improved, systematic methods and standardized measurements. A third type of coordination activity involves learning and transferring knowledge for potentially synergistic effects, such as through student exchanges and co-authoring papers. Deeply involving investigators and graduate students in co-authored papers, seminars, experiments, and other goal-driven intellectual efforts can lead to higher levels of cooperation and improved project achievement.

A fourth and likely the most common type of coordination is direct communication through meetings and spontaneous discussion. Researchers in many fields hold regular lab meetings, meet with graduate students, and discuss their work at conferences and seminars. In collaborations across institutions, they may travel to see one another or take sabbaticals at one another's institution. More frequent communication is associated with greater trust, respect, and participatory norms. Disciplines such as particle physics have benefited from norms of participatory processes (Chompalov et al., 2002).

1.3. Coordination costs in multi-university collaborations

Coordination activities such as those described above are essential to research but they create costs that need to be taken into account when evaluating the effectiveness of collaborations. When multiple universities are involved in a project, complexity increases and the difficulty of coordination activities increases (Hagstrom, 1964; Hobday, 2000). Distance reduces opportunities for spontaneous, informal talk in a shared social setting (Kiesler and Cummings, 2002). Compared with single university projects, projects with investigators at different universities are likely to have more difficulty fostering a collegial social environment (Kraut et al., 2002; Nardi and Whittaker, 2002), building common ground (Clark and Brennan, 1991), maintaining awareness of what others are doing (Weisband, 2002), and making rapid adjustments to surprises (Olson and Olson, 2000). Allen's (1977) rule of thumb is that co-workers should be no more than 30 m apart, beyond which collaboration effectiveness declines precipitously (see Kraut et al., 1990).

Advances in communication and computer technology represent opportunities to collaborate in new ways, but for purposes of coordination, technology is an imperfect substitute for collocation. In studies of business and research projects with dispersed members, researchers have discovered project delays (Espinosa and Carmel, 2004; Herbsleb et al., 2000), misunderstandings (Cramton, 2001), institutional rivalries (Armstrong and Cole, 2002), free riding (Weisband, 2002), distractions from local institutional priorities (Mark et al., 1999), inconsistent procedures across institutions (Curtis et al., 1988), and failures to share information and communicate effectively (Hinds and Mortensen, 2005; Hoegl and Proserpio, 2004). If the project involves a greater percentage of members at different institutions, coordination is more difficult (Cummings and Kiesler, 2005; Mark, 2005).

To summarize, we argue that coordination activities are essential to integrating and utilizing expertise in research projects. Multi-university projects, however, impose greater costs and barriers to coordination that can have negative implications for the outcomes of these projects. Thus we hypothesize:

Hypothesis 1. The more coordination activities in a research project, the better the project outcomes.

Hypothesis 2. The more universities that are involved in a research project, the fewer the coordination activities.

Hypothesis 3. The more universities that are involved in a research project, the worse the project outcomes.

Hypothesis 4. Insufficient coordination activities will explain the negative association between number of universities involved in a research project and project outcomes (statistical mediation).

2. Methods

2.1. Sample and data collection

This study examined the coordination activities and outcomes of projects funded by the Information Technology Research (ITR) Program in the US National Science Foundation (NSF). The ITR was a 5-year NSF-wide priority area for supporting interdisciplinary Information Technology (IT) research and education with innovative research and education projects. The program was a major NSF initiative, growing from US$ 90 M in 2000 to US$ 295 M in 2004. Three kinds of awards were reviewed by separate peer review panels: Small projects (up to US$ 500 K for 3 years), Medium projects (up to US$ 1 M per year for 5 years), and Large projects (up to US$ 3 M per year for 5 years). This study examined Medium and Large ITR projects awarded in the first 4 years of the program, 2000–2004. Because there was substantial overlap in the actual number of senior researchers and project funding for medium and large ITR projects, we combine them into a single analysis reported below. The typical project involved five principal investigators (PIs) and two universities.

The ITR program evolved over the period we studied in several ways. For FY 2000, the ITR emphasized fundamental information technology research and education, in 2001, the application of information technology to science and engineering, in 2002, multidisciplinary information technology, in 2003, the relationship between acquisition and utilization of knowledge and information technology tools, and in 2004, information technology research for national priorities. Administrative changes also took place in the program over the 5 years. For example, in later years NSF imposed increasing proposal submission limits, and in 2004 it required coordination plans and limited submissions to one proposal per PI. At the start, most projects received major funding from the Computer and Information Sciences and Engineering Directorate (CISE), but awards distributed across the National Science Foundation increased over the years. Over 70% of the projects involved two or more disciplines, although roughly 50% of senior researchers were from computer science, with the remaining senior researchers coming from engineering, physical sciences, and other sciences.

The ITR program offered researchers opportunities to form new collaborations and projects, which made it extraordinarily popular in information technology communities around the US. The number of proposals increased from approximately 2100 proposals in 2000 for the first year of the program to over 3100 proposals in 2004. Even with increased ITR funds, the program became more competitive. In 2000, 30% of the medium and large proposals were funded; in 2001 and 2002, 27%; in 2003, 24%; in 2004, 21%. At the same time, awarded project budgets were reduced more in the latter years of the program. In our dataset of 549 large and medium ITR projects, year 2000 projects received 76% of their proposal budget; year 2001 received 68%; year 2002 and 2003 received 50%; year 2004 received 49%.

In the spring of 2004, NSF asked the authors to organize a workshop of research grantees to assess what had happened in the ITR research projects, following a procedure created to assess the previous Knowledge and Distributed Intelligence (KDI) program (see Cummings and Kiesler, 2005). NSF invited the principal investigator (PI) and a co-PI from each of the Medium and Large projects to the workshop (a total of 379 PIs and co-PIs attended along with 37 NSF officers). At this workshop we asked researchers, organized into small groups, to discuss with one another how their research projects were organized and managed, the kinds of outcomes they generated, and the ways in which their experience could inform future program evaluation.

From the workshop notes and documentation from ITR project websites and reports, we created a web-based online survey to systematically assess the coordination activities and project outcomes that workshop participants had described in connection with their own projects. We created items that represented the most frequent coordination activities and project outcomes mentioned in the workshop and in the former survey of the KDI program. In May and June of 2005, we surveyed one PI per university represented on each project, avoiding duplication so that any one person completed only one survey for one project. Each university involved in a collaboration was sampled. For example, on a project with three universities, we surveyed the most senior PI at each university, and averaged the responses to obtain project-level measures. There were 2692 PIs for 549 projects, and to avoid duplicate surveys we requested surveys from only 1302 of them (48%). We received responses from 885 of those sent a survey, for an overall response rate of 68%. Due to missing data from some projects, the analyses here cover 491 of the 549 projects (89%).

2.2. Measures

We obtained descriptive data on each project, such as its start date, budget, senior researchers, and universities from the NSF. We used self-reports on the survey and information available on the web to classify each senior researcher's discipline. ITR project investigators who participated in the online assessment provided information on project participants, coordination activities, and project outcomes to date. We used self-reported outcomes, such as whether they published or not, rather than citation counts, because of the recent nature of the projects. From individual items, we created composites of checkbox items in the online survey. For instance, to measure knowledge outcomes, we listed seven possible specific outcomes related to gains in new knowledge. Groupings of items were decided based on definitions from the Government Performance Results Act (GPRA) of 1993, as defined by NSF, and factor analyses from a previous study of the National Science Foundation KDI program (Cummings and Kiesler, 2005). We also added two other outcome measures regarding the sustainability of the collaborations.

As composites, the items in each coordination activity and outcome category do not measure the same underly-

Table 1
Variables in the study

	Measure
Control variables	
Project start year	Year the project started (range: 2000–2004)
R&D expenditures	Average R&D funding at the universities involved in the project
Project budget	Total budget including overhead across all universities in the project
Number of senior researchers	Number of PIs, co-PIs, and senior researchers in the project
Number of disciplines	The number of major disciplines of senior researchers (PIs, Co-PIs, senior personnel)
Independent variable	
Number of universities	The number of universities of senior researchers involved in the projects
Coordination activities	
Division of responsibilities	Subgroups worked on different tasks/studies; implemented project manager role in project; faculty directly supervised tasks/studies; post-doc(s) supervised tasks/studies; grad student(s) supervised tasks/studies. Alpha = 0.45 (five items)
Shared resources	Common lab space, lab equipment, websites, datasets, materials. Alpha = 0.65 (five items)
Knowledge transfer	Co-authorship; held conference; workshop; seminar; presentation; brainstorming; invited outside speakers; hosted visitors at site, tutorials/training sessions for project staff/participants; retreat/summer camp/management training; offered multi-disciplinary courses; co-advising students; student exchanges. Alpha = 0.78 (13 items)
Meetings	At least monthly face-to-face meetings with most participants; with senior personnel; with students; with project subgroup; at least monthly informal interactions; senior personnel worked on project during a conference or workshop; during sabbatical or leave. Alpha = 0.71 (seven items)
Communication technology	Email at least once a month; telephone at least once a month; conference call at least once a month; video conferencing at least once a month; instant messenger at least once a month; online forum at least once a month; project website. Alpha = 0.63 (seven items)
Project outcomes	
Knowledge outcomes	Started new field or area of research; developed new model or approach in field; came up with new grant or spin-off project; submitted patent application; presented at conference or workshop; published article(s), book(s), or proceeding(s); recognized with award(s) for contribution to field(s). Alpha = 0.63 (seven items)
Tools outcomes	Developed new methodology; created new software; created new hardware; generated new dataset; generated new materials; created data repository; created website to share data; created collaboratory; created national survey; developed new kind of instrument; created online experiment site. Alpha = 0.65 (11 items)
Training outcomes	Grad student finished thesis or dissertation; grad student/post-doc got academic job; grad student/post-doc got industry job; undergrad/grad student(s) received training; undergrad(s) went to grad school. Alpha = 0.70 (five items)
Outreach outcomes	Formed partnership with industry; formed community relationship through research; formed collaboration with researchers; established collaboration with high school or elementary school students; established collaboration with museum or community institution; established collaboration with healthcare institution. Alpha = 0.45 (six items)
Collaboration outcomes	We started collaborations within our ITR project that will continue beyond the ITR; we started collaborations outside our ITR project that will continue beyond the ITR; we shared data with other research projects. Alpha = 0.47 (three items)
Leverage outcomes	We found a way to continue our ITR research; we initiated a new line of research that will continue beyond ITR; we applied for or received funding to develop ITR research further; we applied for or received funding to take ITR applications further; we applied for or received funding to maintain resources created in the ITR project. Alpha = 0.64 (five items)

ing variable and should not be considered scales (though we report Cronbach alphas). Thus, in the category "Knowledge," more items checked means the project produced a greater number of the specific achievements listed (such as patents, awards, and publications). The modest alpha of 0.65 reflects a trend that to be productive in one dimension is somewhat but not highly related to productivity in another dimension. For example, PIs might have published a new computational model but not have won an award for this work at the time of the survey.

2.3. Analysis strategy

The analyses we report in this article are at the project level (i.e., a research collaboration). The survey data for each project were averaged across senior researchers who responded to the survey. Variables used are shown in Table 1. The coordination activities and outcome variables are composite variables: sums of specific behaviors in a category such as holding a workshop in the case of the knowledge transfer coordination activities, and sums of specific outcomes such as applying for a patent in the case of knowledge outcomes.

Because our focus is on the link between coordination activities and project outcomes, our analysis strategy first involved assessing the direct effects of control variables and the impact of coordination activities on project outcomes (H1). Next we examined the independent variable of number of universities on coordination activities (H2). The third step was to assess how the number of universities in a project was related to the project's outcomes (H3). The fourth step was to perform a mediation analysis to test whether coordination activities explained, or mediated, the negative effects of multiple universities on project outcomes (H4). Generally a variable is said to function as a mediator to the extent that it accounts for the relationship between an independent variable and the dependent variable (Baron and Kenny, 1986). In the current analysis, the aim is to identify the coordination activities that might explain why more universities involved in a project predicted fewer positive project outcomes.

3. Results

We conducted preliminary descriptive analyses to examine the distributions of the variables and the raw correlations of variables with one another. Projects with an earlier start date reported more outcomes, which is to be expected because more time had passed for achieving project outcomes. We also found a curvilinear effect of start date with outcomes because investigators whose projects started in 2000, the first year of the ITR program, reported fewer outcomes relative to those in later years. To control for these effects, our regression results are modeled using the linear and quadratic start dates as control variables.

We also examined whether project budgets and the number of senior researchers (measures of the size of projects) were associated with each other and with coordination activities and project outcomes. Overall, budgets were associated with both coordination activities and project outcomes. Researchers with smaller budgets did less coordination and also achieved fewer outcomes. Budget and number of senior investigators were subsequently included in all regressions as controls. We also included as a control variable the R&D expenditures of the universities involved in each project to serve as a proxy measure of the experience and resources of the participating universities.

In our sample, the number of different universities involved in a project ranged from 1 to 13, and the number of disciplines of the PIs and senior researchers ranged from 1 to 5. The number of disciplines increased with the number of universities ($r = 0.29$). This correlation supports the idea that one reason for multi-university collaborations may be to assemble a combination of expertise in disciplines that is not available locally. In all of our subsequent analyses, the number of disciplines in a project was used as a control variable.

3.1. Effects of coordination activities on project outcomes (H1)

We argued that to be successful, research projects must engage in coordination activities. Table 2 presents the direct associations between coordination activities and project outcomes of the 491 ITR projects in our sample. The levels of these correlations are small to moderate, but they are all positive and statistically significant. We then ran regressions testing the impact of each coordination activity on the composite outcome variables, with controls as listed in Table 1. The results are shown in Table 3. As can be seen, the models are highly significant. The most powerful coordination activity was knowledge transfer, which predicted all outcomes. Division of responsibility predicted knowledge, tools, and training outcomes. Shared resources predicted tools and collaboration outcomes, and use of communication technology predicted tools and outreach outcomes. Meetings, as a whole, did not predict outcomes.

Table 4 breaks down the effects further, showing the results of regressions on each category of coordination

Table 2
Means, standard deviations, and correlations ($N=491$ research collaborations)

		Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Control variables																				
1	Project start year	2002.33	1.26	1.00																
2	R&D expenditures	3.90	1.28	−0.06	1.00															
3	Project budget (log)	14.11	0.84	−0.27	0.05	1.00														
4	Number of senior researchers	4.90	3.03	0.02	−0.06	0.40	1.00													
5	Number of disciplines	2.09	0.91	0.02	0.01	0.21	0.55	1.00												
Independent variables																				
6	Number of universities	2.28	1.60	−0.01	−0.15	0.24	0.71	0.29	1.00											
Project outcome variables																				
7	Knowledge outcomes	0.51	0.20	−0.30	0.05	0.13	0.07	0.06	−0.04	1.00										
8	Tools outcomes	0.30	0.16	−0.10	−0.05	0.17	0.13	0.18	0.03	0.41	1.00									
9	Training outcomes	0.47	0.29	−0.47	0.04	0.21	0.01	−0.02	−0.06	0.51	0.29	1.00								
10	Outreach outcomes	0.29	0.18	−0.06	−0.07	0.18	0.09	0.11	0.02	0.39	0.42	0.29	1.00							
11	Collaboration outcomes	0.56	0.30	−0.07	−0.14	0.14	0.17	0.12	0.10	0.38	0.47	0.23	0.41	1.00						
12	Leverage outcomes	0.37	0.25	−0.20	−0.03	0.04	−0.01	0.03	−0.07	0.49	0.40	0.39	0.37	0.43	1.00					
Coordination activities																				
13	Division of responsibilities	0.43	0.22	−0.05	−0.04	0.18	0.08	0.16	−0.13	0.35	0.39	0.31	0.30	0.28	0.23	1.00				
14	Shared resources	0.45	0.27	0.04	−0.08	0.08	0.03	0.10	−0.03	0.26	0.43	0.18	0.31	0.27	0.14	0.44	1.00			
15	Knowledge transfer	0.38	0.19	−0.11	−0.06	0.23	0.08	0.10	−0.07	0.47	0.47	0.32	0.43	0.40	0.34	0.55	0.46	1.00		
16	Meetings	0.39	0.23	−0.05	−0.02	0.10	0.01	0.03	−0.13	0.31	0.31	0.23	0.27	0.21	0.22	0.53	0.43	0.51	1.00	
17	Communication technology	0.29	0.18	0.02	−0.10	0.23	0.12	0.19	0.12	0.21	0.46	0.13	0.36	0.25	0.15	0.41	0.48	0.44	0.41	1.00

Note. For Project outcome variables and Coordination activities, the mean indicates the proportion of category items checked for a project (e.g., 3 of 5 items checked for Division of responsibilities equals 0.6). Correlations of $r=0.10$ are significant at the 0.05 level.

Table 3
Effects of control variables and coordination activities on project outcomes

	Knowledge outcomes	Tools outcomes	Training outcomes	Outreach outcomes	Collaboration outcomes	Leverage outcomes
Control variables						
Project start year	−0.05***	−0.01**	−0.11***	n.s.	−0.02*	−0.05***
Project start year * project start year	−0.02***	n.s.	−0.02*	n.s.	−0.01*	−0.02**
R&D expenditures	0.01*	n.s.	n.s.	n.s.	−0.02*	n.s.
Project budget (log)	−0.02*	n.s.	n.s.	n.s.	n.s.	−0.02*
Number of senior researchers	n.s.	n.s.	n.s.	n.s.	0.01*	n.s.
Number of disciplines	n.s.	0.01t	n.s.	n.s.	n.s.	n.s.
Coordination activities						
Division of responsibilities	0.09*	0.07t	0.24***	n.s.	n.s.	n.s.
Shared resources	n.s.	0.10***	n.s.	n.s.	0.10t	n.s.
Knowledge transfer	0.35***	0.19***	0.20**	0.27***	0.44***	0.38***
Meetings	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Communication technology	n.s.	0.21***	n.s.	0.16***	n.s.	n.s.
Adjusted R^2	0.31	0.33	0.31	0.24	19.5	0.15
F	20.9***	22.8***	21.8***	13.7***	11.8***	9.0***
N	491	491	491	491	491	491

Note. Unstandardized coefficients. The project start year * project start year term tests the quadratic, or curvilinear, effect of year. A negative estimate indicates that fewer outcomes were reported in the first and most recent project year.
t $p \le 0.10$.
* $p \le 0.05$.
** $p \le 0.01$.
*** $p \le 0.001$.

activity. The regressions identify specific coordination activities that were most highly predictive of project outcomes. For example, for achieving knowledge outcomes, the most important division of responsibility activities were assigning subgroup tasks and assigning faculty and post-docs to supervise tasks. Within the knowledge transfer category, the most important activities for achieving knowledge outcomes were student exchanges, co-authorship, and presenting work to the project team. One can see from this table that many different coordination activities predicted project outcomes.

3.2. Effects of multiple universities on coordination activities and project outcomes

We next entered the number of universities involved in the project into our regression models. Table 5 shows the effects of multiple universities on project coordination activities (H2) and Table 6 shows the effects of multiple universities on the outcomes of projects (H3). The main result is a pattern of negative effects of having more universities on a project. In Table 5, bigger projects and those with more disciplines tended to foster more coordination, but controlling for those trends, more universities in a research project predicted fewer coordination activities in the categories of division of responsibility, knowledge transfer, and meetings (H2). In Table 6, more universities predicted significantly fewer outcomes in four of the six measured categories—knowledge, tools, training, and leverage (H3). We display the predicted project outcomes in Fig. 1 to illustrate the direction of the effects.

3.3. Do coordination activities explain the negative impact of more universities on project outcomes (H4)?

To test whether insufficient coordination explained the negative effects of more universities on project outcomes, we conducted a statistical mediation analysis. To do this, we compared the models in Table 6 with and without coordination activities in these models. If coordination mediates the association of more universities with negative project outcomes, then coordination activities would be significant effects in the models and at the same time we would see a reduced statistical effect of number of universities on outcomes. Mediation is shown if the coordination activities variables substitute for the independent variable (number of universities), in explaining variation in the dependent variable (project outcomes).

Table 7 summarizes these analyses and suggests support for our argument that too few coordination activities explain the negative impact of more universities involved

Table 4
Specific coordination activities that predicted project outcomes (arrow indicates $p < 0.05$)

	Knowledge outcomes	Tools outcomes	Training outcomes	Outreach outcomes	Collaboration outcomes	Leverage outcomes
Division of responsibilities						
Subgroups worked on different tasks/studies	↑	↑	↑	↑	↑	↑
Faculty supervision of work	↑	↑	↑	↑	↑	↑
Post-doc supervision of work	↑	↑	↑			↑
Grad student supervision of work			↑		↑	↑
Administrative project director	↑	↑				
Shared resources						
Shared website(s)	↑	↑	↑	↑	↑	↑
Shared dataset(s)		↑			↑	
Shared lab equipment				↑		.
Shared lab space	↑					
Shared materials				↑		
Knowledge transfer						
Student exchange(s)	↑	↑	↑	↑	↑	↑
Co-authorship	↑	↑		↑	↑	↑
Presentation(s)	↑	↑		↑	↑	
Hosted visitor(s) at site		↑		↑	↑	
Held workshop(s)		↑	↑		↑	
Multidisciplinary course(s)	↑		↑			↑
Tutorial(s)/training session(s)		↑		↑		
Co-advised students			↑			
Held conference(s)				↑		
Invited outside speaker(s)						
Retreat/summer camp						
Brainstorming						
Held seminar(s)						
Meetings						
Work during conference/workshop	↑	↑		↑	↑	↑
At least monthly face-to-face meetings w/ most participants	↑	↑	↑			
At least monthly face-to-face meetings w/ project subgroup		↑	↑	↑		
At least monthly face-to-face meetings w/ students	↑		↑			↑
Work during sabbatical/leave	↑				↑	
At least monthly face-to-face meetings w/ senior personnel						
At least monthly informal interactions						
Communication technology						
Project website or webpages	↑	↑	↑	↑	↑	↑
At least monthly IM		↑		↑		
At least monthly email				↑		
At least monthly telephone		↑				
At least monthly conference call		↑				
At least monthly video conference			↑			
At least monthly online forum				↑		

in a project on its outcomes (H4). In these multiple mediation models, with coordination added to the equations predicting outcomes, the negative impact of number of universities shown in Table 6 disappear. Instead, we see the effects of coordination activities predicting variance in outcomes. We performed Sobel tests (MacKinnon et al., 1995) to test the effect of each coordination activity, controlling for the others. We found two coordination activity categories to be significant mediators by these tests. First, division of responsibilities (such as subgroups assigned to work on tasks, faculty and post-doc supervised tasks) mediated effects on knowledge, tools, and training outcomes. Second, knowledge transfer (such as student exchanges, co-authorship, and presentations) mediated knowledge, tools, training, and leverage outcomes, and was the most consistently important coordination activity category. Fig. 2 shows these relationships graphically.

Table 5
Effects of control variables and number of universities on project coordination

	Project coordination activities				
	Division of responsibilities	Shared resources	Knowledge transfer	Meetings	Communication technology
Project start year	n.s.	n.s.	−0.02*	n.s.	n.s.
Project start year * project start year	n.s.	n.s.	−0.01*	n.s.	n.s.
R&D expenditures	−0.01*	−0.02*	−0.01*	n.s.	n.s.
Project budget (log)	0.04**	0.03*	0.05***	0.03*	0.01*
Number of senior researchers	0.01**	n.s.	n.s.	0.01*	0.03**
Number of disciplines	0.03**	0.04*	n.s.	n.s.	0.04***
Number of universities	−0.04***	n.s.	−0.03***	−0.04***	n.s.
Adjusted R^2	0.10	0.03	0.09	0.04	0.05
F	8.7***	2.8**	7.9***	3.5**	5.0***
N	491	491	491	491	491

Note. Unstandardized coefficients.
t $p \leq 0.10$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

Table 6
Effect of control variables and number of universities on project outcomes

	Knowledge outcomes	Tools outcomes	Training outcomes	Outreach outcomes	Collaboration outcomes	Leverage outcomes
Project start year	−0.06***	−0.02**	−.11***	n.s.	−0.03***	−0.05***
Project start year * project start year	−0.02***	−0.01**	−0.02***	−0.01*	−0.03***	−0.02***
R&D expenditures	n.s.	n.s.	n.s.	.01t	−0.03***	n.s.
Project budget (log)	n.s.	.02*	0.03t	.03**	n.s.	n.s.
Number of senior researchers	0.01*	n.s.	n.s.	n.s.	0.01t	n.s.
Number of disciplines	n.s.	.03**	n.s.	.02t	n.s.	n.s.
Number of universities	**−0.02****	**−0.01** t	**−0.02****	n.s.	n.s.	**−0.02**t
Adjusted R^2	0.14	0.08	0.24	0.06	0.08	0.07
F	10.9***	5.6***	23.0***	4.1**	5.8***	5.3***
N	491	491	491	491	491	491

Note. Unstandardized coefficients.
t $p \leq 0.10$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

4. Discussion

We found support for our hypotheses that having multiple universities involved in a research collaboration complicates coordination and reduces outcomes in the project. Our empirical analyses refine these arguments. The results especially bear on the outcomes of new knowledge, tools, training, and leverage for additional research, and the importance of division of responsibility and knowledge transfer activities in achieving those outcomes. These relationships were found even when controlling for other characteristics of projects, such as project duration and size, which also predict outcomes.

Because our study was a one-time survey of ongoing collaborations supported by a single interdisciplinary initiative related to information technology and other sciences, we cannot say whether our findings have generalizability to other fields or programs of research. Our results also do not provide evidence of a specific causal relationship between coordination activities and project outcomes. Indeed, we did not find any statistical moderation effects (interactions between coordination activities and number of universities) indicating that a greater effort to implement coordination would reduce the negative multi-university effects. Lack of moderation suggests that coordination activities reflect something more fundamental about multi-university projects that

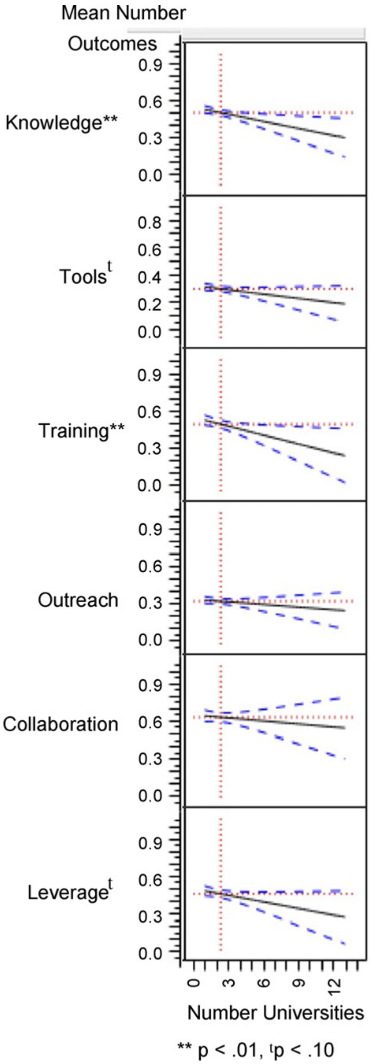

Fig. 1. Predicted project outcomes, with confidence intervals, controlling for project start year, R&D expenditures, project budget, number of senior researchers, and number of disciplines.

cannot be changed simply by asking investigators to submit a management plan or a strategy for coordination. We evaluate two possible alternative explanations for our findings below: selection bias and lack of collaboration experience.

First, it is possible that selection bias caused the multi-university effects we observed. That is, perhaps the research of the multi-university proposals in the ITR program was not as exemplary at the outset as the research of the single university proposals, but was selected for awards for other reasons. Policy influence might have created such a phenomenon. Because the ITR research program was aimed at fostering interdisciplinary collaboration and large high-risk projects, peer reviewers and NSF program officials might have been biased to select multi-institutional projects for funding, perhaps to spread the funds as far as possible or because reviewers were impressed by the diversity of multi-university projects. Maybe reviewers required less intellectual rigor or social organization of projects if more universities were involved. If multi-university projects were not as well conceived initially as single university projects, then we would expect them to be less well coordinated and less productive as well.

To evaluate the possibility of a selection bias, we obtained an anonymous sample of unfunded ITR proposals from the National Science Foundation. The sample of 549 unfunded proposals from the first 4 years of the ITR program was matched with our sample of 549 funded proposals. These yoked pairs were based on the size of their proposed budgets and the R&D expenditures of the institutions that applied. The resulting dataset included the year of the proposal, whether it was a Large or Medium proposal (each category having its own peer review panel), the number of investigators, and number of universities involved in the proposal, and whether or not the proposal led to an award. Number of investigators and number of universities were correlated $r = 0.64$, thus larger projects were more likely to have multiple universities represented. We then ran logistic regressions to assess whether the number of universities predicted whether or not a proposal was awarded a grant. We found that controlling for other variables, the number of universities was a highly significant predictor of whether or not an award was made (Chi square = 10.4, $p < 0.01$). This analysis supports the idea that peer reviewers may have been biased to choose awards based on the number of universities that were involved in the proposal.

A second possible explanation of our results is that multi-university projects began with investigators who did not know each other well and who needed time to form intellectual and social bonds as well as gain experience from doing research together. Lack of collaboration experience would have made these projects inherently slower to get started and more difficult. It is possible that an early lack of intellectual communication and working relationships caused these projects to experience both insufficient coordination and poorer outcomes when we measured them a year or more after beginning.

Table 7
Mediation models testing whether project coordination activities explain (mediate) the effect of number of universities on project outcomes

	Knowledge outcomes	Tools outcomes	Training outcomes	Leverage outcomes
Control variables				
Project start year	−0.05***	−0.01**	−0.11***	−0.05***
Project start year * project start year	−0.02***	n.s.	−0.02*	−0.02***
R&D expenditures	−0.01*	n.s.	n.s.	n.s.
Project budget (log)	−0.02*	n.s.	n.s.	−0.02*
Number of senior researchers	n.s.	n.s.	n.s.	n.s.
Number of disciplines	n.s.	n.s.	n.s.	n.s.
Independent variable				
Number of universities	n.s.	n.s.	n.s.	n.s.
Coordination activities				
Division of responsibilities	**0.09***	**0.06**t	**0.23*****	n.s.
Shared resources	n.s.	0.10***	n.s.	n.s.
Knowledge transfer	**0.35*****	**0.19*****	**0.20****	**0.38*****
Meetings	n.s.	n.s.	n.s.	n.s.
Communication technology	n.s.	0.21*	n.s.	n.s.
R^2adjusted	0.31	0.33	0.32	0.15
F	19.1***	20.9***	19.9***	8.2***
N	491	491	491	491

Note. Unstandardized coefficients. Mediation for the outreach and collaboration outcomes categories is not included because the direct effects of number of universities on these outcome categories were not significant (see Table 6). Boldface estimates are statistically significant in the Sobel tests at $p < 0.05$.

t $p \leq 0.10$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

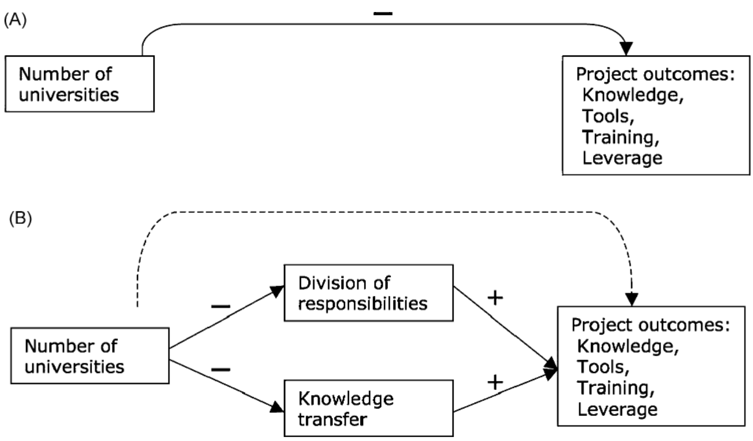

Fig. 2. Description of statistical relationships between the number of universities in a project, its coordination activities, and its outcomes. (A) Shows that more universities in a project predict fewer project outcomes. (B) Shows results of Sobel tests and multiple mediation analysis (Table 7). More universities in a project predict less division of responsibilities and fewer knowledge transfer activities, and each of these coordination activity categories predicts better project outcomes. When these activities are included in a regression model, the direct negative relationship between number of universities and project outcomes disappears. Thus division of responsibilities and knowledge transfer activities are mediator variables, i.e., they account for the negative effect of number of universities on project outcomes.

Several of our survey items measured investigators' relationships prior to the current ITR project: Had you worked with this person (each of the other senior researchers) prior to this project; did you publish a peer-reviewed paper with this person; did you receive research funding with this person. We created a composite measure, called prior collaboration (Cronbach's Alpha = 0.83). With all the controls in the model, the number of universities in a project significantly predicted not having prior collaboration experience (F [1,541] = 7.5, $p < 0.01$). Furthermore, with controls and number of universities in the model, not having prior collaboration experience predicted fewer coordination activities in the current project (division of responsibility F [1,541] = 1.8, $p = 0.06$; shared resources F [1,541] = 5.8, $p = 0.01$; knowledge transfer F [1,541] = 16.7, $p < 0.001$; meetings F [1,541] = 11.8, $p < 0.001$; communication technology F [1,541] = 9.7, $p < 0.01$). However, prior collaboration experience did not mediate or moderate the effect of the number of universities on project outcomes. This finding suggests that prior collaboration experience predicts better coordination and that multi-university projects are likely to lack it, but does not show that requiring prior collaboration in proposals would resolve the comparatively low productivity of multi-university projects.

In sum, our analyses suggest that selection bias and a lack of collaboration experience may contribute to multi-university projects that are not as well organized, at least in the short run, as single university projects.

4.1. Research policy implications

Our analyses are directed at policies related to research programming. Our findings suggest policy tradeoffs for multi-university collaborations. On the one hand, long-term innovation, which we could not measure, may be improved by having universities collaborate with other institutions that can offer expertise the single university cannot develop locally. Perhaps the type of expertise is too scarce to develop locally, is too expensive, or would not improve the competitive advantage of the institution. In the short-term, however, multi-university projects were significantly less successful than projects performed by one university. In our data, even the difference between one and two universities began to show this decline, with significantly negative effects on knowledge, tools, and leverage outcomes. Funding agencies might consider supporting exploratory grants to foster the development of new collaborations across institutions. Future studies could examine the value of training scientists to manage multi-university and multi-disciplinary collaborations.

Our analyses controlled for NSF program experience (start year of project), the R&D expenditures of the universities, the project budget, the number of senior researchers, and the number of disciplines involved in the project. Coordination activities predicted outcomes but changes in these behaviors did not lessen the negative multi-university impact on outcomes. We also examined other possible effects such as the difference between the proposal budget and actual funding, which did not account for the effects. However, perhaps budget cuts were associated with smaller investments in coordination and a stronger focus on local rather than overall project goals. Finally, we can only speculate, but our findings and an analysis of another program, the KDI, suggest that the problem is partly due to an initial selection process that does not require multi-university projects to have the same level of quality, coherence, and evidence of true collaboration as single university projects.

4.2. Extending the knowledge-based view

The knowledge-based view of the firm has been extended to geographical clusters, in which firms are proximate to one another in a particular region so that they can benefit from knowledge flow within the cluster (Maskell, 2001). The knowledge-based view also has been applied to different sites within a research organization (Boh et al., 2007). In the latter study, collaborating across sites markedly increased coordination costs, and returns to collaboration were reduced when there was not careful management attention to the benefits that would be realized by cross-site collaboration. Even so, numerous sites involved in collaboration reduced net financial returns. We are not aware of prior literature extending the knowledge-based view to research collaborations across institutions. We fill this theoretical void by proposing a knowledge-based view of research collaborations, in which the coordination costs are higher when researchers work in different universities and face more barriers to utilizing and integrating their expertise. Institutional and geographic forces do not create problems that can be easily alleviated by providing more shared resources or forcing communication. We believe that coordination costs need to play a more prominent role in discussions of the knowledge-based view, given that key constructs such as transferability, capacity for aggregation, and appropriability (Grant, 1996a,b) depend on the institutional and spatial configuration of members.

4.3. Limitations and future directions

Though we have data on a large number of research collaborations, there are a few significant issues we did not consider. First, we focused on short-term outcomes in research collaboration, rather than the quality of a particular outcome or long-term outcomes. For example, we asked respondents whether or not they published articles based on the research, but we did not collect data on their number of articles or citations. We also examined only outcomes directly related to the collaborations and not the other opportunities foregone by participating in these collaborations. It is possible that having multiple universities in a project has a different impact on the quality of research or long-term outcomes (although we speculate that short-term and long-term outcomes, and quality, are likely related). Second, in addition to multiple universities, there are other factors that influence the success of research, including funding agency structures and university tenure processes that favor disciplinary work (Metzger and Zare, 1999). We do not have information about what led investigators to seek out funding from the NSF ITR program, and what the opportunity costs were of doing so across disciplinary and organizational boundaries. Future work would benefit greatly from understanding the longer term consequences of multi-university collaborations and the decision processes that underlie engaging in multi-university collaborations.

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References

Allen, T., 1977. Managing the Flow of Technology. MIT Press, Cambridge, MA.

Armstrong, D.J., Cole, P., 2002. Managing distances and differences in geographically distributed work groups. In: Hinds, P., Kiesler, S. (Eds.), Distributed Work. MIT Press, Cambridge, MA, pp. 167–186.

Baron, R.M., Kenny, D., 1986. The moderator–mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. Journal of Personality and Social Psychology 51, 1173–1182.

Beaver, D., 2001. Reflections on scientific collaboration (and its study): past, present, and future. Scientometrics 52, 365–377.

Boh, W.-F., Ren, Y., Kiesler, S., Bussjaeger, R., 2007. Expertise and collaboration in the geographically dispersed organization. Organization Science 18, 595–612.

Chompalov, I., Genuth, J., Shrum, W., 2002. The organization of scientific collaborations. Research Policy 31, 749–767.

Clark, H., Brennan, S., 1991. Grounding in communication. In: Resnick, L.B., Levine, J.M., Teasley, S.D. (Eds.), Perspectives on Socially Shared Cognition. APA Books, Washington, DC, pp. 127–149.

Collins, F., et al., 1998-2003. New goals for the U. S. Human Genome Project: 1998–2003. Science 282, 682–689.

Corley, E., Boardman, C., Bozeman, B., 2006. Design and the management of multi-institutional research collaborations: theoretical implications from two case studies. Research Policy 35, 975–993.

Cramton, C.D., 2001. The mutual knowledge problem and its consequences in geographically dispersed teams. Organization Science 12, 346–371.

Cummings, J., Kiesler, S., 2005. Collaborative research across disciplinary and organizational boundaries. Social Studies of Science 35, 703–722.

Curtis, B., Krasner, H., Iscoe, N., 1988. A field study of the software design process for large systems. Communications of the ACM 31, 1268–1287.

de Solla Price, D.J., 1963. Little Science, Big Science. Columbia University Press, New York.

Espinosa, J.A., Carmel, E., 2004. The impact of time separation on coordination costs in global software teams: a conceptual foundation. Software Process: Improvement and Practice 8, 249–266.

Finholt, T., 2002. Collaboratories. Annual Review of Information Science and Technology 36, 73–107.

Gassmann, O., von Zedtwitz, M., 1999. New concepts and trends in international R&D organization. Research Policy 28, 231–250.

Gibson, C.B., Gibbs, J.L., 2006. Unpacking the concept of virtuality: the effects of geographic dispersion, electronic dependence, dynamic structure, and national diversity on team innovation. Administrative Science Quarterly 51, 451–495.

Grant, R.M., 1996a. Prospering in dynamically competitive environments: organizational capability as knowledge integration. Organization Science 7, 375–387.

Grant, R.M., 1996b. Toward a knowledge-based theory of the firm. Strategic Management Journal 17, 109–122.

Hagstrom, W., 1964. Traditional and modern forms of scientific teamwork. Administrative Science Quarterly 9, 241–264.

Herbsleb, J., Mockus, A., Finholt, T., Grinter, R., 2000. Distance, dependencies, and delay in a global collaboration. In: Proceedings of the 2000 ACM Conference on Computer Supported Cooperative Work, Philadelphia, PA, pp. 319–328.

Hinds, P., Kiesler, S. (Eds.), 2002. Distributed Work. MIT Press, Cambridge, MA.

Hinds, P., Mortensen, M., 2005. Understanding conflict in geographically distributed teams: the moderating effects of shared identity, shared context, and spontaneous communication. Organization Science 16, 290–307.

Hobday, M., 2000. The project-based organisation: an ideal form for managing complex products and systems? Research Policy 29, 871–893.

Hoegl, M., Proserpio, L., 2004. Team member proximity and teamwork in innovative projects. Research Policy 33, 1153–1165.

Jeffrey, P., 2003. Smoothing the waters: observations on the process of cross-disciplinary research collaboration. Social Studies of Science 33, 539–562.

Katz, J., Martin, B., 1997. What is research collaboration? Research Policy 26, 1–18.

Kiesler, S., Cummings, J., 2002. What do we know about proximity and distance in work groups? In: Hinds, P., Kiesler, S. (Eds.), Distributed Work. MIT Press, Cambridge, MA, pp. 57–80.

Kogut, B., Zander, U., 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. Organization Science 3, 383–397.

Kraut, R., Egido, C., Galegher, J., 1990. Patterns of contact and communication in scientific research collaboration. In: Galegher, J., Kraut, R., Egido, C. (Eds.), Intellectual Teamwork: Social and Technological Bases of Cooperative Work. Lawrence Erlbaum, Hillsdale, NJ, pp. 149–171.

Kouzes, R., Myers, J., Wulf, W., 1996. Collaboratories: doing science on the Internet. IEEE Computer 29, 40–46.

Kraut, R.E., Fussell, S.R., Brennan, S.E., Siegel, J., 2002. Understanding effects of proximity on collaboration: implications for technologies to support remote collaborative work. In: Hinds, P., Kiesler, S. (Eds.), Distributed Work. MIT Press, Cambridge, MA, pp. 137–162.

Luukkonen, T., 1998. The difficulties in assessing the impact of EU framework programmes. Research Policy 27, 599–610.

Malone, T., Crowston, K., 1994. The interdisciplinary study of coordination. ACM Computing Surveys 26, 87–119.

Mark, G., 2005. Large-scale distributed collaboration: tension in a new interaction order. In: Proceedings of the Social Informatics Workshop, Irvine, CA, Paper available at http://www.crito.uci.edu/si/resources.asp.

Mark, G., Grudin, J., Poltrock, S.E., 1999. Meeting at the desktop: an empirical study of virtually collocated teams. In: Bodker, S., King, M., Schmidt, M.K. (Eds.), Proceedings of the Sixth European Conference on Computer Supported Cooperative Work. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 159–178.

MacKinnon, D.P., Warsi, G., Dwyer, J.H., 1995. A simulation study of mediated effect measures. Multivariate Behavioral Research 30, 41–62.

Maskell, P., 2001. Towards a knowledge-based theory of the geographical cluster. Industrial and Corporate Change 10, 921–943.

Metzger, N., Zare, R., 1999. Interdisciplinary research: from belief to reality. Science 283, 642–643.

Nardi, B.A., Whittaker, S., 2002. The place of face-to-face communication in distributed work. In: Hinds, P., Kiesler, S. (Eds.), Distributed Work. MIT Press, Cambridge, MA, pp. 83–112.

National Academies, 1994. Facilitating Interdisciplinary Research, Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. National Academies Press, Washington, DC, Available at http://newton.nap.edu/catalog/11153.html.

Olson, G.M., Olson, J., 2000. Distance matters. Human Computer Interaction 15, 139–179.

Porac, J., et al., 2004. Human capital heterogeneity, collaborative relationships, and publication patterns in a multidisciplinary scientific alliance. Research Policy 33, 661–678.

Rigby, J., Edler, J., 2005. Peering inside research networks: some observations on the effect of the intensity of collaboration on the variability of research quality. Research Policy 34, 784–794.

Teasley, S., Wolinsky, S., 2001. Scientific collaborations at a distance. Science 292, 2254–2255.

Van de Ven, A., Delbecq, A., Koenig, R., 1976. Determinants of coordination modes within organizations. American Sociological Review 41, 322–338.

von Krogh, G., von Hippel, E., 2003. Special issue on open source software development. Research Policy 32, 1149–1157.

Weick, K., 1979. The Social Psychology of Organizing. Addison-Wesley, Reading, MA.

Weisband, S., 2002. Maintaining awareness in distributed team collaboration: implications for leadership and performance. In: Hinds, P., Kiesler, S. (Eds.), Distributed Work. MIT Press, Cambridge, MA, pp. 311–334.