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Coordination Costs and Project Outcomes in Multi-University Collaborations

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Abstract (100 words)

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

1.1 Introduction

Research is becoming increasingly distributed. R&D labs are spread across continents (Gassmann & Zedtwitz, 1999), open source software projects have contributors from around the world (von Krogh & von Hippel, 2003), and scientific collaborations involve many institutions (Corley, Boardman, & Bozeman, 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, Myers, & Wulf, 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 & Martin, 1997). The EU framework programme encourages 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 research such as the Knowledge and Distributed Intelligence (KDI) and Information Technology Research (ITR) programs. Large programs supported by the National Institutes of Health, such as the Human Genome Project (Collins et al., 1998) and AIDS research (Teasley & 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 & 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 & Zander, 1992) and recent theoretical and empirical research on coordination in distributed work (e.g., Hinds & Kiesler, 2002; Boh et al., 2007). 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.

1.1.1. 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 collaborations 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 & 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 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 (1996) 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.

1.1.2. 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, 1996). 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 & Crowston, 1994; Van de Ven, Delbecq, & Koenig, 1976).

Organization theorists have distinguished among several types of coordination activity 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 coauthoring 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 (Chomplov, Genuth, & Shrum, 2002).

1.1.3. 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 (Allen, 1977). Compared with single university projects, projects with investigators at different universities are likely to have more difficulty fostering a collegial social environment (Kraut, Fussell, Brennan, & Siegel, 2002; Nardi & Whittaker, 2002), building common ground (Clark & Brennan, 1991), maintaining awareness of what others are doing (Weisband, 2002), attending to the project (Kanfer, 1991), and making rapid adjustments to surprises (Olson & Olson, 2000). Allen's (1977) rule of thumb is that coworkers should be no more than 30 meters apart, beyond which collaboration effectiveness declines precipitously (see Kraut, Egido, & Galegher, 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 & Carmel, 2004; Herbsleb & Mockus, 2003), misunderstandings (Cramton, 2001), institutional rivalries (Armstrong & Cole, 2002), free riding (Weisband, 2002), distractions from local institutional priorities (Mark, Grudin, & Poltrock, 1999), inconsistent procedures across institutions (Curtis, Krasner, & Iscoe, 1988), and failures to share information (Hinds & Mortensen, 2005). If the project involves a greater percentage of members at different institutions, coordination is more difficult (Cummings & Kiesler, 2005; Lee-Kelley, 2002; Mark, 2005). Greater geographic distance among members also increases coordination costs (Herbsleb, Mockus, Finholt, & Grinter, 2000; Hoegl & Proserpio, 2004).

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: More coordination activities in a research project will predict better project outcomes.

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

Hypothesis 3: The more universities that are involved in a research project, the fewer project outcomes the project will have.

Hypothesis 4: Insufficient coordination activities will explain the negative association between multi-university projects and project outcomes (statistical mediation).

2.1 Methods

2.1.1. 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 five-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 $90M in 2000 to US $295M in 2004. Three kinds of awards were reviewed by separate peer review panels: Small projects (up to US $500K for three years), Medium projects (up to US $1M per year for five years), and Large projects (up to US $3M per year for five years). This study examined Medium and Large ITR projects awarded in the first four years of the program, 2000 to 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 five 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 2,100 proposals in 2000 for the first year of the program to over 3,100 proposals in 2004. Even with increased ITR funds, the program became more competitive. In 2000, 30 percent of the medium and large proposals were funded; in 2001 and 2002, 27 percent; in 2003, 24 percent; in 2004, 21 percent. 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 percent of their proposal budget; year 2001 received 68 percent; year 2002 and 2003 received 50 percent, and year 2004 received 49 percent.

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. Researchers from 379 ITR projects and 37 NSF officers met to discuss the research program. 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 research 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 3 universities, we surveyed the most senior PI at each university, and averaged the responses to obtain project-level scores. 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%).

2.1.2. Measures

We obtained descriptive data on each project, such as its budget, start date, 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 publication, rather than citation counts, because of the recency 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 of the sustainability of the collaborations funded by the ITR.

Insert Table 1 here

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

2.1.3. 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 & 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. In Appendix A we show an abstraction of a direct and mediation analysis, and how this analysis strategy is applied in our study.

3.1. Results

We carried out 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 than did 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 the size of projects, measured both in terms of the project's budget and the number of senior researchers, was 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 one to 13 and the number of disciplines of the PIs and senior researchers ranged from one to five. Figure 1 shows the number of projects sorted by number of universities and number of disciplines involved in the project. The number of disciplines increased with the number of universities ($r = .29$). 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.

Figure 1 about here

3.1.1. 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 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.

Tables 2-4 about here

3.1.2. 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).

Tables 5 and 6 about here

3.1.3. 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 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, and 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 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 category. Figure 2 shows these relationships graphically.

Table 7 and Figure 2 about here

4.1. 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 (see Table 1) 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 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 four 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 $r = .64$, 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, $p < .01$). 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.

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 investigators) 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 = .83). With all the controls in the model, the number of universities in a project significantly predicted not having prior collaboration experience ($F [1, 541] = 7.5, p < .01$). 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 $F [1, 541] = 1.8, p = .06$; shared resources $F [1, 541] = 5.8, p = .01$; knowledge transfer $F [1, 541] = 16.7, p < .001$; meetings $F [1, 541] = 11.8, p < .001$; communication technology $F [1, 541] = 9.7, p < .01$). However, prior collaboration experience did not mediate or moderate the effect of the number of universities on 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.

4.1.1. 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 (year of project), the number of investigators, the project budget, the experience of the organization, and the number of major 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.

4.1.2. 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, 1996) depend on the institutional and spatial configuration of members.

4.1.3. 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 & 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.

References

Allen, T. 1977. Managing the flow of technology. Cambridge, MA: MIT Press.

Armstrong, D. J., P. Cole. 2002. Managing distances and differences in geographically distributed work groups. P. Hinds, S. Kiesler, eds., Distributed Work. MIT Press, Cambridge, MA, 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(3), 365-377.

Boh, W-F., Ren, Y., Kiesler, S., & Bussjaeger, R. 2007. Expertise and collaboration in the geographically dispersed organization. Organ. Sci.

Campion, M., Medsker, G., & Higgs, A. 1993. Relations between work groups characteristics and effectiveness: Implications for designing effective work groups. Personnel Psychology, 46, 823-855.

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

Clark, H., S. Brennan. 1991. Grounding in Communication. L. B. Resnick, J. M. Levine, S. D. Teasley, eds., Perspectives on Socially Shared Cognition. APA Books, Washington, DC, 127-149.

Collins, F., et al. 1998. 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.

Cramton, C. D. 2001. The mutual knowledge problem and its consequences in geographically dispersed teams. Organ. Sci. 12 346-371.

Cummings, J., & Kiesler, S. 2005. Collaborative research across disciplinary and organizational boundaries. Social Studies of Science, 35(5), 703-722.

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

de Solla Price, D.J. 1963. Little science, big science. New York: Columbia University Press.

Espinosa, J. A., A. Carmel. 2004. The effect of time separation on coordination costs in global software teams: A dyad model. Proc. 37th Hawaii Int. Conf. Syst. Sci.

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

Galbraith, J. 1973. Designing complex organizations. Reading, MA: Addison-Wesley.

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

Grant, R. M. 1996a. Prospering in dynamically-competitive environments: Organizational capability as knowledge integration. Organ. Sci. 7(4) 375-387.

Grant, R. M. 1996b. Toward a knowledge-based theory of the firm. Strategic Manage. J. 17(Winter Special Issue) 109-122.

Hagstrom, W. 1964. Traditional and modern forms of scientific teamwork. Administrative Science Quarterly, 9(3), 241-264.

Herbsleb, J. D., A. Mockus. 2003. An empirical study of speed and communication in globally-distributed software development. IEEE T. Software Eng. 29(3) 1-14.

Herbsleb, J., Mockus, A., Finholt, T., & Grinter, R. 2000. In Distance, dependencies, and delay in a global collaboration. Paper presented at the Computer-Supported Cooperative Work (CSCW) December 1-6, 2000, Philadelphia, PA.

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. Organ. Sci. 16(3) 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 (4), 539-562.

Kanfer. 1991. Motivation Theory and Industrial and Organizational Psychology. D. D. Dunnette, ed., Handbook of Industrial and Organizational Psychology. Consulting Psychologists Press, Palo Alto, CA, 75-170.

Katz, J. 1994. Geographical proximity and scientific collaboration. Scientometrics, 31(1), 31-43.

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 P. Hinds, & Kiesler, S. (Ed.), Distributed work (pp. 57-80). Cambridge, MA: MIT Press.

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

Kraut, R., Egido, C., & Galegher, J. 1990. Patterns of contact and communication in scientific research collaboration. In J. Galegher, Kraut, R., & Egido, C. (Ed.), Intellectual teamwork: Social and technological bases of cooperative work (pp. 149-171). Hillsdale, NJ: Lawrence Erlbaum.

Kouzes, R., Myers, J., & Wulf, W. 1996. Collaboratories: Doing science on the Internet. IEEE Computer, 29(8), 40-46.

Kraut, R. E., S. R. Fussell, S. E. Brennan, J. Siegel. 2002. Understanding effects of proximity on collaboration : Implications for technologies to support remote collaborative work. P. Hinds, S. Kiesler, eds., Distributed Work. MIT Press, Cambridge, MA, 137-162.

Lee-Kelley, L. 2002. Situational leadership: Managing the virtual project team. J. Manage. Dev. 21(5/6) 461-476.

Luukkonen, T. (1998). The difficulties in assessing the impact of EU framework programmes. Research Policy, 27(6), 599-610.

Malone, T., & Crowston, K. 1994. The interdisciplinary study of coordination. ACM Computing Surveys, 26(1), 87-119.

Mark, G. 2005. Large-scale distributed collaboration: Tension in a new interaction order. Proc. Social Informatics Workshop, Irvine, CA, Paper available at http://crito.uci.edu/2/si/resources.asp.

Mark, G., J. Grudin, S. E. Poltrock. 1999. Meeting at the desktop: An empirical study of virtually collocated teams. S. Bodker, M. King, M., K. Schmidt, eds. Proc. Sixth Eur. Conf. Comput. Support. Coop.Work, Kluwer Academic Publishers, Dordrecht, Netherlands, 159-178.

Nardi, B. A., S. Whittaker. 2002. The place of face-to-face communication in distributed work. P. Hinds, S. Kiesler, eds., Distributed Work. MIT Press, Cambridge, MA, 83-112.

MacKinnon, D. P., Warsi, G., & Dwyer, J. H. (1995). A simulation study of mediated effect measures. Multivariate Behavioral Research, 30(1), 41-62.

Maskell, P. 2001. Towards a knowledge-based theory of the geographical cluster. Industrial and Corporate Change, 10(4), 921-943.

McGrath, J. 1984. Groups. Englewood Cliffs, NJ: Prentice Hall.

Metzger, N., & Zare, R. 1999. Interdisciplinary research: From belief to reality. Science, 283(5402), 642-643.

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 http://newton.nap.edu/catalog/11153.html

Olson, G. M., & Olson, J. 2000. Distance Matters. Hum. Comput Interact. 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(7), 1149-1157.

Weick, K. 1979. The social psychology of organizing. Reading, MA: Addison-Wesley.

Weisband, S. 2002. Maintaining awareness in distributed team collaboration: Implications for leadership and performance. P. Hinds, S. Kiesler, eds., Distributed Work. MIT Press, Cambridge, MA, 311-334.

Table 1. Variables in the study

	Measure
Control Variables	
Project year	Year the project started (range: 2000 – 2004)
R & D expenditures	R & D funding at the universities involved in the project.
Total proposal budget	Total budget including overhead across all universities in the project.
Number 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 = .45
Shared resources	Common lab space, lab equipment, websites, datasets, materials. Alpha = .65
Knowledge transfer	Co-authorship; held conference, workshop, seminar; presentations, brainstorming; invited outside speakers, hosted visitors at site, tutorials/training sessions for project staff/participants; retreat/summer camp/management training; offered multidisciplinary courses; co-advising students; student exchanges. Alpha = .78
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 = .71
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 = .63
Communication with other sites	Sum of meetings and communication technology across sites (see two measures above). Alpha = .76
Travel to other sites	Drove car to work at other sites; flew in airplane to other sites. Alpha = -.05.
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 = .63

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 = .65
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 = .70
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 = .45
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 = .47
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 = .64

Table 2. Means, standard deviations, and correlations

		Mean	SD	1	2	3	4	5	6	7	8	9	10	11
	Control Variables													
1	Project year	2002.33	1.26	1.00										
2	R & D expenditures	3.90	1.28	-0.06	1.00									
3	Total awarded 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
	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
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
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
16	Meetings	0.39	0.23	-	-	0.10	0.01	0.03	-	0.31	0.31	0.23	0.27	0.21

				0.05	0.02				0.13					
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
18	Meetings with other sites	0.51	0.45	-0.14	-0.13	0.32	0.36	0.18	0.46	0.18	0.35	0.16	0.23	0.23
19	Communication with other sites	0.54	0.47	-0.15	-0.12	0.35	0.42	0.21	0.52	0.17	0.37	0.11	0.22	0.21
20	Travel to other sites	0.41	0.30	-0.25	-0.04	0.18	0.27	0.16	0.36	0.21	0.22	0.20	0.17	0.14

Note. N for correlations with items 18 – 20 include only projects with more than one university involved. Correlations of r = .10 are significant at the .05 level.

[Table is continued next page]

Table 2. continued

		12	13	14	15	16	17	18	19
	Control Variables								
1	Project year								
2	R & D expenditures								
3	Total awarded budget (log)								
4	Number of senior researchers								
5	Number of disciplines								
	Independent Variables								
6	Number of universities								
	Outcome Variables								
7	Knowledge outcomes								
8	Tools outcomes								
9	Training outcomes								
10	Outreach outcomes								
11	Collaboration outcomes								
12	Leverage outcomes	1.00							
	Coordination Activities								
13	Division of responsibilities	0.23	1.00						
14	Shared resources	0.14	0.44	1.00					
15	Knowledge transfer	0.34	0.55	0.46	1.00				
16	Meetings	0.22	0.53	0.43	0.51	1.00			
17	Communication technology	0.15	0.41	0.48	0.44	0.41	1.00		
18	Meetings with other sites	0.09	0.17	0.21	0.23	0.13	0.41	1.00	
19	Communication with other sites	0.06	0.18	0.21	0.21	0.09	0.49	0.94	1.00
20	Travel to other sites	0.11	0.08	0.15	0.16	0.04	0.18	0.49	0.57

Note. N for correlations with items 18 – 20 include only projects with more than one university involved. Correlations of r = .10 are significant at the .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 year	-.05***	-.01**	-.11***	n.s.	-.02*	-.05***
Project year * project year	-.02***	n.s.	-.02*	n.s.	-.01*	-.02**
R&D expenditures	.01*	n.s.	n.s.	n.s.	-.02*	n.s.
Project $ (log)	-.02*	n.s.	n.s.	n.s.	n.s.	-.02*
Number senior researchers	n.s.	n.s.	n.s.	n.s.	.01*	n.s.
Number of major disciplines	n.s.	.01^{t}	n.s.	n.s.	n.s.	n.s.
Coordination Activities						
Division of responsibilities	.09*	.07^{t}	.24***	n.s.	n.s.	n.s.
Shared resources	n.s.	.10***	n.s.	n.s.	.10^{t}	n.s.
Knowledge transfer	.35***	.19***	.20**	.27***	.44***	.38***
Meetings	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Communication technology	n.s.	.21***	n.s.	.16***	n.s.	n.s.
Adjusted R^2	.31	.33	.31	.24	19.5	.15
F	20.9***	22.8***	21.8***	13.7***	11.8***	9.0***
N	491	491	491	491	491	491

***$p \leq .001$, **$p \leq .01$, *$p \leq .05$, $^{t}p \leq .10$.

Note. The project year * project 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.

Table 4. Specific coordination activities that predicted project outcomes (arrow indicates $p < .05$)

	Knowledge Outcomes	Tools Outcomes	Training Outcomes	Outreach Outcomes	Collaboration Outcomes	Leverage Outcomes
Division of Responsibilities						
Subgroups worked on different problems/aspects	↑	↑	↑	↑	↑	↑
Faculty supervision of work	↑	↑	↑	↑	↑	↑
Post-doc supervision	↑	↑	↑			↑
Grad student supervision			↑		↑	↑
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 conf/wkshop	↑	↑		↑	↑	↑
At least monthly mtgs f-f most	↑	↑	↑			
At least monthly mtgs f-f sub		↑	↑	↑		
At least monthly mtgs f-f stude	↑		↑			↑
Work during sabbatical/leave	↑				↑	
At least monthly mtg f-f senior						
At least monthly informal						
Communication Technology						
Project website or webpages	↑	↑	↑	↑	↑	↑
At least monthly IM		↑		↑		
At least monthly email				↑		
At least monthly telephone		↑				
At least monthly conference c.		↑				
At least monthly video c.			↑			
At least monthly online forum				↑		

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 year	n.s.	n.s.	-.02*	n.s.	n.s.
Project year * project year	n.s.	n.s.	-.01*	n.s.	n.s.
R&D expenditures	-.01*	-.02*	-.01*.	n.s.	n.s.
Project $ (log)	.04**	.03*	.05***	.03*	.01*
Number senior researchers	.01**	n.s.	n.s.	.01*	.03**
Number of major disciplines	.03**	.04*	n.s.	n.s.	.04***
Number of universities	-.04***	n.s.	-.03***	-.04***	n.s.
Adjusted R^2	.10	.03	.09	.04	.05
F	8.7***	2.8**	7.9***	3.5**	5.0***
N	493	493	493	493	493

***$p \leq .001$, **$p \leq .01$, *$p \leq .05$, $^{t}p \leq .10$.

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 year	-.06***	-.02**	-.11***	n.s.	-.03***	-.05***
Project year * project year	-.02***	-.01**	-.02***	-.01*	-.03***	-.02***
R&D expenditures	n.s.	n.s.	n.s.	.01^{t}	-.03***	n.s.
Project $ (log)	n.s.	.02*	.03^{t}	.03**	n.s.	n.s.
Number senior researchers	.01*	n.s.	n.s.	n.s.	.01^{t}	n.s.
Number of major disciplines	n.s.	.03**	n.s.	.02^{t}	n.s.	n.s.
Number of universities	**-.02****	**-.01** ^{t}	**-.02****	n.s.	n.s.	**-.02**^{t}
Adjusted R^2	.14	.08	.24	.06	.08	.07
F	10.9***	5.6***	23.0***	4.1**	5.8***	5.3***
N	491	491	491	491	491	491

***$p \leq .001$, **$p \leq .01$, *$p \leq .05$, $^{t}p \leq .10$.

Note. The project year * project 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.

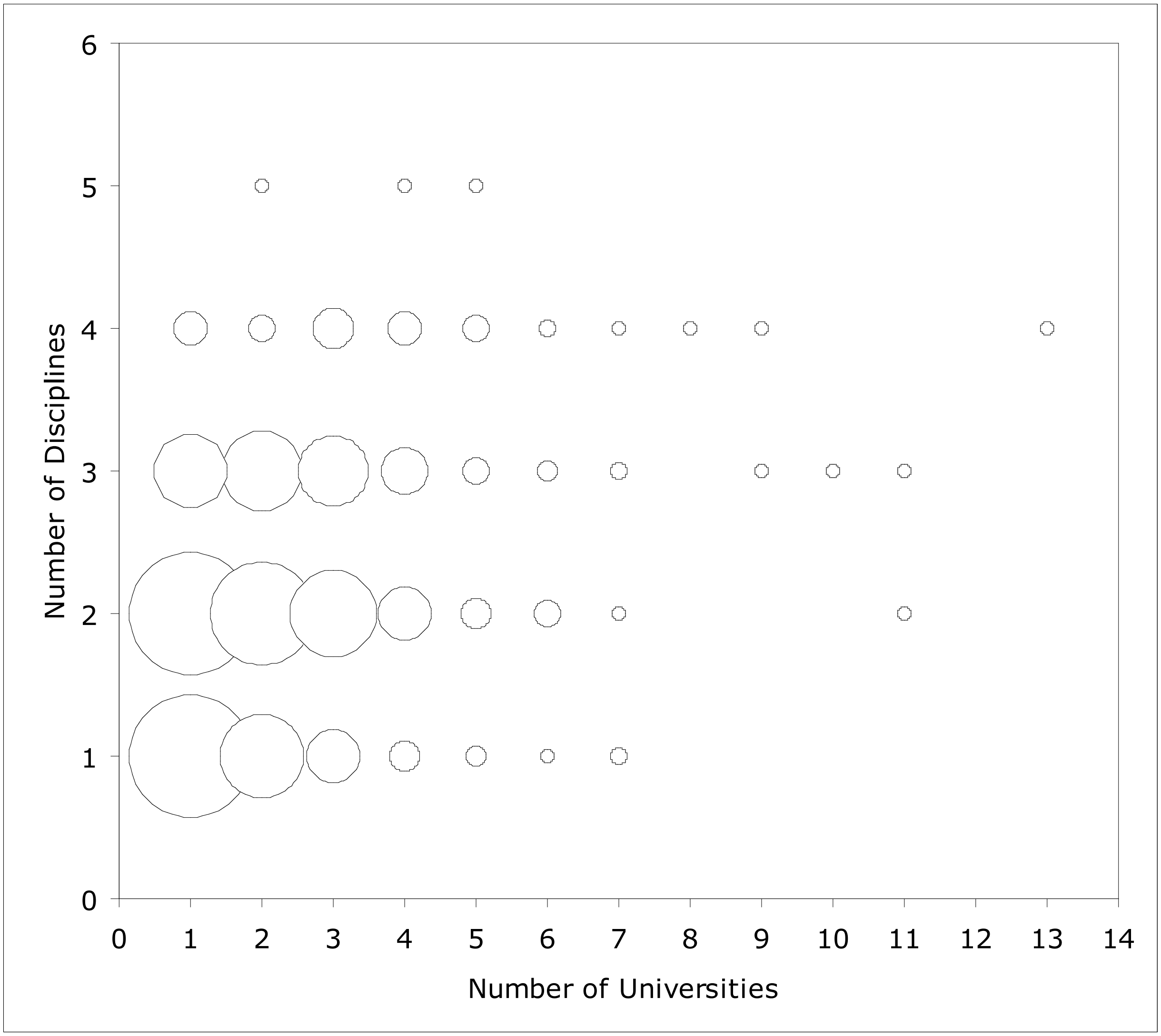
Table 7. Mediation models testing whether project coordination activities explain (mediate) the effect of number of universities on project outcomes.

	Knowledge Outcomes	Tools Outcomes	Training Outcomes	Leverage Outcomes
Control variables				
Project year	-.05***	-.01**	-.11***	-.05***
Project year * project year	- .02***	n.s.	-.02*	-.02***
R&D expenditure	.01*	n.s.	n.s.	n.s.
Project $ (log)	-.02*	n.s.	n.s.	-.02*
Number of senior researchers	n.s.	n.s.	n.s.	n.s.
Number of major 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	**.09***	**.06** ^{t}	**.23*****	n.s.
Shared resources	n.s.	.10***	n.s.	n.s.
Knowledge transfer	**.35*****	**.19*****	**.20****	**.38*****
Meetings	n.s.	n.s.	n.s.	n.s.
Communication technology	n.s.	.21*	n.s.	n.s.
Rsquare adjusted	.31	.33	.32	.15
F	19.1***	20.9***	19.9***	8.2***
N	491	491	491	491

***$p \leq .001$, **$p \leq .01$, *$p \leq .05$, $^{t}p \leq .10$

Note. Mediation for the outreach and collaboration outcomes categories are not included because the direct effects of number of universities on these outcome categories were not significant (see Table 6). Boldface and italicized estimates are statistically significant in the Sobel tests at p < .05 or better.

Figure 1. Distribution of collaborative projects involving different numbers of universities and disciplines.



Note. Size of circles reflect a count of projects having each structure. The largest circle represents 90 projects involving one university and one discipline.

Figure 2. Description of statistical relationships between the number of universities in a project, its coordination activities, and its outcomes (see Table 7).

Figure 1a. More universities in a project is associated with fewer project outcomes.

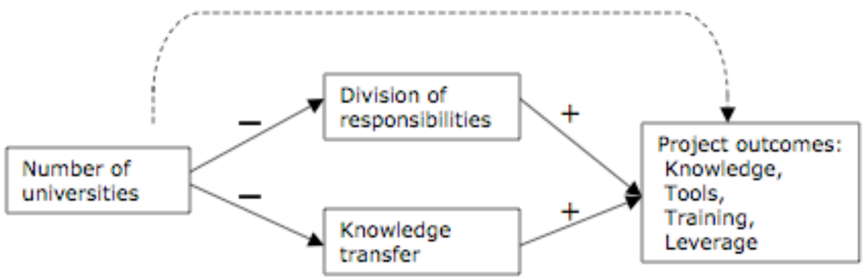
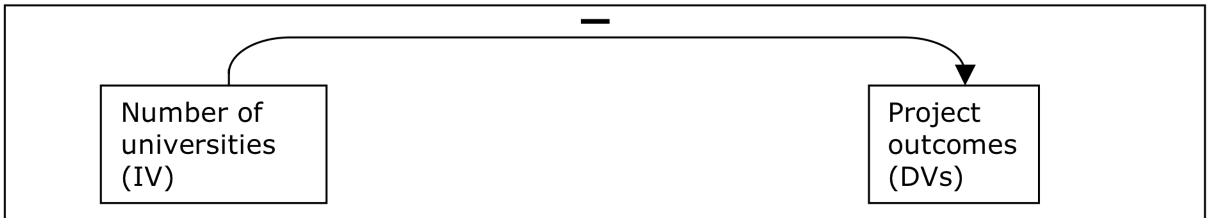


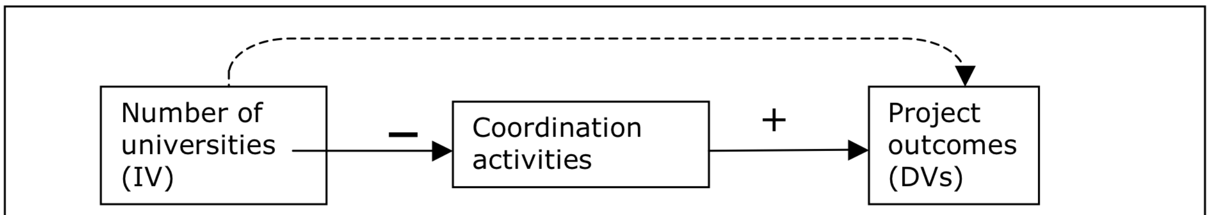
Figure 1b. Results of Sobel tests and multiple mediation analysis (Table 7). More universities in a project is associated with less division of responsibilities and fewer knowledge transfer activities and each of these activity categories is associated with better project outcomes. When these activities 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 "explain" the negative effect of number of universities on project outcomes).

Appendix A. Mediation Explained

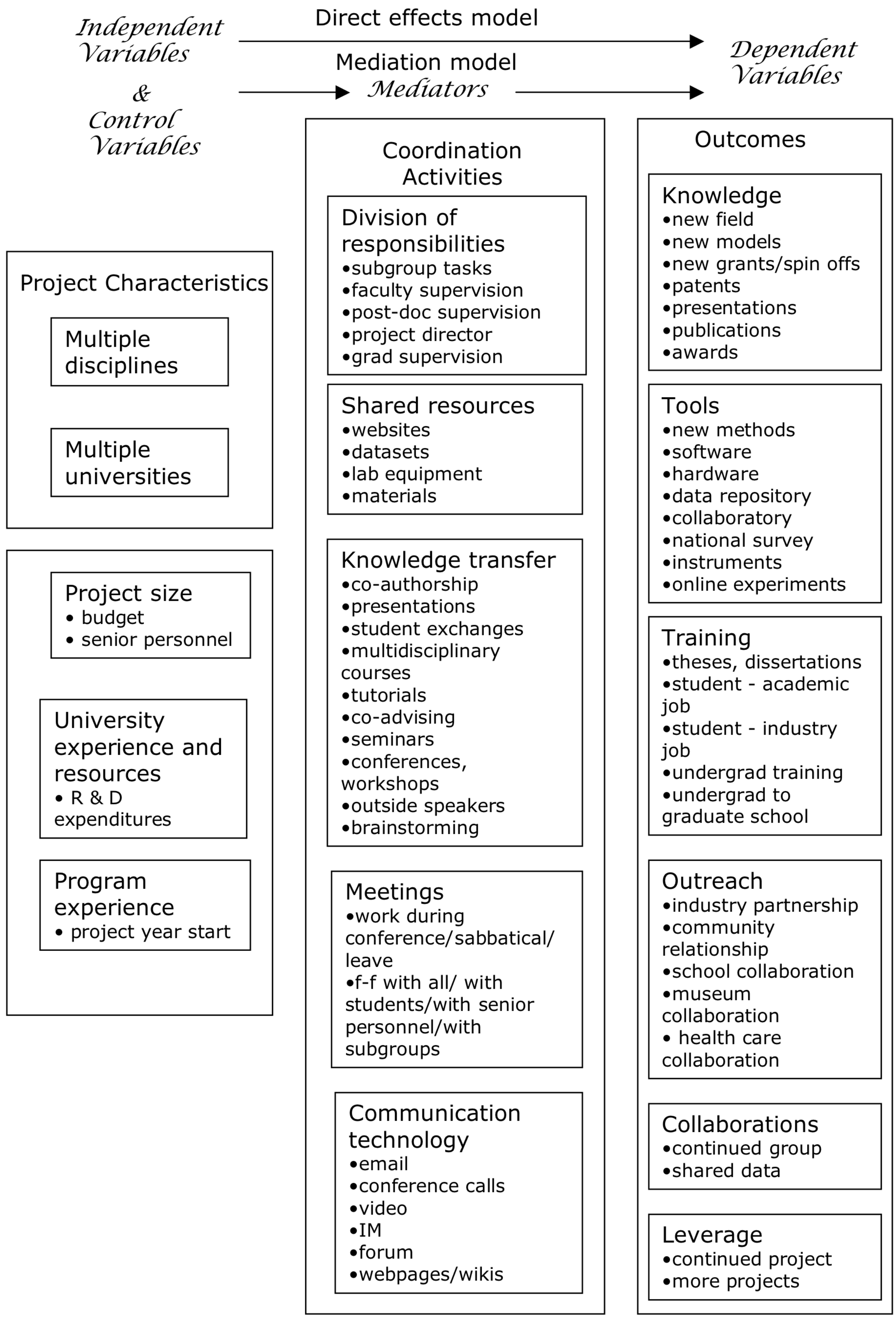
Upper graphic shows the direct effects abstract model. The lower graph shows how coordination activities may explain the direct effects. Mediation is supported when the mediators (coordination activities) are significant and reduce the direct effects in the model. Lower graphic shows the mediation analysis performed in this study.



Direct effects model



Mediation model


Independent Variables
&
Control Variables
Direct effects model
Mediation model
Mediators
Dependent Variables
Project Characteristics
Multiple disciplines
Multiple universities
Project size
• budget
• senior personnel
University experience and resources
• R & D expenditures
Program experience
• project year start
Coordination Activities
Division of responsibilities
•subgroup tasks
•faculty supervision
•post-doc supervision
•project director
•grad supervision
Shared resources
•websites
•datasets
•lab equipment
•materials
Knowledge transfer
•co-authorship
•presentations
•student exchanges
•multidisciplinary courses
•tutorials
•co-advising
•seminars
•conferences, workshops
•outside speakers
•brainstorming
Meetings
•work during conference/sabbatical/ leave
•f-f with all/ with students/with senior personnel/with subgroups
Communication technology
•email
•conference calls
•video
•IM
•forum
•webpages/wikis
Outcomes
Knowledge
•new field
•new models
•new grants/spin offs
•patents
•presentations
•publications
•awards
Tools
•new methods
•software
•hardware
•data repository
•collaboratory
•national survey
•instruments
•online experiments
Training
•theses, dissertations
•student - academic job
•student - industry job
•undergrad training
•undergrad to graduate school
Outreach
•industry partnership
•community relationship
•school collaboration
•museum collaboration
• health care collaboration
Collaborations
•continued group
•shared data
Leverage
•continued project
•more projects