Group Heterogeneity Increases the Risks of Large Group Size:

A Longitudinal Study of Research Group Productivity

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Abstract

Heterogeneous groups are valuable but differences among members can weaken group identification, raising group motivation and coordination costs. Weak group identification may be especially problematic in larger groups, which, in contrast with smaller groups, require more attention to motivating members and coordinating their tasks. We hypothesized that productivity in larger (vs. smaller) groups would decrease with greater heterogeneity. We studied the longitudinal productivity of 549 research groups varying in disciplinary heterogeneity, institutional heterogeneity, and size. We examined their publication and citation productivity before their projects started and 5 to 9 years later. Larger groups were more productive than smaller groups but their marginal productivity declined as their heterogeneity increased, either because their members belonged to more disciplines or to more institutions. These results provide evidence that group heterogeneity moderates the effects of group size, and suggest that desirable diversity in groups may be better leveraged in smaller, more cohesive units.

An enduring interest in psychology is to understand how working in groups affects member and group productivity (Hackman, 2002; Levine & Moreland, 1998). Because science is increasingly performed in groups, this question applies to how we conduct science. Evidence of the change in science is seen in the growing number of co-authored scientific papers; the number of authors per publication doubled from two in the 1960s to almost four in the 2000s (Wuchty, Jones, & Uzzi, 2007). Many research groups are large, complex arrangements of scientists from different disciplines and institutions. We examine here how member heterogeneity and group size affects the productivity of such groups. Although different streams of research have addressed the effects of group size (Mueller, 2012; Wheelan, 2009) and group heterogeneity (Mannix & Neale, 2005; Williams & O'Reilly, 1998), they have not been linked theoretically, particularly in the context of research groups in science and other fields. We conducted a longitudinal study of research group productivity to ask: How is member heterogeneity and group size related to research group productivity? Our analysis suggests group heterogeneity is particularly challenging in large research groups.

Group Heterogeneity

Lab and field studies suggest that group heterogeneity derived from member differences in knowledge, expertise, or experience can increase group creativity, but only if group members build on their social and intellectual differences and work on behalf of the group as a whole (Ancona & Caldwell, 1992; Homan et al., 2007; Stasser, Stewart, & Wittenbaum, 1995). This goal can be difficult to achieve. Group heterogeneity creates barriers to identification with the group as a whole because members do not feel psychologically connected to those who are different (O'Reilly, Caldwell, & Barnett, 1989; Tsui, Egan, & O'Reilly, 1992). Social identity theory (e.g., Abrams & Hogg, 1990; Brewer, 1991; Tajfel & Turner, 1986) suggests why it is particularly difficult for members to overcome differences with other members and identify with the group as a whole. Because people define themselves in terms of their meaningful social groups, they tend to view in-group members more favorably than out-group members. Categorizing people as having a different identity than oneself can lead to stereotyping and prejudice; thus it is not surprising that heterogeneous groups enjoy their group interactions less and like each other less well than do homogeneous groups (Mannix & Neale, 2005; Williams & O'Reilly, 1998).

Heterogeneity in Large Groups

The classic view of group size in the social psychology literature is Steiner's (1972) theory of group productivity. According to Steiner, having more members provides more resources available to meet task demands. Larger groups sometimes perform better than smaller groups as a result of having more people (for example, recalling an important piece of information [Horowitz & Bordens, 2002]). Nonetheless, the potential productivity gained from having more people working on parts of the task can be offset by process losses associated with the need to motivate members to participate and coordinate their work. In larger groups, each member contributes less, on average, than in smaller groups (Liden, Wayne, Jaworski, & Bennett, 2004). One reason for this decline in marginal productivity is social loafing; members of larger groups perform less than their share of the work (Latane, Williams, & Harkins, 1979). Also, larger groups have more difficulty than smaller groups reaching a common definition of the group's goals, managing the flow of work, sustaining members' attention and cooperation, minimizing turnover, and encouraging knowledge sharing over time (Chompalov, Genuth, & Shrum, 2002; Faraj & Xiao, 2006; Jackson et al., 1991; Malone, 1987; Okhuysena & Bechky, 2009).

Greater heterogeneity, and thus weakened identification with the group as a whole, should exacerbate motivation and coordination costs in larger groups. Motivation costs will rise because larger groups that are heterogeneous have to spend extra effort managing and sustaining positive member relationships (Mueller, 2011). Psychological distance is greater in larger than smaller groups (Latane, 1981); members will have less motivation to overcome and build on their differences. Meetings are less spontaneous, more formal, and less interactive in groups (Fay, Garrod, & Carletta, 2000), making it harder to form bonds through informal communication. Group members are then more likely to remain more identified with their smaller (and more homogeneous) subset of members than with the larger heterogeneous group (Hinds & Mortensen, 2005). Coordination costs will rise as well because larger groups must coordinate many people's work (Mueller, 2011), and heterogeneity will increase the differences among different approaches to work. In short, as a result of the additional motivation and coordination burdens of larger groups, weakened group identification due to heterogeneity should undermine productivity even more in these groups than in smaller groups.

Most field studies of group size and heterogeneity have examined either group heterogeneity (Mannix & Neale, 2005; Mueller, 2011) or group size (Haleblian & Finkelstein, 1993; Jackson et al., 1991) as control variables or main effects. Further, group productivity often is measured subjectively (Cummings & Kiesler, 2005; 2007). In the current study, we are interested in how group heterogeneity moderates the effects of group size on group productivity measured objectively and over time. We propose, with Steiner (1972), that group productivity will be higher in larger groups because more people contribute to the whole, but draw on social identity theory to argue that these performance improvements will be marginally reduced as group heterogeneity increases.

Group Size and Heterogeneity in Research Groups

A belief that scientists gain from exposure to different approaches, and that important problems require heterogeneous research groups, has taken hold across the sciences. Rather than depending on the gradual flow of ideas from one field to another, policy makers are promoting research that integrates the contributions of different experts no matter where they reside (e.g., Cacioppo, 2007). Funding agencies, such as the National Institutes of Health, the National Science Foundation (NSF), and the European Union's Framework Programme have promoted team science and funded sizeable projects that span disciplines and universities (Finholt & Olson, 1997). These projects are tackling complex topics in areas such as neuroscience, bioengineering, and medicine (Corley, Boardman, & Bozeman, 2006; Jordan, 2006; Metzger & Zare, 1999).

Our theoretical analysis suggests that increasing the heterogeneity and size of research groups will exact additional process losses in those groups. For instance, it may be essential for a research group's goals to recruit and add experts from another discipline, but these experts are unlikely to share the same social identity as the rest of the group. The group must then expend extra effort to develop trust and overcome differences of language and norms about the research process (Palmer, 1999). The same can be said of a research group that is dispersed and comprised of people from different institutions (Herbsleb, Mockus, Finholt, & Grinter, 2000; Olson & Olson, 2000). The group, at the same time, typically has become larger, so it faces bigger motivation and coordination challenges. Without strong group identification, these challenges may not be met. For instance, in a small group of researchers, the researchers can use conventional online tools to talk, share resources, arrange meetings, come to know each other's students, learn about each others' perspectives and skills, all of which should contribute to their identification with the group. In a large research group, however, addressing heterogeneity will be more difficult. As anyone who belongs to a large research group can attest, finding meeting times for a large group, much less carrying out informal collegial communication, can be difficult.

We propose that heterogeneity will interfere with the marginal productivity of large research groups, reducing the additional gains that ordinarily would accrue to the larger group. In one longitudinal analysis of awarded grants, the director of the National Institute of General Medical Sciences (NIGMS) reported that the largest labs were significantly less productive and had less impact than mid-size labs (Wadman, 2010), but this study did not control for many other factors that could have reduced large labs' productivity, including their heterogeneity. We therefore set out to examine the hypothesis that research group heterogeneity will moderate the effects of group size on group research productivity.

A Longitudinal Study of the Effects of Research Group Size and Heterogeneity

Method

We examined the relationships of research group size, heterogeneity, and productivity in 549 research groups created by all of the "Medium" (up to US$ 1M per year for 5 years) and "Large" (up to US$ 3M per year for 5 years) Information Technology Research (ITR) research projects funded by the National Science Foundation from 2000 to 2004. ITR was a five-year NSF-wide priority area, growing from $90M in 2000 to $295M in 2004. Together, these projects involved more than 2,200 principal investigators (PIs) along with numerous other researchers, staff, and students. Because there was substantial overlap in the actual number of PIs and project funding for medium and large ITR projects, we combined the datasets. A typical research group comprised five PIs and their students from two top U.S. universities, had representation from two or three disciplines, and $2M in funding over five years (Table 1). Many projects were aimed at developing techniques or theory from computer science for other disciplines such as biology, physics, engineering, and psychology. The program was very popular (2,100 proposals in the first year of the program) and the program became more competitive over time. In 2000, 30% of the medium and large proposals were funded with 70% of their proposed budget but by 2004, just 21% were funded with 49% of their budget.

Table 1 about here

Productivity Measures

To assess these projects' outcomes, in 2009, four to nine years after the projects started, we used four measures of productivity. One measure was the publications the PIs listed in their final reports to the NSF (or latest annual report, if no final report had been submitted yet). Publications in final reports include archival conference proceedings, journal publications, chapters in books, and public reports by PIs, other researchers, and students on the project. When considering PI project publications, we pooled all publications authored by PIs and removed duplicate publications when PIs coauthored a paper. Three additional productivity measures were group member's cumulative publications using the Google Scholar search engine, and their cumulative publications and citations in the ISI Web of Science and Social Science database. We divided their publications into those published prior to their ITR project start date and those published after this date. To check the quality of these automatically extracted publications, we took a 10% sample and evaluated them manually using Amazon's Mechanical Turk. For each extracted publication, we asked Turkers to find the corresponding author's webpage or résumé with their publications listed, and check that the automatically extracted publication was indeed correct. We asked five Turkers to check each publication, and assumed correctness if at least four were the same. Overall, 94% of the extracted publications were correct.

Research Group Size and Heterogeneity

We measured research group size as the total number of PIs listed on the project grant. This information was obtained from the NSF awards database posted on its website (National Science Foundation, 2009). We measured heterogeneity in two ways: (1) the number of PIs' disciplines, and (2) the number of institutions in which the PIs worked. We obtained the disciplines of PIs from their departmental affiliation and manually checked those that were ambiguous. Their institutions were listed in the NSF awards website.

Control Variables

A number of factors other than research group size and heterogeneity can influence research productivity. As noted above, we were able to use measures of each PI's publications (or citations) prior to their ITR project as a control for their research productivity at the start of the project. We controlled for the number of other active NSF grants held by the PIs at project start because PIs' other grants provide additional resources. We also controlled for the start date of the project because older projects will have had more time to work. Because ITR was a new program, we also entered a quadratic factor to account for projects funded in the first year that could have had a particularly rough start. We also controlled for the average R&D funding of the universities involved in the project because universities with more research experience may provide better institutional support. Jones et al. (2008) show that multi-institutional collaborations are increasingly concentrated within top-tier universities, and that co-authored papers are more highly cited when they include an author from a top-tier university. We also controlled for the amount of funding awarded to the project.

Analyses

We examined all projects' publication output from their start date (2000 to 2004) through 2009, which yielded 46,850 publications listed in project reports to the NSF. Hierarchical regression models examine the predictors of these publications, controlling statistically for PIs' productivity before their project began (an estimate of the baseline likelihood of their future productivity). An important aspect of this prospective methodology is that we considerable variation in number of disciplines, number of institutions, and group size, as well as variation in the marginal productivity of projects. We are not limited to successful projects, or to those PIs who had published papers.

Our regression analysis tests the hypothesis by assessing how groups with many disciplines or universities represented among the PIs fared when the groups were small or large. To remove the possibly undue effect of unusually large or heterogeneous projects, all analyses use truncated measures of group size (1 to 13 or more investigators), disciplinary heterogeneity (1 to 4 or more disciplines), and institutional heterogeneity (1 to 7 or more institutions). In the statistical analyses, when determining the quantity of publications, whether from NSF final report publications, or Google Scholar or Web of Science publications, we count a group's publication only once, no matter how many authors it had from the project. Similarly, in determining the quality or impact of publications using Web of Science citations, we rely on the citations for each unique publication.

Interviews

To obtain information on PIs' retrospective perceptions of motivation and coordination in the research groups, in 2009 we conducted structured interviews with 55 PIs from 52 of the research projects. The sample was chosen blind to the productivity data. We drew a stratified random sample from projects at top-ranked universities in locations reflecting the distribution of projects overall: 15 researchers from the Northeast, 13 from the South, 7 from the Midwest, and 20 from the West. When possible, we interviewed the lead PI. Our interview questions drew from Kraut, Galegher, and Egido's (1987) model of research collaboration, which posits three stages of research: the initiation phase (e.g., preparing a proposal; finding experts), execution phase (e.g., collecting data, running experiments), and dissemination phase (e.g., writing and publishing papers). PIs were encouraged to discuss their project experiences, how they found their collaborators, planned their budgets and projects, and organized their work and wrote papers. We coded interviews iteratively using NVivo software, and then used frequently-coded themes to help develop our theoretical arguments and derive plausible explanations of the longitudinal study results.

Results of Longitudinal Analysis

Table 1 shows the means and correlations among the variables, and Table 2 presents the results of the hierarchical regression analyses using four dependent measures of group research productivity, controlling for prior PI research productivity. We consider the publications listed in the PIs' final reports to be the best measure, because these reports would be less likely than Scholar or Web of Science to include the results of PIs' other projects and collaborations. (PIs had to acknowledge the grant in the publications they listed.) In Table 2, group size has a significantly positive effect on productivity. The result is to be expected; as each PI is added, there is one more researcher to contribute to the group's publishable research. We also see that heterogeneity does not generally influence productivity (although more institutions in a group is a consistently negative trend).

As hypothesized, the interactions of size and heterogeneity are statistically significant (size x disciplines: *std*. $b = -.13$, $p < .01$; size x institutions: *std*. $b = -.13$, $p < .01$). The meaning of these interactions is displayed in the plots in Figure 1. Having more PIs predicts higher productivity overall, but when the research group is heterogeneous, either because it has multiple disciplines or the PIs come from multiple institutions, the results change. Simple slopes analyses (Aiken & West, 1991) confirm that research groups lowest in heterogeneity (one discipline or one institution) increased their productivity with more members (t [1] = 5.23, $p < .0001$, $d = .45$; t [1] = 4.88, $p < .0001$, $d = .42$, respectively). At medium levels of heterogeneity (3 disciplines; 4 institutions) groups also increased their productivity with more members, but not as much (t [1] = 2.79, $p < .01$, $d = .24$; t [1] = 2.5, $p = .01$, $d = .22$). Groups highest in heterogeneity (4 or more disciplines; 7 or more institutions) did not increase their productivity with more group members (*t* [1] = .64, n.s.; *t* [1] = .13, n.s.). See figure 1a and 1b.

Table 2 and Figure 1 about here

To get a sense of these effects, consider that the average project produced 85.5 unique publications (not double-counting project members on the same publication). Controlling for other factors, a typical five-member group (that is, mean and median size) with three disciplines produced 119 publications, whereas a larger group of 9 PIs and three disciplines produced 150 publications. Although 150 is greater than 119, per PI output is nearly 24 publications in the smaller group and just 17 publications in the larger group. In a group as large as 13, per-PI output goes down to 14 publications. The pattern and significance of the moderator effect is the same when we use different measures of productivity, including citations. Table 2 shows the regressions predicting the interaction effects of size and the number of disciplines on productivity (Google Scholar publications: *std. b* = -.09, $p < .01$; Web of Science publications: *std. b* = -.22, $p < .001$; Web of Science citations, *std. b* = -.16, $p < .001$) and the effects of size and more institutions involved in the project (Google Scholar publications: *std. b* = -.07, $p < .05$; Web of Science publications: *std. b* = .17, $p <. 001$; Web of Science citations, *std. b* = -.11, $p < .001$).

Interview Findings

Among the 55 interviewees, many recalled problems in communication that they attributed to heterogeneity (64%) or to large group size (34%). Some said these problems had interfered with sharing information (55%) or resources (18%), and had led PIs to go their separate ways (24%). For example, when writing their proposals, some groups added PIs from another discipline to obtain more expertise on the topic and to bolster their interdisciplinary credentials but lack of familiarity interfered with group chemistry and encouraged members to work with group members they already knew. (One example: "Why would I want to build a personal relationship and start work with someone else when I could work with my buddy? It's more fun.") When executing research, PIs may have intended to use project resources to support groundbreaking interdisciplinary work, but their first responsibility, in their view, was to their own part of the project, especially their students' publishing in the top journals of their discipline. At the dissemination stage, the process of tailoring reporting interdisciplinary work in specific venues of interest to each discipline strained relationships. These findings suggested to us that a lack of identification and integration with the research project as a whole was a key failing of large, heterogeneous groups.

Discussion

Our analysis of the productivity of 549 research groups indicated that more PIs on a project increased productivity, but heterogeneity reduced the marginal productivity of research groups when members were from multiple disciplines or institutions. These results are not due to the personal productivity of PIs or to their access to other funding, to how long the projects have run, to differences in their project budgets, or to their universities' experience with research. Both forms of heterogeneity we measured, multiple disciplines and multiple universities, were problematic.

Working across disciplines entails different communication challenges than working across institutions. Yet both of these situations require that PIs actively manage relationships and accommodate different perspectives. Our findings suggest that most researchers struggled to perform these tasks in large projects. Reviewing our data, however, we identified a few heterogeneous large research groups with unusually high publication rates. An interview we had with the lead PI of one of these groups suggested that having a strong leader who insisted on frequent project meetings and status reports from everyone might have helped his group overcome member differences. This PI said, "One of the advantages [was that] I was PI. And I have worked in this cross-disciplinary space for a long time. And so basically people knew I wouldn't tolerate any hiding in your discipline. So it was like if you're not part of this cultural change to meld together across these things then we don't need you on the project." Another interview with the PI of a successful large group suggested that having a balance of expertise at each site or in each discipline rather than token or siloed experts could help people cross subgroup boundaries (cf. Jackson, 1999): "An awful lot of the work is learning to understand each others' vocabulary. . . I don't know a lot about her field and vice versa. . , It helped that [in my lab] I had a junior faculty member [in the other field] working on the project as well and so he could act as the translator between the two of us." We believe that such "translation" activities might have helped the members develop common goals and stronger group identity.

Implications for understanding groups

Diversity of perspectives and skills in a group makes innovation possible, but acquiring this diversity may mean adding members. Our data suggest limits to the advantages of adding people, and that diversity may be applied better in smaller, more manageable groups. Examining other group tasks will be important to test the generalizability of our findings. For example, in creative design groups, the benefits of heterogeneity may outweigh the costs of having more members. Steiner (1972) suggested that large groups perform better if they can easily subdivide tasks and re-assemble the results. This argument foreshadows the advent of crowd-sourced science, whereby ordinary citizens and scientists collect or analyze data for the benefit of the whole. We also do not know if our findings generalize to really large research groups on the order of what has been required to sequence the human genome or conduct high energy physics experiments. Perhaps a 15-person research group is very different than a 100 to 1000-person research organization. We also do not know the time frame in which heterogeneity begins to cause trouble for larger groups, and the extent to which groups can overcome their differences. Although heterogeneous groups may just take longer to become productive when they are large, our sense from the interviews is that if there are few successes early on, they are unlikely to come later.

The impact of perceiving the entire group as a cohesive unit has been studied as a problem in entitativity (Lickel et al., 2000). It would seem plausible that if members identified mainly with those in their own discipline or with others at their own institution, then the research group could be considered a collection of subgroups (Carton & Cummings, 2012). If so, psychological distance among subgroups might be an important theoretical mechanism linking heterogeneity, group size, and productivity (see Trope, Yaacov, & Liberman, 2010).

Within the limitations of the data from the NSF program we studied, we have shown that big diverse groups are not as marginally productive as comparatively smaller projects. We hope these findings encourage more research on the processes of managing heterogeneity and group size. Given today's complex problems, we need better ways to more constructively marshal a variety of people and resources to tackle them.

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The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Table 1. Means, standard deviations, and correlations among the variables (N=549).

	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12	13
Control Variables															
1. Project year start	2002.3	1.3	1.00												
2. R&D expenditures of institution(s)[a]	4.2	.7	-.07	1.00											
3. Project budget	1.9M	2.2M	-.19	.05	1.00										
4. Number active NSF grants	2.9	2.7	-.03	.01	.25	1.00									
5. Google Scholar pre-project[b]	154.8	95.5	.02	-.02	.49	.47	1.00								
6. Web of Science pre-project[b]	78.9	68.2	.28	-.03	.36	.33	.71	1.00							
7. Web of Science citations pre-project[b]	920.9	1,129.9	.21	-.02	.29	.24	.53	.77	1.00						
Group Size and Heterogeneity															
8. Number principal investigators (PIs)	4.9	3.0	.00	-.07	.49	.47	.94	.73	.55	1.00					
9. Number institutions of PIs	2.3	1.6	-.01	-.13	.37	.37	.67	.52	.46	.72	1.00				
10. Number disciplines of PIs	2.1	.9	.02	-.01	.18	.25	.53	.40	.32	.57	.33	1.00			
Productivity Outcomes															
11. Google Scholar[c]	151.9	95.6	-.09	-.01	.51	.48	.94	.66	.48	.92	.65	.53	1.00		
12. Web of Science [c]	151.8	102.6	-.04	-.06	.48	.47	.90	.72	.57	.93	.65	.55	.90	1.00	
13. Web of Science citations[c]	1,028.8	1,240.2	-.20	.05	.48	.25	.54	.43	.48	.54	.37	.31	.54	.61	1.00
14. Final report publications[d]	85.5	67.6	.09	-.07	.36	.25	.55	.40	.30	.54	.35	.33	.57	.51	.30

[a]1 = bottom 20% of institutions, 5 = top 20% of institutions
[b]Number unique publications prior to project start by PIs on the project
[c]Number unique publications from start of project to 2009 by PIs on the project
[d]Number of publications reported in the project's final report (or last annual report if project ongoing)

Table 2. Hierarchical regression models of the effect of research group size and group heterogeneity (multiple disciplines or institutions) on group productivity. (Standardized coefficients shown. N = 549)

Predictor	Dependent Variable 1: Log NSF Final Report Publications			
	Step 1	**Step 2**	**Step 3**	**Step 4**
Control Variables				
Log publications prior to project[a]	.33***	.17***	.12*	.10[t]
Number active NSF grants at time of project start	.02	-.09	.00	.00
Project year start	-.02	.04	-.03	-.03
Project year * project year	-.47***	-.47***	-.47***	-.47***
Average R&D funding of project institutions	-.06[t]	-.04	-.03	-.03
Log (project funding)	.20***	.16***	.16***	.16***
Main Effects				
Number investigators (1 – 13+)[b]		.27***	.37***	.37***
Number of disciplines (1 – 4+)[b]		.02	.00	-.03
Number of institutions (1 – 7+)[b]		-.07	-.04	-.06
Two-Way Interactions				
Number investigators x number disciplines			-.11*	-.13**
Number investigators x number institutions			-.10*	-.13**
Disciplines x institutions			.08	.03
Three-Way Interaction				
I * I * D				.14*
R-square adjusted	.41	.43	.44	.44

(Table continued on next page.)

Predictor	Dependent Variable 2: Log Google Scholar Publications			
	Step 1	**Step 2**	**Step 3**	**Step 4**
Control Variables				
Log publications prior to project[a]	.82***	.65***	.62***	.61***
Number active NSF grants at time of project start	.07**	.04[t]	.04*	.04[t]
Project year start	-.15***	-.16***	-.16***	-.16***
Project year * project year	-.05*	-.06**	-.05**	-.06**
Average R&D funding of project institutions	-.02	-.00	.00	.01
Log (project funding)	.07***	.03	.04[t]	.04[t]
Main Effects				
Number investigators (1 – 13+)[b]		.21***	.27***	.27***
Number of disciplines (1 – 4+)[b]		.04	.03	.02
Number of institutions (1 – 7+)[b]		-.01	.00	-.00
Two-Way Interactions				
Number investigators x number disciplines			-.07**	-.09**
Number investigators x number institutions			-.06[t]	-.07*
Disciplines x institutions			-.03	-.00
Three-Way Interaction				
I * I * D				.09*
R-square adjusted	.78	.79	.80	.80

(Table continued on next page.)

Predictor	Dependent Variable 3: Log Web of Science Publications			
	Step 1	**Step 2**	**Step 3**	**Step 4**
Control Variables				
Log publications prior to project[c]	.65***	.45***	.39***	.33***
Number active NSF grants at time of project start	.18***	.07**	.08**	.07**
Project year start	-.21***	-.17***	-.15***	-.14***
Project year * project year	-.01	.01	.01	
Average R&D funding of project institutions	-.05[t]	-.02	-.01	-.00
Log (project funding)	.08**	-.02	-.01	-.01
Main Effects				
Number investigators (1 – 13+)[b]		.41***	.53***	.53***
Number of disciplines (1 – 4+)[b]		.08*	.07*	.03
Number of institutions (1 – 7+)[b]		-.06[t]	-.02	-.04
Two-Way Interactions				
Number investigators x number disciplines			-.19***	-.22***
Number investigators x number institutions			-.13***	-.17***
Disciplines x institutions			.09*	.00
Three-Way Interaction				
I * I * D				.20***
R-square adjusted	.54	.63	.67	.67

(Table continued on next page.)

Predictor	Dependent Variable 4: Log Web of Science Citations			
	Step 1	**Step 2**	**Step 3**	**Step 4**
Control Variables				
Log citations prior to project[d]	.62***	.52***	.48***	.47***
Number active NSF grants at time of project start	.11***	.03	.04	.04
Project year start	-.26***	-.25***	-.24***	-.24***
Project year * project year	-.06[t]	-.05	-.05	-.05
Average R&D funding of project institutions	.02	.02	.03	.03
Log project funding	.10**	.03	.04	.04
Main Effects				
Number investigators (1 – 13+)[b]		.31***	.39***	.38***
Number of disciplines (1 – 4+)[b]		.03	.02	.00
Number of institutions (1 – 7+)[b]		-.11**	-.08[t]	.09*
Two-Way Interactions				
Number investigators x number disciplines			-.14**	-.16***
Number investigators x number institutions			-.10*	-.11**
Disciplines x institutions			.08[t]	.04
Three-Way Interaction				
I * I * D				.09
R-square adjusted	.47	.51	.53	.53

[t]$p < .10$, [*]$p \leq .05$, [**]$p \leq .01$, [***]$p \leq .001$

[a] Estimated from Google Scholar cumulative publications prior to the project start.
[b] Truncated independent variable.
[c] Estimated from Web of Science cumulative publications prior to the project start.
[d] Estimated from Web of Science citations prior to the project start.

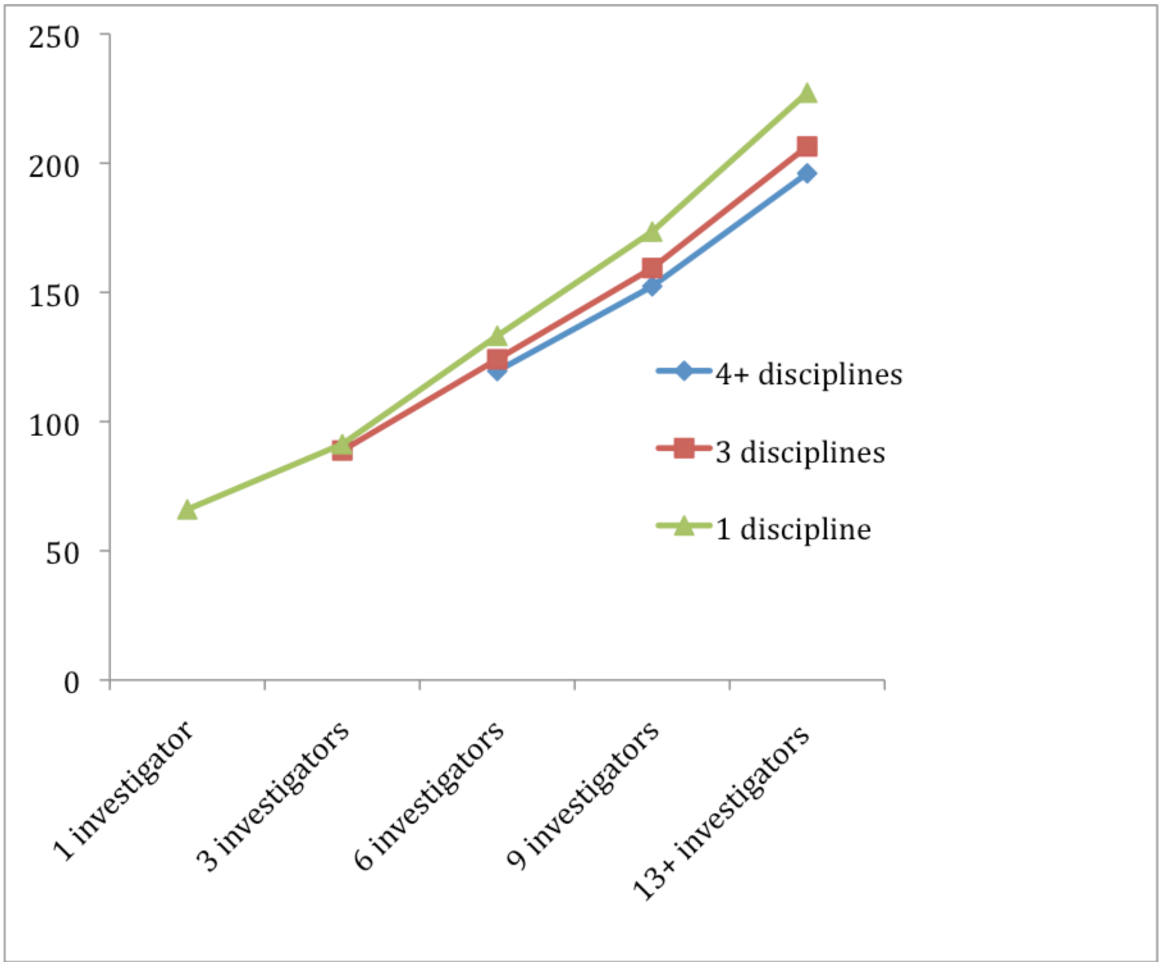

Figure 1a. Predicted number of publications as a function of research group size and heterogeneity as measured by number of disciplines of the investigators. Shown are slopes for low and high heterogeneity (low $t = 5.23$, $p < .0001$, $d = .45$; high $t = .64$, n.s.) The slope in the middle is shown for purposes of illustration: Above 3 disciplines ($t = 2.79$, $p < .01$, $d = .24$), the slopes are not statistically significant.

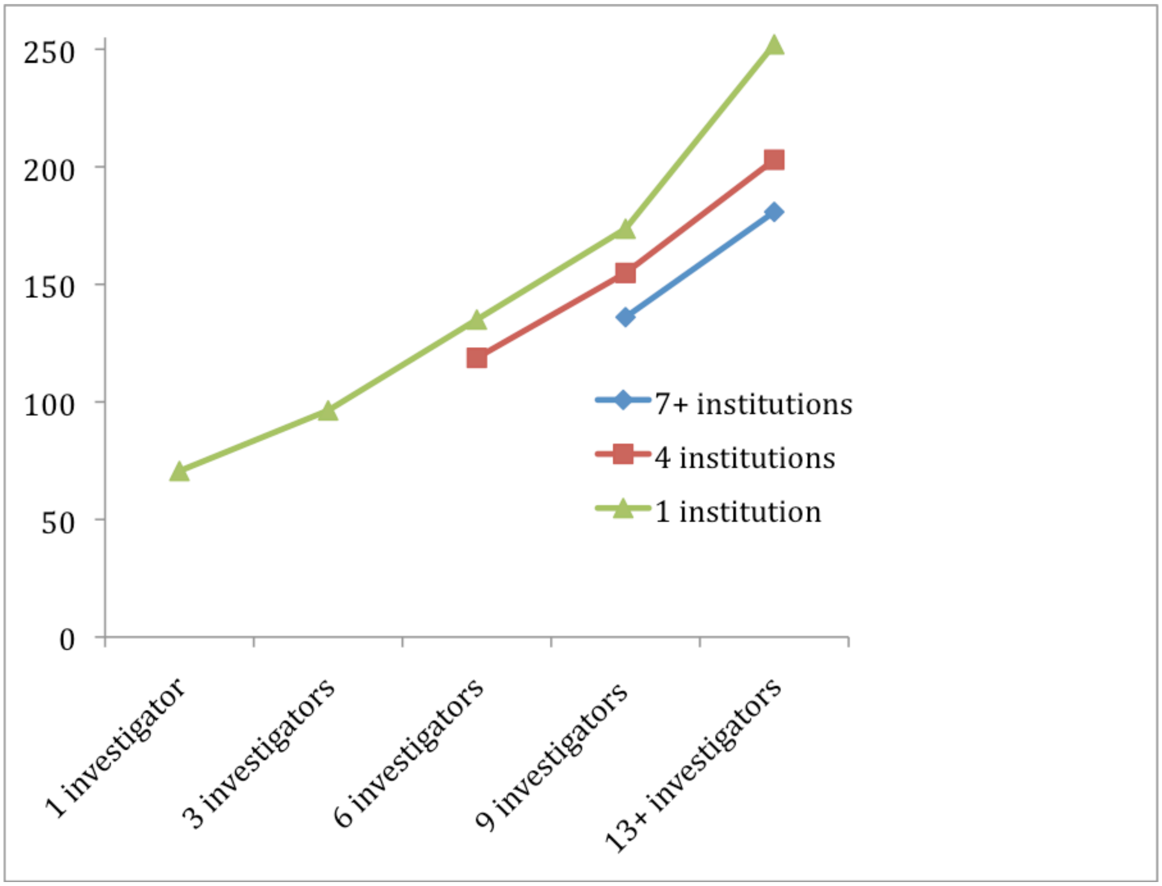

Figure 1b. Predicted number of publications as a function of research group size and group heterogeneity as measured by number of institutions involved in the research. Shown are slopes for low and high heterogeneity (low $t = 4.88$, $p < .0001$, $d = .42$; high $t = .12$, n.s.) The slope in the middle is shown for purposes of illustration. Above 4 institutions ($t = 2.5$, $p = .01$, $d = .22$), the slopes are not statistically significant.