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Scientists' collaboration strategies: implications for scientific and technical human capital

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Abstract

"Scientific and technical human capital" (S&T human capital) has been defined as the sum of researchers' professional network ties and their technical skills and resources [Int. J. Technol. Manage. 22 (7–8) (2001) 636]. Our study focuses on one particular means by which scientists acquire and deploy S&T human capital, research collaboration. We examine data from 451 scientists and engineers at academic research centers in the United States. The chief focus is on scientists' collaboration choices and strategies. Since we are particularly interested in S&T human capital, we pay special attention to strategies that involve mentoring graduate students and junior faculty and to collaborating with women. We also examine collaboration "cosmopolitanism," the extent to which scientists collaborate with those around them (one's research group, one's university) as opposed to those more distant in geography or institutional setting (other universities, researchers in industry, researchers in other nations). Our findings indicate that those who pursue a "mentor" collaboration strategy are likely to be tenured; to collaborate with women; and to have a favorable view about industry and research on industrial applications. Regarding the number of reported collaborators, those who have larger grants have more collaborators. With respect to the percentage of female collaborators, we found, not surprisingly, that female scientists have a somewhat higher percentage (36%) of female collaborators, than males have (24%). There are great differences, however, according to rank, with non-tenure track females having 84% of their collaborations with females. Regarding collaboration cosmopolitanism, we find that most researchers are not particularly cosmopolitan in their selection of collaborators—they tend to work with the people in their own work group. More cosmopolitan collaborators tend have large grants. A major policy implication is that there is great variance in the extent to which collaborations seem to enhance or generate S&T human capital. Not all collaborations are equal with respect to their "public goods" implications.

Keywords: Collaboration; Scientific and technical human capital; Scientific publication; Co-authorship; Mentoring

1. Introduction

If we think of "scientific and technical human capital" (S&T human capital) as the sum of researchers' professional network ties and their technical skills and resources, then the question arises "how do scientists acquire and deploy these assets?" One answer, as economists' studies (e.g. Becker,

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1962) of human capital have shown, is formal education. Researchers acquire and impart knowledge through formal education processes, often resulting in credentials that signify scientific assets. Sociologists have shown that informal network ties, such as invisible colleges, can be just as important to the acquisition and transmission of scientific knowledge. Tacit knowledge often plays an important role in S&T human capital, as demonstrated by recent studies (Nelson and Nelson, 2002; Balconi, 2002).

Our study focuses on one particular means by which scientists acquire and deploy S&T human capital, research collaboration. The relation of research collaboration to S&T human capital is a topic considered by at least a few other researchers (e.g. Laudel, 2001; Glaser, 2001), but it is not a common theme. The literature on scientists' research collaboration shows us that collaboration choices are governed by a wide variety of factors including inter-institutional structures (Landry and Amara, 1998), formal (Wen and Kobayashi, 2001) and informal research networks, research alliances and covenants (Pisano, 1991), and arrangements for sharing expensive or scarce scientific resources and equipment (Kelves, 1995).

Melin (2000, p. 32) notes, "if we move from macro to micro, we see that intertwined with these structural circumstances there are other, more individual reasons for collaboration." Our study focuses on the "individual reasons," particularly *strategies* researchers pursue in their collaboration choices. We certainly do not discount the significance of external environmental constraints and institutions, but we maintain that many of the factors governing individual scientists' collaboration choices remain very much within the control of the individual, especially when the researcher works in an academic institution.

Much previous research on collaboration focuses on co-authorship. A co-author concept of collaboration has many advantages. Katz and Martin (1997) point out four key advantages of using co-authorship as a measure of collaboration including its verifiability, stability over time, data availability and ease of measurement. But they also note that co-authorship is no more than a partial indicator of collaboration. Our study foregoes the advantages of co-author approaches in favor of a broader conception of collaboration, one that seems to us more appropriate to the study of motives and strategy.

Using questionnaire data, we employ a self-reported concept of collaboration, permitting the respondent to determine what is and is not "collaboration."

While a focus on a strategy-based, self-reported concept of collaboration presents its own problems, chiefly a lack of operational precision, it avoids some of the problems of a publication-based measure of collaboration. For instance, in an early case study to investigate collaboration, Hagstrom (1965) found evidence that some publications listed authors for purely social reasons. Stokes and Hartley (1989) showed that sometimes a researcher may be listed as a co-author, simply by virtue of providing material or performing a routine assay. At the other extreme, an individual may provide a key idea for research but, for any of a variety of reasons, not be included as a co-author. La Follette (1992) showed that the practice of making colleagues "honorary co-authors" has become quite common.

Our study examines data from 451 scientists and engineers[1] at academic research centers in the United States, data from the spectrum of collaborators, ranging from post-doctoral researchers to full professors and research directors. While the respondents to our mailed questionnaire are from a wide variety of universities and from different research fields, all of them work in multidisciplinary settings with a strong propensity toward collaboration. In many of these centers, an avowed objective is to provide quality training and to enhance the research capacities of the persons affiliated with the centers.

In the next section of this paper (Section 2), we define the concept of scientific and technical human capital and discuss how this definition is different from past research on human capital and social capital models. We also discuss in Section 2 the concept of research collaboration and how scientific collaboration can play a critical role in developing scientific and technical human capital. In Section 3 of the paper, we describe the data collection methods that were used to complete the analyses that are presented in the paper. The next section of the paper introduces a conceptual model of how research collaboration is related to the development of scientific and technical human capital.

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[1] Hereafter, we use the term "scientists" rather than the more cumbersome "scientists and engineers." But our study includes data for both scientists and engineers and we make the distinction when needed.

In addition, we present and discuss four research hypotheses that operationalize (in an empirical way that can be tested with the data available) the relationship between scientific and technical human capital and research collaboration patterns. In Sections 5 and 6 of the paper, we present the results of our statistical analyses and discuss how the findings relate to the four, previously discussed, research hypotheses. In the last section of the paper (Section 6), we draw some general conclusions for the research project and present several implications for science and technology policy.

2. Scientific and technical human capital and collaboration

Scientific and technical human capital (S&T human capital) is the sum of scientific, technical and social knowledge, skills and resources embodied in a particular individual (Bozeman et al., 2001). It includes both human capital endowments, such as formal education and training, and social relations and network ties that bind scientists and the users of science together knowledge value collective. S&T human capital is the unique set of resources the individual brings to his or her own work and to collaborative efforts. Generally, human capital models (Becker, 1962; Schultz, 1963) have developed separately from social capital models (Bourdieu, 1986; Bourdieu and Wacquant, 1992; Coleman, 1988, 1990), but in the practice of science and the career growth of scientists, the two are not easily disentangled. Thus, S&T human capital is the sum of skills, knowledge, and social relations needed to participate in science.

We propose that scientific collaboration often plays a critical role in developing S&T human capital, especially in those cases where the collaboration takes on mentoring characteristics, that is, when a more experienced scientist collaborating with a junior scientist, a post-doctoral researcher, or a graduate student. In such cases, the junior partner can, at least under the right circumstances, develop a wide variety of S&T human capital assets, not only enhanced S&T knowledge, but craft skills, know-how, the ability to structure and plan research and of course, increase contacts with other scientists, industry, and funding agents. In many instances, collaborations are about much more than just "getting the work out the door."

In addition to a concern with mentoring, we also pay particular attention to collaborations involving women. By most measures and in most fields, women and minorities remain underutilized in science and engineering. Because of decades of barriers to entry, barriers that are only recently beginning to be removed, they are on average younger and less experienced than men. Thus, we pay particular attention to women's collaboration patterns, especially mentor-oriented collaboration. (For the same reasons, we would be interested in minority collaboration patterns, but there are too few minority scientists in our data set to permit us to make valid inference.)

While there has been little work on scientific collaboration taking a S&T human capital perspective, there is a significant and relevant literature on collaboration. In the section below, we examine the literature, focusing on those aspects most relevant to the accumulation, use, and diffusion of S&T human capital.

2.1. Collaboration as strategic choice: relevant research

For many years, co-author-based studies of collaboration dominated studies of scientific collaboration (e.g. Price and Beaver, 1966; Merton, 1973) and such studies remain important (Melin, 2000; Seglen and Aksnes, 2000; Zitt et al., 2000; Garg and Padhi, 2001; Liang et al., 2001; Wagner-Dobler, 2001). While such studies have advanced our knowledge of social dynamics of science, the approach is less useful for an analysis of S&T human capital.

Studies examining motives for collaboration and the strategies arising from those motives tend to be based on either interview or questionnaire data. Within this body of research, the most commonly cited reasons for research collaboration include access to expertise (Katz and Martin, 1997; Melin, 2000; Thorsteinsdottir, 2000; Beaver, 2001), access to equipment or resources one does not have (Meadows and O'Connor, 1971; Meadows, 1974; Melin, 2000; Thorsteinsdottir, 2000; Beaver, 2001), to encourage cross-fertilization across disciplines (Beaver and Rosen, 1978, 1979a,b; Katz and Martin, 1997; Melin, 2000), to improve access to funds (Smith, 1958;

Clarke, 1967; Heffner, 1981; Beaver, 2001), to obtain prestige or visibility (Crane, 1972; Beaver and Rosen, 1978, 1979a,b; Katz and Martin, 1997; Beaver, 2001), to learn tacit knowledge about a technique (Beaver and Rosen, 1978, 1979a,b; Katz and Martin, 1997; Beaver, 2001), to pool knowledge for tackling large and complex problems (Maanten, 1970; Goffman and Warren, 1980; Thorsteinsdottir, 2000; Beaver, 2001), to enhance productivity(Thorsteinsdottir, 2000; Beaver, 2001), to educate a student (Crane, 1972; Beaver and Rosen, 1978, 1979a,b; Melin, 2000; Beaver, 2001), increasing specialization of science (Bush and Hattery, 1956; Smith, 1958; Jewkes et al., 1959; Melin, 2000), and for fun and pleasure (Katz and Martin, 1997; Melin, 2000; Thorsteinsdottir, 2000; Beaver, 2001).

Even though several studies (mentioned above) have shown that socio-cognitive factors can drive researchers to collaborate, scholars hold different opinions about the role of social or intellectual forces in stimulating collaboration. On the one hand Price (1963) claimed that social and intellectual forces do not play a large role because collaborative authorship arises more from economic than from intellectual dependence. Others have argued that co-authorship reflects mutual intellectual and social influence (Edge, 1979; Stokes and Hartley, 1989).

Many scholars, however, do agree that collaborations often begin informally and stem from informal conversations between colleagues (Edge, 1979; Hagstrom, 1965; Price and Beaver, 1966). Spatial proximity also seems to encourage collaboration (Allen, 1977) because it often leads to informal communication (Hagstrom, 1965; Kraut and Egido, 1988). The closer two potential collaborators are in spatial proximity; the more likely they are to engage in informal communications that will lead to collaboration. In fact, Katz (1993) found that co-authorship decreases exponentially with the distance separating pairs of institutional partners.

Taking together the various studies of motives and strategies for collaboration, we infer that different the implications for S&T human capital vary according to strategy. For example, some approaches to collaboration seemed to have greater potential for mentoring and the development of young scientists, whereas others may have greater implications for joint productivity.

3. Data

Detailed information about the larger project from which the data reported here are drawn is provided in Gaughan and Bozeman (2002). We provide a brief summary here. In 2000 and 2001 we collected data from the curriculum vitae (CVs) of 1041 Ph.D. level scientists. Our target population was scientific researchers working in multidisciplinary work groups or research areas, especially in centers funded by the National Science Foundation and by the Department of Energy, the sponsors of our research. The data are not representative of all university scientists because, among other reasons, the participants are affiliated with centers and the centers tend to be more multidisciplinary, somewhat more applied in orientation, and to have more industry linkages. The data are representative of individuals working in NSF and DOE centers in universities.

The Survey of Careers of Scientists and Engineers was conducted from October 2001 to March 2002. A mailed questionnaire was sent to the 997 university faculty members, a systematic sample from the original CV database, including all those in the database except those who provided only partial data, were not university faculty, were graduate students or were retired. After two mailings we received 451 questionnaires, for a response rate of 45%. The questionnaire included questions about research collaboration, grants and contracts, job selection, work environment, and demographic information. The respondents include 63% tenured faculty, 37% non-tenured faculty or post-doctoral researchers, 86% males, 14% females, 70% native born and 30% immigrant scientists. The gender ratio and native/immigrant ratio in this sample is close to the national level.

4. Model and hypotheses

Our analysis is premised on a conceptual model relating collaboration to S&T human capital (Fig. 1). As the figure shows, we conceptualize S&T human capital as dynamic and embodying cognitive skills, knowledge, and craft skills. These skills are deployed and also supplemented in social capital exchange relationships. For simplicity's sake we depict only three broad categories of network ties—collaboration ties,

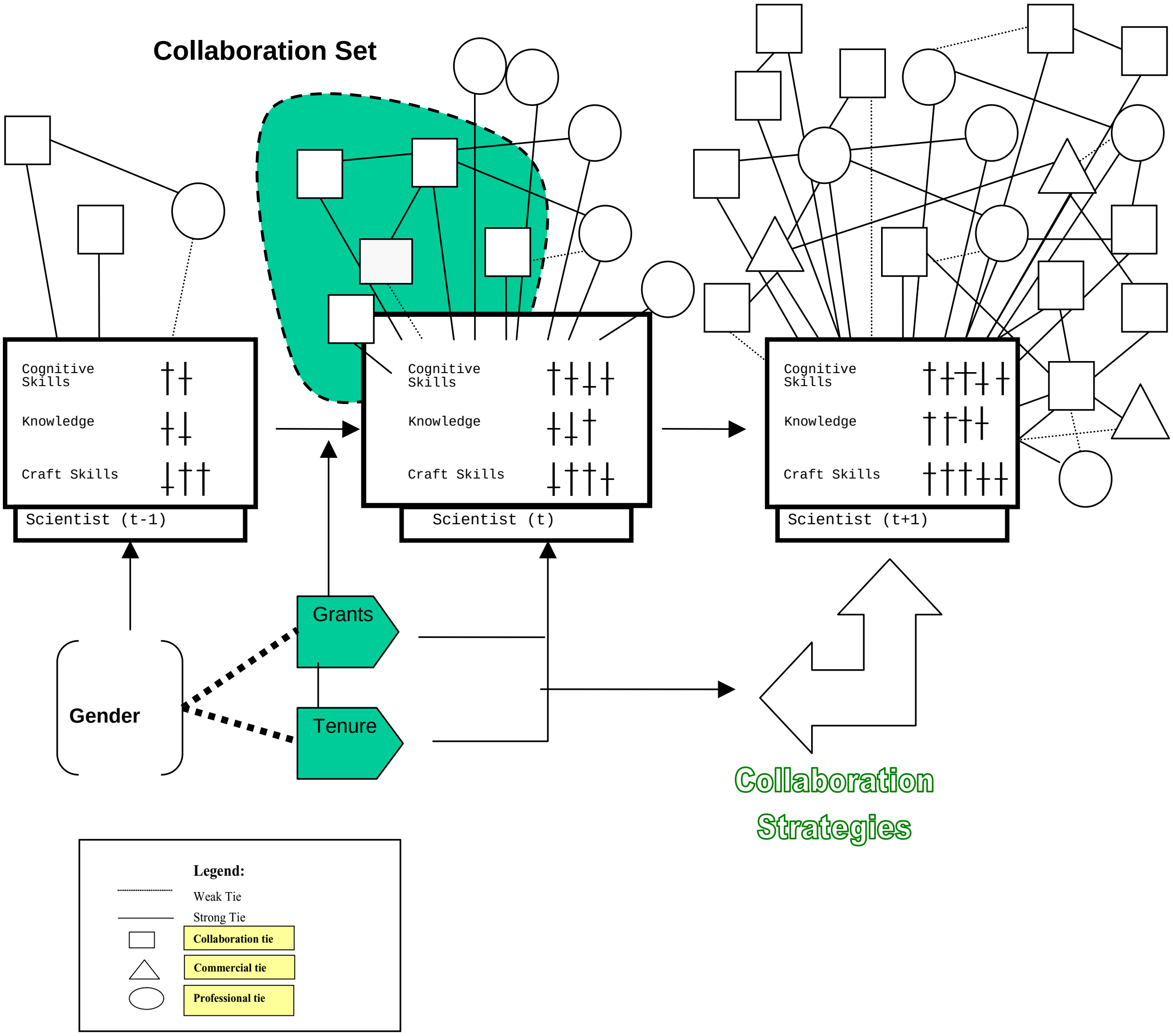

Fig. 1. Life cycle of collaboration and S&T human capital.

commercial ties and professional ties. Clearly there is overlap among these categories and the broad categories mask sophisticated, detailed behaviors. But our basic point is to show collaboration in the context of S&T human capital. From this model we can derive that collaboration is part and parcel of S&T human capital, that it is a particular sort of social tie that both draws from human capital endowments and enriches them, that collaboration enables and is re-enforced by other sorts of ties.

Our data provide us with information about the numbers of research collaborations of various types and with various categories of people. We asked respondents to tell us about the reasons why they choose to collaborate and from those responses, we develop a set of "collaboration strategies" representing those motivations. Thus, the chief dependent variables for this study pertain to the number of collaborations, the types of people with whom the respondents collaborate (e.g. numbers and percentages by rank, gender, and location) and the strategies for collaboration. Among the strategies, we are especially interested in knowing about collaborations motivated by the desire to serve as mentors to graduate students and junior colleagues.

We use the same simple model for the three sets of dependent variables (though an extended model for one). In each case we are interested in the impacts of gender, grants, and tenure on various aspects of collaboration. In articulating the hypotheses, we provide information about the measurement of key variables.

4.1. Hypothesis: number of collaborators

H1. Number of collaborators is positively associated with (1) gender (1: male, 0: female), (2) dollar size of grants, and (3) tenure (controlling for effects of scientific discipline).

Despite its limitations (Katz and Martin, 1997), our measures of self-reported collaborations provide the advantage of permitting the respondent to determine which relationships are worthy of being deemed collaborations.[2]

Our reasoning for this hypothesis is that persons who are principal investigators with large grants will have more collaborators in part because they have more work, more active projects, and a higher rate of productivity. Related, many of the projects receiving grants are by their nature large, complex and specialized and performed with teams (Seglen and Aksnes, 2000). We expect that individuals with large grants will more often serve as mentors in their collaborations because they will more often be surrounded by graduate students and post-doctoral researchers and thus, will have greater exposure and opportunity.

The relationship of tenure to number of collaborators is, we feel, explained by the fact that those with tenure have developed increased levels of S&T human capital which both require and enable additional collaboration. We expect females to have few collaborators in part because there are fewer females available for them to collaborate with (in almost all cases) and collaboration is related to shared attributes of many types, including gender (Hagstrom, 1965). Not only is the “supply” more limited but perhaps the “demand” will be depressed if men are more comfortable collaborating with men.

In this hypothesis and others, we control for scientific fields. Studies (Garg and Padhi, 2001; Liang et al., 2001; Wagner-Dobler, 2001) have shown that collaboration dynamics vary across fields.

4.2. Hypothesis: percentage of female collaborators

H2. The percentage of female collaborators with whom one collaborates is (1) negatively associated with gender (1: male, 0: female), (2) not significantly associated with dollar size of grants, and (3) positively and significantly associated with tenure (controlling for effects of scientific discipline).

Previous studies of collaboration have shown that even though women scientists are generally just as likely to collaborate as men scientists, they have significantly fewer numbers of different collaborators (Cole and Zuckerman, 1984; Cameron, 1978). We hypothesize that women will have fewer collaborators, partly due to constraining social dynamics. Mary Frank-Fox has contended that we must consider how collegial interaction, work climate, collaborative opportunities, and institutional settings might affect the productivity rates of men and women in academic settings (Fox, 1991, 1985). Within academia, major decisions about rank, status, and position are typically decided in quite informal settings within the collegial network (Fox, 1991).

In one respect, the formal status of women graduate students is equal to men. Studies show that men and women graduate students are almost equally likely to receive financial support during graduate school (Centra, 1974; National Research Council, 1983). But women report more isolation from fellow graduate students, faculty members, and research advisors throughout their graduate training than men do (Centra, 1974; Holmstrom and Holmstrom, 1974; Kjerulff and Blood, 1973).

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[2] The data for total number of collaborators was simply the sum of the responses by category of collaborator. The item on the questionnaire: *For the past twelve months, please tell us the number of people in each of the following categories with whom you have had research collaborations: Male university faculty; Male graduate students; Male researchers who are not university faculty or students; Female university faculty; Female graduate students; Female researchers who are not university faculty or students.*

4.3. Hypothesis: "cosmopolitan" collaboration patterns

H3. More "cosmopolitan" collaboration patterns is positively associated with (1) gender (1: male, 0: female), (2) dollar size of grants, and (3) tenure (controlling for effects of scientific discipline).

In our questionnaire, we asked respondents to tell us the percentage of their work time spent working alone, with the immediate work group, with researchers in the same university but not the same group, with researchers in other US universities, with researchers in US industry, with researchers in US government laboratories and researchers in other nations.[3] From these responses we developed a scale of the extent to which researchers collaboration patterns are "cosmopolitan." Thus, one who spent most of her time working alone and in the immediate work group would be less cosmopolitan in collaboration than one who spent most of her time collaborating with researchers in industry and with researchers in other nations.

We hypothesize that females will have somewhat less cosmopolitan collaboration patterns. In part, this is due to the greater barriers women face in being included in social networks and invisible colleges (Fox, 1991, 1985). Sonnert (1995) found that women scientists often felt exempt from many informal social events. Sonnert explained that it was a disadvantage for women to be absent from these events because more than half of his interviewees believed that social interactions with peers had an effect on the path of a scientist's career.

We expect those with larger grants will be more cosmopolitan in their collaborations. Many of the largest grants actually require or at least encourage inter-institutional cooperation and thus, those involved should, all else equal, more extensive collaboration networks. Further, in some cases grants acquisition is an important primary motive in establishing collaborations (Smith, 1958; Clarke, 1967; Heffner, 1981; Beaver, 2001). Finally, large grants are often associated with large equipment and joint access to equipment is often an important motive for collaboration (Meadows and O'Connor, 1971; Meadows, 1974; Melin, 2000; Thorsteinsdottir, 2000; Beaver, 2001).

We anticipate that tenured faculty will be more cosmopolitan in their collaborations. Tenured faculty will have developed greater S&T human capital. In the first place, tenure faculty have "survived" the vetting processes and in all likelihood S&T human capital has been both a cause of that positive outcome and a result of time, experience and career success (Stephan and Levin, 2001; Mangematin, 2001).

4.4. Collaboration strategies

H4. Scientists will vary with respect to the factors influencing their decisions to collaborate; determinants of collaboration strategies include (1) gender, (2) grants, and (3) tenure. Those pursuing "mentoring" motivated strategies (i.e. helping graduate students and junior colleagues), (1) are as likely to be women as men; (2) have larger levels of grants funding; (3) have tenure; (4) are more cosmopolitan in their collaborations; (5) have a higher percentage of graduate student collaborations; (6) have a higher percentage of female collaborators; (7) have a favorable orientation toward industrial work.

Despite some concern with the motives for scientists' collaboration, few studies have treated collaboration as a strategic choice (Katz and Martin, 1997). While many institutional and contextual factors govern collaboration, there is still considerable discretion involved. We asked respondents to indicate the importance of a variety of factors with respect to their decision to collaborate.[4] These thirteen factors included such common motivations as the desire to help graduate students, to have complementary re-

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[3] The preface to the question: While most scientists spend some time working entirely on their own, much work is also performed in research groups. For the *past twelve months*, could you please estimate the percentage of your research-related work time devoted to each of the following categories [*Note: should add to 100%*].

[4] The preface to the response choice: In this section, we define research collaboration as "working closely with others to produce new scientific knowledge or technology." In your *current* career stage, how important are each of the following factors in your decisions to collaborate? [*Please put an 7on the appropriate column.* The choice was Likert scale type: "very important," "somewhat important," "not important," "not relevant."

search skills, and to have collaborators who stick to schedule.

Our chief interest is in collaboration motives related to mentoring: the desire to help junior colleagues and graduate students. These motives seem especially likely to increment S&T human capital, particularly at the outset of scientists' careers. Long and McGinnis (1981) found that one of the most beneficial acts that an advisor can provide doctoral students is to collaborate in publishing before the student graduates.

We expect that mentors will have a higher percentage of female collaborators chiefly because they are more likely than others (by virtue of a mentor orientation) to recognize that women are especially in need of increased mentoring opportunities. Finally, we anticipate that mentors will have a more positive view toward industry because they will have the task of helping find jobs for graduate students and since doctoral level scientists are increasingly drawn to industry jobs, their mentors will have more industry ties (Behrens and Gray, 2000).

5. Descriptive results

The mean number of (total) collaborators for all participants in our study is 13.76 (with a median of 12 collaborators). Males in the sample tend to have slightly more collaborators, with a mean of 14.04 for males and 12.02 for females. Not too surprisingly, the number of collaborators a researcher has increases with job rank. Post-docs had the fewest collaborators at a mean of 9.87. Non-tenure track faculty, research faculty and research group leaders had a mean of 10.67, 12.09, 12.22 collaborators, respectively. Respondents in the sub-disciplines of materials engineering (average of 19.17), zoology (average of 18.17), other engineering (average of 17.75), electrical engineering (average of 17.34), and chemistry (average of 14.95), had the highest average number of collaborators. On the other hand the sub-disciplines with the lowest average number of collaborators included general biology (average of 6.91), other biological and life sciences (average of 7.81), other disciplines (average of 9.39), civil engineering (average of 10.87), and industrial engineering (average of 11.00).

6. Findings

6.1. Number of collaborators

In modeling the number of collaborators we examine independent variables and a series of dummy variables. We hypothesized that number of collaborators is a function of tenure status of faculty (tenured or not tenured), the grants variable discussed above, and gender. We included a series of dummy variables for scientific field. Table 1 provides the OLS regression results. In this regression and subsequent ones, we show the field dummies only when they are significant. For this regression model, none of the scientific field variables are significant; however, the grant variable is significant and the regression coefficient is positive and in the expected direction. Therefore, as grant funding increases, the total number of collaborators increases. The ANOVA results of this regression indicate that the model is statistically significant with an F-value of 2.616 ($P < 0.0001$). Neither gender nor tenure status is significant in this model.

6.2. Percentage female collaborators

In considering issues of S&T human capital there is particular interest in collaboration opportunities of

Table 1
OLS regression analysis (dependent variable: total number of collaborators)[a]

Independent variables[b]	Unstandardized coefficients			t-value	P-value
	B	S.E.	β		
Constant	8.58	3.24		2.65	0.009
Tenured faculty	0.54	1.11	0.03	0.49	0.626
Grant variable[c]	1.47	0.39	0.21	3.81	<0.001
Gender	−0.06	1.53	0.00	−0.04	0.966

[a] ANOVA: $F = 2.616$ ($P < 0.0001$).

[b] Additional independent variables include the following insignificant dummy variables for degree fields (dummy variables significant at 0.05 level for fields are shown in the table): biochemistry/biophysics, general biology, zoology, other biological and life sciences, computer science, chemical engineering, civil engineering, electrical engineering, industrial engineering, materials engineering, mechanical engineering, other engineering, health professions and related sciences, mathematics, chemistry, physics, other physical sciences, psychology, and other disciplines.

[c] 0: No current grant; 1: US$ 1–227,500; 2: US$ 227,500–450,000; 3: US$ 450,000–1,000,000; 4: over US$ 1,000,000.

Table 2
OLS regression analysis (dependent variable: percent female collaborators)[a]

Independent variables[b]	Unstandardized coefficients			t-value	P-value
	B	S.E.	β		
Constant	26.17	5.30		4.94	<0.001
Tenured faculty	0.39	1.84	0.01	0.21	0.832
Grant variable[c]	−0.22	0.64	−0.02	−0.35	0.728
Gender	−5.52	2.50	−0.12	−2.21	0.028
Other biological and life sciences	14.41	5.84	0.23	2.47	0.014
Health professions and related sciences	17.97	7.71	0.15	2.33	0.020
Chemistry	10.99	5.56	0.21	1.98	0.049
Psychology	22.07	7.19	0.21	3.07	0.002

[a] ANOVA: $F = 2.697$ ($P < 0.0001$).

[b] Additional independent variables include the following insignificant dummy variables for degree fields (dummy variables significant at 0.05 level for fields are shown in the table): biochemistry/biophysics, general biology, zoology, computer science, chemical engineering, civil engineering, electrical engineering, industrial engineering, materials engineering, mechanical engineering, other engineering, mathematics, physics, other physical sciences, and other disciplines.

[c] 0: no current grant; 1: US$ 1–227,500; 2: US$ 227,500–450,000; 3 = $450,000–1,000,000, 4 = over $1,000,000.

junior research and female researchers. Our descriptive results (not reported in detail here) showed that female researchers who hold the rank of non-tenure track faculty, research faculty, tenure track faculty, research group leader, or tenured faculty collaborate with a higher percentage of other females than male researchers in the same ranks do. With regard to collaboration with graduate students, tenure track female faculty and tenured male faculty are the most likely to collaborate with graduate students.

Especially noteworthy is the extent to which non-tenure track females collaborate with other females (83.33%). In no other group do females comprise more than 41.5% of collaborators (female research faculty). Possibly, women seeking jobs, tenure, or promotion are more likely to collaborate with males. An alternative hypothesis is that these groups are less likely to receive collaboration invitations and since most of the scientists are male, most invitations would, at least from a probability standpoint, likely be proffered by males.

Table 2 provides the results of a regression of the percent female collaborators dependent variable upon the independent and dummy variables. In this regression, four scientific field dummy variables were significant and the regression coefficients for those dummy variables were positive. Researchers in the fields of psychology, chemistry, health professions, and other biological and life sciences are more likely to have a higher percentage of female collaborators (and of course, these fields have a high percentage of females than found in the other physical and natural sciences and much higher than in engineering).

The other significant variable in this regression was gender, which had a negative regression coefficient. Since male is coded “1” and female “0,” this indicates that women are likely to collaborate with women. This is in line with expectations and previous research.

6.2.1. The collaboration cosmopolitanism scale

Using the data on the location of collaborators, we developed a summary “cosmopolitan scale.” We were interested in developing this aggregate scale in order to use it as a dependent variable in the regression models reported below. The cosmopolitan scale is a measure of how close or far away a participant’s collaborators are (i.e. a participant with more collaborators in foreign countries would rank higher on the cosmopolitan scale than a participant with collaborators only in the US). This is not, of course, a true physical distance scale since, for example, a collaborator foreign country may be closer than a collaborator in another part of the US. The scale was calculated by multiplying the fraction of their time each participant spent working with a type of collaborator by the cosmopolitan rank of that variable (measured on a 1–5 scale).[5]

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[5] Research time spent working alone is given a value of 0 on the cosmopolitan scale. Similarly, research time spent working with members of the same work group is assigned a value of 1

Table 3
Cosmopolitan scale by gender, rank, and grant amount

Researcher attributes	Mean cosmopolitan scale[a]	N
All participants	1.58	440
Female	1.46	55
Male	1.60	385
Post-doc	1.13	18
Non-tenure track	1.32	16
Research faculty	1.49	34
Tenure track	1.52	68
Research group leader	1.73	11
Tenured	1.63	247
Academic administrator	1.66	29
No current grants	1.38	103
Current grant amount (first quartile) under US$ 227,500	1.48	84
Current grant amount (second quartile) US$ 227,500–450,000	1.61	96
Current grant amount (third quartile) US$ 450,000–1,000,000	1.69	78
Current grant amount (fourth quartile) over US$ 1,000,000	1.77	81

[a] The scale was computed by multiplying the fraction of their time each participant spent working with a type of collaborator by the cosmopolitan rank of that variable (measured on a 1–5 scale). The result is that a person who works solely alone will have a cosmopolitan scale of 0. On the other end of the scale, a person who works with people in other nations only could potentially reach the maximum cosmopolitan scale value of 5.

Table 3 presents the results of the cosmopolitan scale for researchers by gender, rank, and current grant amount. The table demonstrates that male researchers are slightly more cosmopolitan than their female counterparts and that the research group leaders are the most cosmopolitan. As would be expected, the post-doc is the least cosmopolitan rank. Also, the cosmopolitan scale is directly proportional to current grant amount with the least cosmopolitan researchers being those who have no grants. The cosmopolitan scale increases as grant size increases.

We examined results of the cosmopolitan scale by discipline. The five most cosmopolitan fields are zoology, mathematics, other engineering, materials engineering, and psychology. The six least cosmopolitan fields are industrial engineering, health professions, biochemistry, other biological and life sciences, and mechanical engineering (tied with general biology).

6.3. Collaboration cosmopolitanism

The dependent variable for the third regression was the cosmopolitan scale (see Table 4). The grant variable is significant and the coefficient has the expected positive sign. As anticipated, those with more grant money have a more diverse and cosmopolitan set of collaboration choices. If grants actually *cause* this behavior, the policy significance is noteworthy. Cosmopolitanism is a close conceptual cousin to S&T human capital and these findings at least suggest that grants have a strong impact on enhancing

Table 4
OLS regression analysis (dependent variable: cosmopolitan scale)[a]

Independent variables[b]	Unstandardized coefficients			t-value	P-value
	B	S.E.	β		
Constant	1.19	0.20		6.11	<0.001
Tenured faculty	0.05	0.06	0.04	0.88	0.378
Grant variable[c]	0.10	0.02	0.24	4.81	<0.001
Gender	0.08	0.09	0.04	0.93	0.352
Mathematics	0.59	0.30	0.11	1.97	0.049

[a] ANOVA: $F = 3.089$ ($P < 0.0001$).

[b] Additional independent variables include the following insignificant dummy variables for degree fields (dummy variables significant at 0.05 level for fields are shown in the table): biochemistry/biophysics, general biology, zoology, other biological and life sciences, computer science, chemical engineering, civil engineering, electrical engineering, industrial engineering, materials engineering, mechanical engineering, other engineering, health professions and related sciences, chemistry, physics, other physical sciences, psychology, and other disciplines.

[c] 0: no current grant; 1: US$ 1–227,500; 2: US$ 227,500–450,000; 3: US$ 450,000–1,000,000; 4: over US$ 1,000,000.

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and time spent working with others in the same university, but a different work group is assigned a value of 2. Working with researchers at a different university counts as a value of 3 on the cosmopolitan scale and working with others in industry or government laboratories are both assigned a value of 4. Lastly, working with researchers in other nations counts as a value of 5 on the cosmopolitan scale. For instance, if I work alone 10% of the time, within my own work group 20% of the time, with scholars at other universities 30% of the time, with industry 10% of the time, government 10% of the time and with scholars at other nations 20% of the time, my cosmopolitan score would be 2.6 (i.e., $0.1(0) + 0.2(1) + 0.3(2) + 0.1(4) + 0.1(4) + 0.2(5)$). The result is that a person who works only alone will have a cosmopolitan scale of 0. At the other end of the scale, a person who works only with people in other nations could have the maximum cosmopolitan scale value of 5.

S&T human capital. But, of course, getting a grant is not a randomly distributed variable, obtaining several large grants probably implies something about scientific ability and reputation which, in turn, likely has reciprocal effects with S&T human capital.

Somewhat surprisingly, only one of the scientific field dummies is positive. Researchers in the area of mathematics are more likely to be cosmopolitan in their collaboration choices. This may well be because their numbers are quite small in most universities and they are unlikely to have close colleagues working on similar problems. Also, many sub-disciplines within mathematics are quite theoretical, rather than experimental. As Price (1963), Meadows and O'Connor (1971), and Gordon (1980) have shown experimentalists tend to collaborate more than theoreticians. The results of this regression might imply a further argument that theoreticians also are more "cosmopolitan" in their collaborations than experimentalists are. Of course, this hypothesis would have to be explored in more depth in future work to be confirmed.

6.4. *Collaboration strategies*

Since our interest is in collaboration strategies rather than single motives, it is important to understand the dimensional properties of motives, conceptualizing clusters of inter-related motives as strategies. For the purposes of creating a reconstructed set of variables to be used as summary indices, factor analysis seemed an appropriate choice. Before examining the results of our hypothesis, we first report on the development of collaboration strategy scales.

6.4.1. *Collaboration strategies: results of factor analysis*

One of our chief objectives in this study was to identify strategies of collaboration, looking especially for archetypal strategies. Our expectation was that certain collaboration strategies might be especially beneficial from the standpoint of developing S&T human capital. In particular, senior colleagues working with graduate students, post-docs and junior untenured colleagues is likely to pay dividends for whole scientific fields as new generations of scientists are socialized, develop skills and develop network ties.

We asked respondents to tell us the relative importance to their own collaboration decisions of a large number of hypothesized collaboration determinants we provided in our mailed questionnaire.[6] Respondents were told "we define research collaboration as 'working closely with others to produce new scientific knowledge or technology.' In your *current* career stage, how important are each of the following factors in your decisions to collaborate?" The response choices were "very important," "somewhat important," "not important," and "not relevant."

To reduce the data, as well as to infer possible strategies from aggregations of individual items, we factor analyzed the responses. The factor analysis was based on the 13 Likert-type statements that the participants responded to which categorized the reasons why the respondent collaborates with other researchers. The 13 statements are listed in Table 5 as "Variables Describing Collaboration Preferences." The factor analysis was completed using principal components analysis with a varimax rotation, imposing an orthogonality constraint (i.e. each of the factor dimensions is statistically independent of the others). This was appropriate inasmuch as our interest was not only in representing the original variance in the factor matrix, but also in developing indices useful in subsequent analysis.

We extracted factor dimensions to the level of one eigenvalue (i.e. with the constraint that any one dimension extracted would explain at least as much variance in the original factor matrix as accounted for by any single variable). Using this procedure, the results of the factor analysis yielded six dimensions, six independent collaboration strategy types. We labeled the respective dimensions based on the factors loading strongest.

The "Taskmaster" is the first type of collaborator and these researchers tend to choose a collaborator based on work ethic attribution and whether or not the

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[6] The choices included: Length of time I have known the person; responding to requests of my administrative superiors; Interest in helping junior colleagues; desire to work with researchers who have strong scientific reputations; desire to work with researchers whose work skills and knowledge complement my own (rather than overlap with my skills); quality and value of my previous collaborations with the person; interest in helping graduate students; the extent to which working with the individual is fun or entertaining (apart from the work itself); desire that the collaborator be highly fluent in my language; desire to work with researchers from the same country of origin; the collaborator should have a strong work ethic; the ability of the collaborator to stick to a schedule; practices for assigning credit (e.g. order of authorship).

Table 5
Principal components analysis of collaboration preferences

Variables describing collaboration preferences	Component[a]					
	1	2	3	4	5	6
Length of time that respondent has known person					0.72	
Someone in administration requested the collaboration				0.67		
Collaborate to help junior colleagues			0.83			
Collaborator has a strong science reputation				0.78		
Respondent and collaborator have complementary skills						0.82
The quality *of previous collaborations with a person*					0.57	
Collaborate to help graduate students			0.80			
Collaborator is fun or entertaining					0.62	
Collaborator is fluent in respondent's language		0.80				
Respondent and collaborator are of same nationality		0.84				
Collaborator has strong work ethic	0.79					
Collaborator sticks to the schedule	0.81					
Collaborator knows how assign credit						

Factor I: "Taskmaster"; Factor II: "Nationalist"; Factor III: "Mentor"; Factor IV: "Follower"; Factor V: "Buddy"; Factor VI: "Tactician".

[a] Principal components analysis; rotation method: varimax.

person sticks to a schedule. The "Nationalist" is the second type of collaborator and these researchers tend to choose collaborators who are fluent in their own language and are of the same nationality. "Mentors," the third type of collaborator, are motivated to help junior colleagues and graduate students by collaborating with them.

The "Follower" is the fourth type of collaborator. These researchers choose collaborators mostly because someone in administration requested that they work with the collaborator and the potential collaborator has a strong science reputation. The "Buddy" is the fifth type of collaborator and these researchers choose collaborators based on the length of time they have know the person, the quality of previous collaborations and whether or not the collaborator is fun and entertaining. The final type of collaborator is the "Tactician." "Tacticians" choose collaborators based on whether or not the collaborator has skills complementary to their own.

6.4.2. Findings: collaborator strategies

After completing the factor analysis, we calculated factor scores (coefficients relating the respondents to the dimensions) facilitating the use of the collaboration strategy dimensions as dependent variables. While we report results for each of the collaboration strategies represented in the respective dimensions, our chief focus is on the Mentor strategy, the strategy we view as particularly crucial to S&T human capital accumulation and diffusion.

6.4.3. Predicting a mentor collaboration strategy

For all the strategy variables we tested the basic regression model (with tenure, gender, grants, and discipline dummies), but for the Mentor strategy we tested an extended model that includes all the variables of the basic model (except the dummies) as well as: (1) percent of collaborators that are female, (2) number of graduate students the respondent collaborates with, (3) position on the cosmopolitan scale, (4) motivation to "pursue research for greater industrial applications or industry ties" and (5) responses to "I would be very interested in starting a new company."

The reasoning behind the extended model is straightforward. On the one hand we are interested in the extent to which an avowed Mentor strategy matches up to the reality of working with graduate student and female collaborators. Since these are groups that could, arguably, benefit especially by enhanced opportunities for S&T human capital, we are interested to see if Mentors tend disproportionately to work with these groups. We are also interested in the extent to which an industry orientation coincides with a Mentor relationship. The reasoning here is that persons with an industry orientation are quite likely to have diverse social and professional networks and thus, to enhance S&T human capital by providing a

Table 6
Extended regression model for mentor (dependent variable: mentor)[a]

Independent variables	Unstandardized coefficients			t-value	P-value
	B	S.E.	β		
Constant	−1.73	0.28		−6.26	<0.001
Tenured faculty	0.61	0.11	0.30	5.65	<0.001
Grant variable[b]	0.02	0.04	0.02	0.39	0.697
Gender	0.03	0.15	0.01	0.18	0.856
Percent of female collaborators	0.01	0.00	0.19	3.62	<0.001
Cosmopolitan Scale	0.00	0.09	0.00	0.04	0.969
Number of grad student collaborators	0.03	0.01	0.16	3.01	0.003
Pursue research for greater industrial applications or industry ties	0.23	0.07	0.19	3.60	<0.001
I would be very interested in starting a new company	0.10	0.06	0.10	1.85	0.066

[a] ANOVA: $F = 11.23$ ($P < 0.0001$).

[b] 0: no current grant; 1: US\$ 1–227,500; 2: US\$ 227,500–450,000; 3: US\$ 450,000–1,000,000; 4: over US\$ 1,000,000.

broader range of network ties. Incidentally, this sample is especially apt for understanding the role of a business orientation because many of the respondents are in Science Centers or Engineering Research Centers that focus explicitly on developing industry ties.

Table 6 provides the results for the extended model predicting the Mentor strategy.[7] We can see from the results that tenured faculty are more likely to evince a Mentor strategy but this is perhaps, at least in part, a function of mentoring opportunity. Post-docs do not often have the chance to mentor. The Mentor strategy is not related to gender. It would be interesting to know if females are more attracted to a Mentor strategy when those mentored are females. But we have not direct data pertaining to this question (but the earlier finding suggesting that women are somewhat less likely to collaborate with women seems to hold little promise that women are more attracted to a female mentoring).

Perhaps surprisingly, the Grants variable is not significant. With the other variables in the equation (especially tenure) the effect of Grants is likely suppressed. Moreover, most people in the sample have grants and so, we cannot conclude that grants have no impact on a Mentor strategy, only that the size of grants seems to have no bearing.

The results show that those professing a Mentor strategy for collaboration are, indeed, more likely to work with females and to collaborate with more graduate students. It is certainly not surprising that Mentors are especially likely to work with graduate students; the result is more a test of convergent validity than anything else. However, there is no obvious reason to expect that Mentors would be more likely to work with women. One possibility is that there are more mentoring opportunities among women, who in this sample and in the general population of university-based scientists tend to be more junior. Another possibility is simply that some researchers recognize the need to help women develop S&T human capital and set about in systematic pursuit of that goal. Results reported earlier show that this finding is not likely caused by women seeking out other women as mentors and or understudies. Men are somewhat more likely to have female collaborators.

It is noteworthy that an industry orientation is related to a Mentor strategy. Those who report an interest in pursuing industrial applications and industry ties are more likely to be Mentors. The variable pertaining to interest in starting a new company is not significant at the 0.05 level, but is significant at the 0.10 level and in the expected direction. It is difficult to know exactly why an industry orientation is related to a Mentor strategy. It could be related to selection effects of various types, or to different mentoring experiences, or to expanded contacts, or to the different workings of different networks (academic science versus industry science).

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[7] This model does not include the field dummies, but a similar model including the dummies showed that a few of the field dummies are significant: zoology, electrical engineering and “other physical sciences” are positively associated with the Mentor strategy.

6.4.4. Alternative collaboration strategies: "Tactician"

In analyses not reported here, we examined models for each of the other collaboration strategies. We do not present the tables for these alternative collaboration strategies, in part because the findings are not impressive or robust and in part because our chief focus is on the strategy seemingly most relevant to S&T human capital, the Mentor strategy. (The additional findings are available from the authors.) We briefly summarize these results.

Using the variables grants, tenure and gender, as well as the scientific field controls, only the results for the "Tactician" strategy proved significant. As shown in Table 7, several factors predict this strategy, including: the grant variable, gender, general biology, chemical engineering, materials engineering, mechanical engineering, other engineering, health professions, chemistry, physics, other physical sciences, and psychology. Therefore, males are more likely to be "Tacticians" as are individuals with larger grants. Also, researchers in the above mentioned list of fields are more likely to use the Tactician mode of collaboration. It is important to note that the use of a single variable factor dimension as a dependent variable is controversial and thus, the findings for this analysis must be treated with special caution.

7. Conclusions: summary and policy implications

Our interest in scientific collaboration is largely an instrumental one. We wish to understand the ways in which collaboration affects scientists' and engineers' S&T human capital. From previous studies we assume that collaboration often has salutary effects with respect to socialization, training, transmission of know-how and just as important, the ability to develop the network ties and contacts so critical to scientists' and engineers' career success.

While we were not able to examine all the elements and relationships of the Life Cycle Model of Collaboration and S&T Human Capital (Fig. 1), we were able to shed some light on the determinants of collaboration and infer implications for S&T human capital. Before extending the discussion beyond our findings, we summarize the most important findings, including their implications for the hypotheses we developed and for our conceptual model.

Table 7
OLS regression analysis (dependent variable: Tactician)[a]

Independent variables[b]	Unstandardized coefficients			t-value	P-value
	B	S.E.	β		
Constant	−0.55	0.32		−1.72	0.086
Tenured faculty	0.15	0.11	0.07	1.37	0.170
Grant variable[c]	0.09	0.04	0.13	2.49	0.013
Gender	−0.43	0.15	−0.14	−2.92	0.004
General biology	0.92	0.42	0.15	2.19	0.029
Chemical engineering	0.93	0.33	0.28	2.77	0.006
Materials engineering	1.12	0.42	0.18	2.67	0.008
Mechanical engineering	0.88	0.37	0.20	2.39	0.017
Other engineering	0.72	0.36	0.17	2.01	0.045
Health professions and related sciences	0.84	0.41	0.14	2.05	0.041
Chemistry	0.75	0.33	0.23	2.24	0.026
Physics	0.66	0.33	0.20	1.98	0.049
Other physical sciences	0.81	0.37	0.17	2.19	0.029
Psychology	1.06	0.42	0.17	2.52	0.012

[a] ANOVA: $F = 1.972$ ($P = 0.006$).

[b] Additional independent variables include the following insignificant dummy variables for degree fields (dummy variables significant at 0.05 level for fields are shown in the table): biochemistry/biophysics, zoology, other biological and life sciences, computer science, civil engineering, electrical engineering, industrial engineering, mathematics, and other disciplines.

[c] 0: no current grant; 1: US$ 1–227,500; 2: US$ 227,500–450,000; 3: US$ 450,000–1,000,000; 4: over US$ 1,000,000.

An especially important finding pertains to the delineation of collaboration strategies. The dimensional properties of collaboration variables were easily interpretable in terms of factor-based strategies. Among the "Taskmaster," "Nationalist," "Follower," "Buddy," "Tactician," and Mentor" strategies, our chief interest is in the latter, the one we assume has particularly important implications for S&T human capital. Regression results sustained many elements of our hypothesis about the Mentor strategies. Those pursuing a Mentor strategy are likely to:

1. be tenured;
2. more likely to work with graduate students and junior faculty (as professed by the strategy);
3. more likely to collaborate with women; and
4. have a favorable view about industry and research on industrial applications.

We feel these findings are rife with policy implications. It is particularly important that mentors are more likely to collaborate with women. If our assumptions, and previous researchers' (e.g. Fox, 1991; Cameron, 1978) are correct, about the barriers women scientists face in linking to the social networks that transmit S&T human capital, identifying individuals who employ a Mentor strategy to collaboration could be a useful means of enhancing scientific effectiveness and productivity. Similarly, the finding that a Mentor strategy is associated with a favorable orientation to industry work has important implications for cooperative research. An examination of our original data showed that those tenured professors who have actually worked in industry at some point in their careers are more likely to have a Mentor strategy for collaboration.

We were somewhat surprised to find that our research Grants variable was not significantly associated with the Mentor strategy. This finding is confounded, however, by the fact that nearly 90% of the respondents have grants; it is quite possible that having a grant is more important to a Mentor strategy than the size of one's grants (which our variable measured).

Regarding the number of reported collaborators, our hypothesis was sustained only in part. Those who have larger grants have more collaborators (though the relationship is not entirely linear). Those with no current grants (11 collaborators) are well below the mean (14). Tenure and gender seem not to have strong independent effects on number of collaborators (as reported in the regression analysis), though the descriptive data show that females have somewhat fewer collaborators (12) than males (14) and that tenured faculty (14.5) are slightly above the mean (14).

Considering the percentage of female collaborators, we found, not surprisingly, that female scientists have a somewhat higher percentage (36%) of female collaborators, than males have (24%). There are great differences, however, according to rank, with non-tenure track females having 84% of their collaborations with females. By contrast, tenured females collaborate with only 34% females. One especially interesting finding, not easily explained, is that tenure-track (but untenured) females have collaboration patterns almost identical to tenured males.

Our findings concerning collaboration cosmopolitanism may have implications for policy-makers seeking to stimulate cross-institutional collaboration. An important finding is that most researchers are not particularly cosmopolitan in their selection of collaborators—they tend to work with the people in their own work group. Supporting our hypothesis, more cosmopolitan collaborators tend have large grants. The other variables in the model, tenure and gender, have only trace effects, not statistically significant.

Returning to our conceptual model, our results suggest that the hypothesized determinants of S&T human capital endowment, gender, grants, and tenure, affect the two collaboration strategies that have most obvious implications for S&T human capital, Mentor and Tactician (which is, in a sense, the "self-interested" strategy). Taking gender as a precursor variable seems to make sense in terms of the results. Women do, indeed, have different experiences with collaboration and S&T human capital and often these experiences are unfavorable compared to men.

From a policy standpoint, the effect of grants is particularly important. The results are somewhat complicated by the fact that almost 90% of the respondents have grants, but it does appear that grants have significant implications for shaping S&T human capital as exhibited in the relationships to cosmopolitan collaboration and number of collaborators.

In our judgment, the results are sufficiently encouraging to justify additional inquiry along the same lines. In particular we would hope to see research delving more deeply into the relationship of grants to collaboration and S&T human capital. Are there threshold sizes that have effects? What are the different implications of traditional investigator-led grants versus centers grants and cooperative agreements? We are particularly anxious to follow up on a theme just hinted at here—the salutary effects of industry work and collaboration on S&T human capital. There is a need for a better model of the impacts of gender on collaboration and S&T human capital. What are the external (e.g. family circumstance) factors that affect collaboration and do these have implications for S&T human capital? How do male mentors differ from females? How do mentors of women different than the mentors of men? The answers to such questions seem to bear mightily on S&T human capital and ultimately, on the social health, well-being and productivity of scientists.

We would particularly like to know more about the predictors of *successful* collaboration, especially as success pertains to S&T human capital (e.g. new network ties, increased know-how and tacit knowledge, experience in acquiring and managing resources). We expect that the nature of external network ties is quite different with respect to industry and science application networks than in traditional scientific networks and related, that different collaboration strategies may be effective. But this is not a question amenable to valid answer via mailed questionnaire.

The public policy relevance of our study is broad and diffuse, rather than narrow and specific. The chief implication is that it is important to ensure that collaborations generate S&T human capital. Under the procedures of some government agencies, research proposals get "points" for including graduate students and female and minority scientists and engineers. But it is important to ensure that this inclusion is neither window-dressing nor exploitive. The inclusion of early career and underrepresented scientists in funded projects does not insure that they will have collaboration opportunities and it does not ensure that the collaboration opportunities afforded will help them significantly to enhance their S&T human capital.

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