Strategic Management Journal, Vol. 18 (Summer Special Issue), 143–164 (1997)

HETEROGENEITY OF FIRM CAPABILITIES AND COOPERATIVE RESEARCH AND DEVELOPMENT: AN EMPIRICAL EXAMINATION OF MOTIVES

MARIKO SAKAKIBARA*
Anderson Graduate School of Management, University of California, Los Angeles, California, U.S.A.

This article proposes capability heterogeneity of R&D consortia participants as a condition to distinguish two competing motives for cooperative R&D: cost-sharing vs. skill-sharing. An analysis of 398 questionnaire responses from participants in Japanese government-sponsored R&D consortia finds that the relative importance of the cost-sharing motive in R&D consortia increases when participants' capabilities are homogeneous or projects are large, while the relative importance of the skill-sharing motive in R&D consortia increases with heterogeneous capabilities. The skill-sharing motive is likely to increase a firm's R&D spending, implying an additional consideration for management's evaluation of cooperative R&D participation, as well as adding a new public policy implication of cooperative R&D. ©1997 by John Wiley & Sons, Ltd.

INTRODUCTION

Cooperative R&D is an arrangement among a group of firms to share the costs and results of an R&D project. Cooperative R&D can be executed in many forms, including R&D contracts, R&D consortia, and research joint ventures. These forms are collectively referred to in this article as R&D consortia or cooperative R&D projects. In the economic literature, cooperative R&D is seen as a means to set cost-sharing and/or output-sharing rules for the participants in an R&D project in order to correct market failures which would otherwise prevent firms from conducting the socially optimum level of R&D. An organizational perspective, however, views cooperative R&D as a vehicle by which firms overcome their resource constraints through the learning of skills and capabilities from other participants. Two competing motives for participating in cooperative R&D arise from these different perspectives: cost-sharing vs. skill-sharing. The purpose of this article is to analyze under what circumstances one or the other of these two motives becomes relatively more important in R&D consortia. The focus of analysis is the relationship between these motives and the differences in the participating firms' capabilities, as well as differences in the structure of the underlying competition. I suggest that capability heterogeneity among the firms participating in the project can determine the motives for participation in R&D consortia. I also assess the roles that these two motives play in R&D investment. In particular, I show that the skill-sharing motive may increase R&D investment. This article suggests that skill-sharing R&D cooperation can be competition enhancing, while cost-sharing R&D cooperation can be competition suppressing in terms of their roles in R&D competition.[1]

Key words: cooperative R&D; alliances; capabilities; learning; complementary knowledge
*Correspondence to: Mariko Sakakibara, Anderson Graduate School of Management, University of California, Los Angeles, 110 Westwood Plaza, B508, Los Angeles, CA 90095-1481, U.S.A.

[1] This analysis concentrates on R&D consortia. There are alternative forms for firms to obtain R&D outcomes, including

CCC 0143–2095/97/S10143–22 $17.50

The distinction between the cost-sharing and the skill-sharing motives has important implications for management and public policy because current policy makers and other advocates of cooperative R&D tend to pursue the cost-sharing model. Japan is regarded as a forerunner in the practice of cooperative R&D. The most celebrated example is the VLSI (Very Large Scale Integrated circuit) project, conducted between 1975 and 1985, designed to help Japan catch up in semiconductor technology. All of the major Japanese semiconductor producers participated in this project. The perceived success of the VLSI project motivated other countries to emulate this 'Japanese style' of collaboration. The 1984 U.S. National Cooperative Research Act was enacted to relax antitrust regulations in order to allow the formation of research joint ventures. Major cooperative R&D projects followed, including SEMATECH in 1987, a consortium of semiconductor manufacturers, and the Department of Defense sponsored flat-panel display project in 1994. All of these developments appear to be aimed at achieving the VLSI project style, using a cost-sharing or catch-up model with single-industry cooperation. This project, however, is atypical of Japanese cooperative R&D.

Organizational economics and organizational theory document the difficulties involved in organizing cooperative ventures in general (Killing, 1983; Harrigan, 1985, 1986; Pucik, 1988; Borys and Jemison, 1989), and R&D consortia in particular (Doz, 1987; Hladik, 1988; Osborn and Baughn, 1990; Jorde and Teece, 1990). Though cooperative ventures and R&D consortia are increasing rapidly, and are considered as a vital alternative for a corporate strategy (Hergert and Morris, 1988; Hladik, 1988; Hagedoorn and Schakenraad, 1990), this article suggests that the R&D costs in a cooperative setting, in addition to the organization costs, should enter the calculations of managers who intend to participate in cooperative R&D.

Cooperative R&D has been examined empirically by only a few studies and comprehensive empirical research is almost nonexistent. There are many case studies (e.g., Katz and Ordover, 1990; Fransman, 1990; Murphy, 1991; Ouchi and Bolton, 1988; Dunning and Robson, 1988), but most treatments have been based on anecdotal evidence, or on the accounts of a few highly publicized cooperative R&D projects. A deeper understanding of cooperative R&D requires a more systematic, cross-sectional analysis. The focus of the past empirical research has been on the industry and firm characteristics of participants in cooperative R&D (Scott, 1988; Link and Bauer, 1987; Kleinknecht and Reijnen, 1992; Kodama, 1991; Shirai and Kodama, 1989) or on a simple comparison of two different sets of cooperative R&D (Aldrich and Sasaki, 1995). In general, the existing research on alliances does not provide any significant empirical evidence regarding the factors that determine cooperation, or on the likely outcomes of such cooperation (Smith, Carroll, and Ashford, 1995).

The issue of motives has not been extensively examined with a few notable exceptions. Brockhoff, Gupta, and Rotering (1991) found from their survey that the most important reason for cooperative R&D arrangements in Germany is the possibility of developing synergy from the exchange of complementary technical knowledge. Hagedoorn (1993) found from his analysis of a journal article data base that technology complementarity is one of the most frequently cited motives for technology cooperation. This literature, however, does not identify the conditions which drive different motives to cooperate in R&D. Building upon this literature, this article is a first attempt to analyze a large cross-section of cooperative R&D projects by considering both the motives to participate and the underlying firm capabilities and structure of competition. Japanese government-sponsored R&D consortia are examined in this article because of their importance in public policy debates. Given the qualitative nature of the issues, questionnaires were distributed to corporate R&D managers in order to gather information.

This article is organized as follows. The second section examines the existing literature to develop a model that integrates and contrasts cost-sharing and skill-sharing motives within the context of differences in firm capabilities. In the third section, the data on government-sponsored R&D consortia in Japan are described. The next two sections describe the research methods and the

in-house R&D or simple market transactions. Firms' choice of different modes of R&D execution is not a focus of this analysis, and so this analysis is 'conditional' in the sense that it examines firms which choose to participate in R&D consortia.

results obtained. In the final section, implications are drawn from the findings.

FRAMEWORK FOR ANALYSIS

Motives for participation in cooperative R&D: Cost sharing vs. skill-sharing

In the economic literature, firms' motives for participating in cooperative R&D can be divided into two major classes: reasons related to R&D, and reasons unrelated to R&D. There are two major R&D-related reasons: to enhance R&D productivity through cooperation on R&D inputs and to change the appropriability conditions of R&D outputs (Katz, 1993; Geroski, 1993). Reasons unrelated to R&D include improved market access through partners and the collection of government subsidies.

Past economic theoretical research that examines how cooperation in the R&D input market enhances R&D productivity focuses on three primary motivations for cooperation: fixed cost-sharing among R&D participants, the realization of economies of scale in R&D, and the avoidance of 'wasteful' duplication (Katz, 1986; D'Aspremont and Jacquemin, 1988; Choi, 1990; Katz and Ordover, 1990; Motta, 1992). All three are scale-based motives and they imply that the principal purpose of cooperative R&D is to set cost-sharing rules.

The emphasis on cost-sharing arises from the assumptions made regarding the nature of the firms' capabilities and the structure of competition. This literature typically assumes that firms are symmetrical in terms of their capabilities or knowledge, which implies that the cooperating firms come from a single industry. Firms seek to achieve a single R&D outcome, and it is implicitly assumed that there is only one efficient way to yield this outcome. The participant firms, therefore, benefit from this efficient, nonduplicative approach. The game is over once this outcome is achieved. A basis for these assumptions is the desire to obtain interesting equilibrium outcomes from the game theoretic models. As a result, however, this literature only addresses a limited range of cooperative activity.

In the organizational literature the motives for cooperation among firms are examined more extensively, and under quite different assumptions. Cooperation among firms can take many forms, such as joint ventures, consortia, long-term contracting, and licensing. Such cooperation is often referred to as alliances. Following Williamson (1991), alliances are defined as inter-organizational relationships in which the parties maintain autonomy but are bilaterally dependent to a nontrivial degree. Firms in alliances are often recognized to possess heterogeneous capabilities, and they may or may not be direct competitors in the product market. The resource-based view suggests that a firm can be conceived as a portfolio of core competencies (Prahalad and Hamel, 1990). Alliances can be viewed as opportunities for one partner to internalize the skills or competencies of the other(s) to create next-generation competencies (Hamel, 1991). Firms consist of a knowledge base, and this knowledge—particularly technological knowledge—is often 'tacit' (Polanyi, 1958) and not easily diffused across the firm's boundaries. An organizational vehicle, such as alliances, is required to effect this transfer (Kogut, 1988).

This learning function of alliances becomes especially important when firms try to enter a new business, to redefine their core industries, or when they respond to shifting industry boundaries. Firms whose activities are beginning to cross industry boundaries must acquire knowledge from other organizations in other industries. In this context, cooperative strategies can become an indispensable mechanism for learning (Westney, 1988; Kogut and Zander, 1992).

These learning-based arguments imply that a key objective of cooperative R&D is complementary knowledge or skill-sharing among participants. Complementary knowledge here is defined as knowledge that, in combination, yields better R&D results. Examples of such skill-sharing include the combination of optics and electronics, which led optoelectronics and the development of fiber-optics communication systems, and the fusing of mechanical and electronics technologies producing the mechatronics revolution, which has transformed the machine tool industry (Kodama, 1992).

One benefit of sharing complementary knowledge is that such sharing can correct market failures in the R&D input market. The market for R&D inputs such as research personnel and previous R&D results is imperfect and subject to asymmetric information and opportunism (Arrow, 1962; Katz, 1993). Moreover, the resource-based view literature argues that the procedures and competencies utilized by R&D are likely to be highly specific to organizations and the technologies they employ, and may often be embodied in organizational routines. Many competencies or assets needed to conduct R&D are therefore non-tradable (Barney, 1991; Dierickx and Cool, 1989) even in the absence of opportunism. Cooperative R&D can be considered as a means to internalize and combine complementary resources and knowledge that firms possess to overcome these problems. Cooperative R&D is also helpful to shorten research time as compared to the firms setting up their own research efforts from scratch (Contractor and Lorange, 1988), as the acquisition of competitively significant competencies may be a slow and uncertain process (Milgrom and Roberts, 1990).

Complementary knowledge can also enhance innovative productivity (Teece, 1992). Kodama (1992) noted that 'technology fusion' or the combining of existing technologies into hybrid technologies becomes increasingly important for innovation. He identified cross-industry cooperative R&D as the most important element of this fusion. Also, in order to commercialize the innovative new product or process in a profitable and timely manner, firms must secure access to complementary technologies and complementary assets on favorable terms (Teece, 1986). An application of this line of argument is Sinha and Cusumano (1991), where various conditions of R&D cooperation are analyzed under the assumption that cooperation among firms with complementary skills and resources increases the probability of a successful outcome.

In the following argument, I focus on cost-sharing vs. skill-sharing as the primary motives for firms to participate in cooperative R&D. Another frequently mentioned motive to participate in cooperative R&D is to share and/or reduce risks or uncertainties (Hagedoorn, 1993). The risk-sharing motive can coexist with the cost-sharing or skill-sharing motives, and it is difficult to separate out its individual effects. In this article, I deal with government-sponsored R&D consortia, which occur at the basic, or relatively early stages of R&D. I assume that the risk-sharing motive, though important, is a secondary issue here, as opposed to the more primary role it plays in purely-private R&D cooperation which typically occurs at the near-commercial stage.

Other frequently mentioned motives for alliances related to market access or reduction of the commercialization period are not the focus of this article, since the cooperative R&D I examine occurs at the early stage of the R&D process, and additional R&D efforts and product market competition typically follow. These two motives are more relevant to the later stages of R&D.

Heterogeneity of firm capabilities and motives for R&D cooperation

There have been some attempts to examine the underlying conditions which lead firms to cooperate in R&D. In this subsection, three major conditions, including transaction costs, appropriability, and capability heterogeneity, are discussed. These three conditions are not necessarily mutually exclusive. Each emphasizes a different aspect of R&D cooperation; therefore, they are best seen as complementary.

The most frequently argued condition, which determines the mode of cooperation, is transaction costs (see, for example, Hennart, 1988; Kogut, 1988). Major sources of transaction costs in cooperative R&D include investments in transaction-specific or relation-specific assets, uncertainties regarding R&D outcomes and the execution of the contractual agreement (Pisano, 1991), and costs to monitor and bond parties to an agreement (Kogut and Singh, 1988). Cooperation in R&D is assumed to economize on the costs of transferring or exchanging knowledge. The transaction costs argument, however, does not view cooperative R&D as a means of knowledge creation, nor does it address the learning motives (Kogut, 1988), which are key aspects of R&D cooperation.

A related basis for cooperation is appropriability conditions. Firms in industries with high spillovers might be motivated to internalize externalities of R&D through the formation of R&D consortia, and they might choose more hierarchical modes of cooperation over simple contractual relationships such as licensing. Appropriability conditions might be useful to explain differences in the willingness to cooperate in R&D by different industry sectors. As Levin *et al*. (1987) pointed out, however, there are many other alternatives to improve appropriability conditions.

The resource-based view suggests that the degree of heterogeneity in participating firms' capabilities is another condition which leads firms to cooperate in R&D. Capability heterogeneity is defined here as the breadth or diversity of technological capabilities that firms possess. Today's highly sophisticated innovations often depend upon work across several areas of science and technology (Hagedoorn, 1993). Few firms have the breadth of knowledge required for such undertakings (Randor, 1991), and so a new combination of core competencies is necessary to build core competencies (Hagedoorn, 1995; Tyler and Steensma, 1995).

The degree of capability heterogeneity can distinguish the different motives to participate in cooperative R&D. In the case of skill-sharing or learning-based R&D cooperation, what is important is not only the outcome of the project, but also the process of resource accumulation, or learning in an R&D consortium. Participants with a skill-sharing motive might find it easier to reach an agreement to cooperate without a clear end result in mind than firms whose primary motive for cooperation is cost-sharing. In addition, skill-sharing is an important means for a firm to enter a new business, implying that this motive is more likely in precompetitive R&D where conflicts of interests are less apparent. Moral hazard and adverse selection problems will, therefore, be under control in this form of cooperation, implying that R&D consortia motivated by skill-sharing can be sustainable without having a clear agreement. Firms from different industries, therefore, might find it easy to cooperate when their motivation is skill-sharing, even though they fully recognize that participants become direct competitors in the target industry of an R&D consortium. Also, the capabilities of participants in skill-sharing ventures are likely to be heterogeneous so as to best combine complementary resources and knowledge. This implies that participants are likely to come from a wide range of industries.

In contrast, cost-sharing, or scale-based R&D cooperation, requires a relatively clearer understanding of the objective and configuration of a cooperative R&D project, because the benefits of cost-sharing and the realization of economies of scale have to be understood by member firms before the execution of the project. Participants in R&D consortia motivated by cost-sharing are likely to belong to a single industrial sector, because they are more likely to have similar prior knowledge, which makes the agreement easier to achieve. Their capabilities are, therefore, likely to be homogeneous. Participants motivated by cost-sharing might face fewer transaction cost issues than skill-sharing cases, because cost-sharing motivated participants will have fewer asset specificity problems and uncertainties associated with a research path. This transaction cost aspect, therefore, facilitates agreements among participants with homogeneous capabilities.

The cost-sharing and skill-sharing motives are not necessarily mutually exclusive. An R&D consortium can pursue both motives simultaneously. What I propose here is that the relative importance of these motives can be distinguished by the degree of capability heterogeneity among the consortium's participants. Thus I hypothesize:

> *Hypothesis 1: The skill-sharing motive is relatively more important (than the cost-sharing motive) in R&D consortia where the participants possess more heterogeneous capabilities.*

Cost-sharing is generally assumed to be the objective of cooperative R&D in much of the theoretical economic literature, but there are serious reasons to question this emphasis. Company outlays on R&D that is closely related to cooperative R&D projects typically comprise only a small share of the company's total R&D expenditure.[2] Also, Shirai and Kodama (1989) documented that R&D consortia participants in Japan tend to be large, listed companies. Therefore, even if sharing fixed costs is a motive for R&D cooperation, it cannot be due to capital constraints unless the scale of a project is very large. In some technology fields, minimum efficient scale in R&D might be so large that a single company cannot conduct an R&D project on a technologically meaningful scale. Thus I hypothesize:

> *Hypothesis 2: The importance of the cost-sharing motive in firms' decisions to participate in R&D consortia is positively associated with project size.*

[2] Based on interviews with Japanese company executives.

Effects of cooperative R&D on R&D spending

The effects of cooperative R&D on a participating firm's R&D spending will differ according to their motives for participation. The economic literature typically assumes that participant firms in cooperative R&D limit their project-related activities to their role in the project. It is often the case, however, that participating firms follow up the cooperative project with related, independent R&D. The R&D spending examined here, therefore, includes both the firms' R&D spending within the cooperative R&D project and related R&D spending that occurs competitively outside of the project.

There are four major effects of R&D cooperation on a firm's R&D spending. The first is an increase in R&D efficiency. Firms whose primary motivation for participation is cost-sharing can achieve increased efficiency through economies of scale and avoidance of wasteful duplications, while firms whose motivation is skill-sharing find efficiencies in the easier acquisition of necessary complementary resources for R&D.

The second effect is the spillover of a firm's own R&D on others' R&D productivity. Spence (1984) argued that the existence of R&D spillovers makes it difficult for innovators to capture the full social benefits of their innovative activity, which depresses the incentives to conduct R&D. Through R&D cooperation, firms internalize the externality created through spillovers, thus restoring the incentive to conduct R&D. If the original level of spillover is low, and if cooperation in R&D increases spillover rates among consortia participants, everything else being equal, cooperation tends to increase R&D expenditure (Katz, 1986). It is possible that R&D consortia with wide industry participation, whose original level of spillover among firms is supposed to be lower than the case with single industry participation, tend to increase the R&D spending of consortia participants.

The third effect of cooperative R&D on the firm's R&D spending is from learning, which affects the intra-consortia spillover level. The sharing of complementary knowledge implies that learning from other participants and from cooperative R&D results is important. Cohen and Levinthal (1989) showed that a high spillover rate in R&D among competitors can provide a positive incentive to conduct R&D when a company's own R&D increases its learning capability. Cooperative R&D can be viewed as a 'forced' spillover scheme. This learning effect is likely to be large for firms whose motivation is skill-sharing, while it will be minimal where cost-sharing is the primary objective.[3]

The fourth effect relates to the impact of R&D cooperation on product market competition. Katz (1986) argues that if a higher level of R&D makes market competition more intense by lowering firms' marginal cost of production, then the resulting decline in profits will reduce their incentive to conduct R&D. R&D consortia can result in less R&D as firms seek to lessen the severity of competition in the product market. Katz's argument applies to the case of R&D consortia whose participants come from a single industry and are motivated by cost-sharing concerns.

The balance between these four effects cannot be deduced analytically. There is an extensive theoretical literature which examines the determinants of R&D intensity (for a summary of this literature, see Reinganum, 1989). The outcomes of these models are highly sensitive to underlying assumptions, such as the R&D investment and pay-off structure, the nature and timing of available information, and the extent of asymmetries between firms. Moreover, few of the models in the existing literature can be easily nested (Cockburn and Henderson, 1994).

The relative weight of these four effects is, therefore, an empirical question. Assuming the sum of the second, third, and fourth effect dominates the first effect for firms which participate as a result of skill-sharing motives, which might not be an unrealistic assumption, cooperative R&D conducted by such firms will tend to increase their R&D spending, while the R&D spending of firms motivated by cost-sharing concerns will tend to decrease. Thus I hypothesize:

Hypothesis 3: Firms which are motivated relatively more by skill-sharing concerns to

[3] In the long run, firms which participate in skill-sharing R&D consortia will increase their capabilities to learn from others over time and, as a result, firms' R&D spending for learning purposes might decrease. In this sense, this article is focused on the short-run effect.

participate in cooperative R&D are likely to increase R&D spending as a result of their participation, while firms whose relatively greater motivation is cost-sharing will likely decrease their R&D spending.

The key differences between cost-sharing and skill-sharing motives to participate in cooperative R&D are summarized in Table 1.

R&D CONSORTIA IN JAPAN

The empirical analysis in this article concentrates on Japanese R&D consortia sponsored by governmental organizations.[4] This form of cooperative R&D is chosen because these ventures are most frequently cited as being important to industry competitiveness, particularly among Western observers. It is also chosen because it is comprehensive and detailed data are available.

Government-sponsored R&D consortia in this article include all significant company-to-company cooperative R&D projects formed with a degree of government involvement. The nature of government involvement in R&D consortia varies. The government can have significant influence on the formation of consortia, including input on the type of participants who will be involved and the directions the consequent research will take. One means by which the government wields this influence is through the provision of subsidies to the consortia that meet established criteria. In this article, a principal criterion to be identified as government-sponsored R&D consortia is that the projects of the R&D consortia involved cooperation among private companies. In other words, projects which were primarily government procurement, and those in which government agencies simply allocated tasks without the private sector's initiative, were excluded. Projects which were essentially the implementation of existing technology were also excluded. Appendix 1 provides a detailed explanation of the data.

A large number of government-sponsored R&D consortia occurred between 1959 and 1992, of which 237 were included in my data set. 1171 companies participated in these consortia during this period and many were involved in multiple projects. Inclusion of these multiple projects yields a data set with 3021 company–project pairs. This data set was collected from each ministry through direct contacts after examining a wide range of government White Papers and other government publications, and is as close as possible to an exhaustive list of all the government-sponsored R&D consortia in Japan.

In previous work (Sakakibara, 1997), I conducted a statistical analysis of the government-sponsored R&D consortia in Japan. This analysis identified several illustrative characteristics of these projects. Three industrial sectors experienced many projects and were characterized by relatively large project budgets. These sectors are: semiconductors/computers, power generation and distribution, and petroleum/chemicals. The average project size is $54 million in 1985 prices.

Table 1. Comparison of motives: Cost-sharing vs. skill-sharing

Motive	Cost-sharing/Scale-based	Skill-sharing/Learning-based
Nature of competition in R&D consortia	Single-industry competition	Wide industry participation
Nature of firm capabilities in R&D consortia	Homogeneous Substitutable	Heterogeneous Complementary
Role of R&D consortia	Vehicle to divide tasks	Vehicle to create/transfer knowledge
Private R&D spending	Can decrease	Can increase
Major constraints firms face	Financial resources	Research capabilities

[4] This data set was originally prepared for *The Two Japans: Reexamining the 'Japanese Model' of Competitiveness* (Porter, Takeuchi, with Sakakibara, forthcoming).

Participants are typically large, listed companies and, on average, the sales of frequent consortia participants are in the order of several hundreds of billions of yen, although many small companies have also participated.

QUESTIONNAIRE DESIGN AND SURVEY METHODS

Questionnaires to R&D consortia participants were used to obtain the data for this article. The questionnaire was aimed at high-level R&D managers who have supervised or participated in R&D consortia. In order to minimize misinterpretation of questions, the questionnaire was pre-examined by several managers in industry and government officials who have coordinated R&D consortia.

The questionnaire's unit of analysis is a company–project pair: a company's answer to questions relating to a particular R&D consortium. The questionnaire consisted of three parts. Part one focused on the motives for participating in R&D consortia. Part two focused on issues relating to the design of the R&D consortium, including goals, industry participation patterns, and organizational and coordination characteristics. Part three focused on the outcomes of the projects, including both the perceived merits and demerits, as well as on the overall evaluation of the project, and on the contribution of the project to the establishment of the participants' competitive position. In this article, the analysis concentrates on the selected results of parts one and two of the survey. Most answers were reported on a 5-point Likert scale. For some questions, respondents were asked to complement these numerical responses with detailed comments. This questionnaire was administered in July to October 1993.

Questionnaires were distributed to all companies who were members of the Japan Research Industries Association (JRIA), a nonprofit organization, and who had ever participated in government-sponsored R&D consortia. JRIA was formed by companies interested in building their R&D capabilities, and its member firms come from a wide range of industries. This organization was chosen in order to achieve a high response rate, and to obtain exact and objective answers.

This organization's affiliation to the government (MITI) could be a potential source of bias in the answers. To minimize any biases, questions were asked only about cooperative R&D projects which have ended or reached the 'near-completion' stage. Questions which directly evaluated the role of the government were minimized. In addition, complete anonymity was guaranteed. It turned out that responses were quite frank, and comments on questionnaires included responses that were critical of the government, respondents' own companies, and other participating companies. Therefore, it is reasonable to say that these answers reflected the honest opinions of the R&D managers in participating companies. There are, however, other potential biases that arise from the use of survey data. The methods used to control for other such biases in the interpretation of the questionnaire responses are examined below in the analysis section.

Consortia participants were identified from the list of government-sponsored R&D consortia mentioned earlier. 89 companies were asked to answer for 88 projects, which brings the overall potential sample to 512, because many projects had multiple participants whose responses were all sought. There were 398 useable responses from 67 companies concerning 86 projects, and the overall response rate was 77.7 percent. The projects covered represent 41 4-digit SIC industries. Some questions were left unanswered; therefore the number of effective responses per question ranges from 355 to 398. Questions on multiple projects conducted by a single company were typically answered by different R&D managers, ruling out a bias by the same respondent. The selection of the questionnaire respondent for each firm was made by that firm's contact person at the JRIA. These contacts were asked to choose the most knowledgeable and highest-ranking R&D managers available who had participated in a particular R&D consortium.

Questionnaire respondents are mostly listed companies, reflecting the fact that the majority of the frequent consortia participants are typically listed companies. Projects about which responses were obtained include world-famous ones such as the VLSI Project and the Fifth-Generation Computer Project, as well as more obscure projects such as the coal gasification or processed food production technology-related projects.

I followed a methodology used by Levin *et al.* (1987) to analyze these answers. I treated ratings along a 5-point semantic continuum as if they were interval data. This interpretation, rather than treating the data as ordinal, allowed me to make comparisons among questions. Questionnaires were designed to ensure that cross-question comparisons would arise naturally in the minds of the respondents. The same scale, 1–5, was printed on each question.

Although the use of semantic scales to assess, for example, the importance of alternative motives of R&D consortia participation introduces considerable measurement error, more readily quantifiable proxies were not available. One could argue about the subjective nature of the data, since the scale of the responses is arbitrary, and may be quite nonlinear (responses might tend to concentrate on the middle score 3, or some might systematically favor high scores). There are many techniques available to control for differences among respondents in means and variances, but their application generally means abandoning one or more dimensions along which the data might be informative. For example, I am interested in interconsortia or interfirm differences in answers to a single question; controlling for fixed effects among respondents would vitiate such measures, since I expect a respondent's mean score over all questions to depend on his/her own consortia or firm. Standardizing the variance of each respondent's answers also raises similar problems: the distribution of 'correct' responses is unknown and it almost certainly differs among consortia or firms. Cockburn and Griliches (1987), for example, tried various transformations on the data in Levin *et al*. (1987) to correct for these effects. Their transformations did not appreciably change the performance of the variables.

I examined the distribution of questionnaire responses to check if there is any consortium or industry which drives the result to one way or other and confirmed there are no apparent 'outliers.'

ANALYSIS

Motives for participation in cooperative R&D

Firms' motives for participating in R&D consortia were examined by asking about the general objective of the projects. There is a measure of the skill-sharing motive, asked as 'to gain access to the complementary knowledge of other participants' (1 = not important, 5 = very important), and two measures of the cost-sharing motives, asked as 'to share fixed costs among participants and realize economies of scale in R&D' and 'to avoid wasteful duplication of research by dividing the tasks among participants'.[5] Other motives which are considered to be especially relevant to participation in government-sponsored R&D consortia in Japan, such as catching up with advanced technologies already developed by overseas competitors, are included with those of cost- or skill-sharing. The correlation matrix of these variables and all other variables used in this study is in Appendix 2.

Table 2 illustrates the general pattern of responses. In addition to the overall sample means, it presents an analysis of variance calculated in two ways: one based on the difference among projects; the other on the difference among industries to which the projects belong. Industries are aggregated into the 12 clusters proposed by Porter (1990).

It is found that firms perceive gaining access to complementary knowledge as the most important objective of the project. Sharing fixed costs is one of the least important objectives. I conducted a two-tailed *t*-test on the difference of mean rankings between complementary knowledge-sharing and other motives. The test is on the distribution of the difference between answers using paired observations, where the null hypothesis is that the mean of differences is zero. The mean of the complementary knowledge-sharing objective is significantly different from that of the second most important objective, entering a new business, at the 5 percent level, and it is significantly different from all the other reasons at the 1 percent level.

The analysis of variance columns show that the importance of sharing complementary knowledge is robust among projects or industry clusters. The importance of this motive is not significantly different across projects or industry clusters. These results suggest that the importance of sharing complementary knowledge is pervasive. On the other hand, there is substantial variation

[5] Although the use of a single question to address the skill-sharing motive could potentially bias this construct, this concern is mitigated by management comments from questionnaire preexaminations which indicate that the meaning of this question was well understood.

Table 2. General objective of the project from participants' point of view:[a] Analysis of variance of differences among projects and among industries

Objective of the participation in the project	Overall sample means	Analysis of variance of differences (F-ratios)	
		Among projects[b]	Among industry clusters[c]
To gain access to the complementary knowledge of other participants	3.69 (0.05)	0.99	0.94
To enter a new business area/technology	3.51 (0.07)	2.19***	2.74***
To avoid wasteful duplication of research by dividing the tasks among participants	3.15 (0.06)	1.69***	1.94**
To catch up with advanced technologies already developed by overseas competitors	2.99 (0.07)	3.47***	5.88***
To share fixed costs among participants and realize economies of scale in R&D	2.95 (0.06)	1.80***	1.81**
To catch up with advanced technologies already developed by domestic nonparticipants	1.69 (0.05)	1.21	1.50

Source: Author's calculations from 373 to 387 responses.
[a]Range: 1 = not important; 5 = very important. Standard errors in parentheses.
[b]Covers 355–367 responses for 70 projects after eliminating projects which have only a single response; figures are F-ratio. Approximate 0.05 significance level (**) is 1.4, and 0.01 significance level (***) is 1.6.
[c]Covers 373–387 responses for 12 industry clusters; figures are F-ratio. Approximately 0.05 significance level (**) is 1.8, and 0.01 significance level (**) is 2.2.
Note: Standard errors in tables are shown as $s/n^{1/2}$, standard errors of means.

among projects and industry clusters on the responses relating to the objectives of catching up with overseas competitors and entering new businesses. This finding suggests that the importance of these reasons has changed, most likely, over time. Project and industry variations are significant for the cost-sharing and avoidance of wasteful duplication objectives. This result highlights the importance of analyzing the differences in capabilities of participating firms over various projects. Catching up with domestic nonparticipants is not found to be an important reason to form R&D consortia, and this finding is robust among both projects and industries.

Motives of participation and capability heterogeneity of participants

In order to test Hypotheses 1, I constructed a variable, RELATIVE, which represents the relative importance of the skill-sharing motive *vis-à-vis* the cost-sharing motive. The skill-sharing motive is measured as the response to the question 'to gain access to the complementary knowledge of other participants,' and the cost-sharing motive is measured as the average response to the questions 'to share fixed costs among participants and realize economies of scale in R&D' and 'to avoid wasteful duplication of research by dividing the tasks among participants.' RELATIVE is defined as the difference of these two constructs.

Since the scores of questionnaire answers may not follow the normal distribution, the full data sample is split into subgroups according to the degree of capability heterogeneity—homogeneous and heterogeneous—of the participating firms in the R&D consortia. The means of the scores for the RELATIVE variable for each of the two subgroups are then compared. These subgroups were designated in several ways. In all of the classifications, measures of the breadth of industry participation are used as a proxy for the degree of capability heterogeneity among participants. It is assumed that the degree of heterogeneity between industries is greater than that within an industry. In other words, wider industry participation is assumed to bring less overlapping and potentially more complementary knowledge.

The first classification of capability heterogeneity used to split the sample is obtained by using the questionnaire responses to the question 'How wide was participation from other industries?' (1 = from single industry, 5 = wide variety of industries), with responses of 3 or less classified as homogeneous, and of 4 or more classified as heterogeneous. This split was determined by the mean of the overall scores.

The other classifications used to split the sample are obtained by calculating several measures of the participating firms' diversity of core businesses in each R&D consortium. The heterogeneity/homogeneity distinction is determined by splitting the full sample in half by the means of these measures. This calculation requires the assumption that the firm's core technology resides in its main line of business, implying that the more diversified is the participants' industry mix, the more heterogeneous the technological capabilities of the participants become. In some consortia, a project consists of several subprojects. The diversity of the whole project, therefore, may not reflect the extent of participating firms' actual interaction. One advantage of the classification based on the questionnaire responses is that it reflects the 'perceived' heterogeneity in the participating firms' capabilities, compensating this potential bias of the diversity measures. The diversity measures, on the other hand, give a more objective measure of the capability heterogeneity in R&D consortia.

The use of 'heterogeneity in industry background' as a proxy for capability heterogeneity is a potential source of measurement error. Some industries might consist of diverse groups of firms whose capabilities are highly differentiated, while firms in different industries may have similar skills. The technological 'closeness' of industries, however, is reflected in the SIC classification, and one could argue that this is what the SIC classification is for (Griliches, 1992), supporting the validity of this proxy. Empirically, a better proxy is not readily available.

The diversity measures I use here are drawn from the diversification literature. In this analysis, the diversity measures used in Palepu (1985) and Montgomery (1982) are calculated for each R&D consortium by using the 3-digit SIC codes of the participating firms' main businesses. These measures are Palepu's total (DT) and unrelated (DU) entropy measures, and Montgomery's 2- and 3-digit product count measures. The details of the diversity measures' calculation and the method of main business identification are explained in Appendix 3.

The results of this analysis are shown in Table 3. The differences in the means of the RELATIVE measure between the heterogeneous and homogeneous subgroups are significant under all subgroup classifications, and this significance is at the 1 percent level for all four of the diversity

Table 3. Relative importance of the skill-sharing motive *vis-á-vis* the cost-sharing motive and the capability heterogeneity of firms in R&D consortia

Score: Relative importance of the skill-sharing motive *vis-à-vis* the cost-sharing motive (RELATIVE)[a]

Measures of capability heterogeneity of firms in R&D consortia	Means of the scores in the subgroup[b]	
	Homogeneous	Heterogeneous[c]
Questionnaire response measure[d]	0.552 (0.08)	0.771** (0.07)
Palepu total entropy measure[e]	0.448 (0.07)	0.798*** (0.08)
Palepu unrelated entropy measure	0.423 (0.08)	0.781*** (0.07)
Montgomery 2-digit SIC measure	0.373 (0.09)	0.775*** (0.07)
Montgomery 3-digit SIC measure	0.414 (0.09)	0.763*** (0.07)

Source: Author's calculations from 362 responses.
[a]The skill-sharing motive is measured as the response to the question 'to gain access to the complementary knowledge of other participants', and the cost-sharing motive is measured as the average response to the questions 'to share fixed costs among participants and realize economies of scale in R&D' and 'to avoid wasteful duplication of research by dividing the tasks among participants' (range: 1 = not important; 5 = very important). The relative importance of these two motives is the difference of these two constructs. The range of this relative importance measure is from −4 to 4.
[b]The means of the scores for the RELATIVE variable for subgroups are shown. Standard errors in parentheses.
[c]*T*-Tests are comparisons of the means for two subgroups, homogeneous and heterogeneous. ***Significant at the 1% level; **significant at the 5% level, *significant at the 10% level, using a two-tailed test.
[d]Responses to the question 'How wide was participation from other industries?' (1 = from single industry, 5 = wide variety of industries), with responses of 3 or less classified as homogeneous, and of 4 or more classified as heterogeneous.
[e]Explanations of diversity measures are in Appendix 3. The split is determined by the overall sample means of these measures.

measures. These results provide support for Hypothesis 1.

I conducted a sensitivity analysis by testing alternative segmentations of the sample between homogeneous and heterogeneous. These alternative segmentations were obtained by splitting the sample differently such as by moving one answer class to the other side or by using the median to split the sample. I found that the results are robust with respect to these changes.

It is worth noting that, as the results of Table 2 suggest, firms find that, on average, the skill-sharing motive is more important than the cost-sharing motive in R&D consortia. Table 3 reflects this finding, with the average score of the skill-sharing motive being higher than that of the cost-sharing motive in both the homogeneous and heterogeneous subgroups.[6]

There are potential biases which might distort these results. All of the questions were asked after the project was completed, or at the near-completion stage. One could argue that the project's success or failure might change the perception of the associated R&D managers towards it. An organization's past performance has been shown to influence a host of managerial perceptions and actions (Milliken and Lant, 1991). For example, one can argue that if a project turned out to be a success, managers might give higher scores to skill-sharing motives relative to cost-sharing motives. To eliminate this bias, I regressed the scores of the relative importance measure on the response to the question 'What is your overall evaluation of the project?' (1 = complete failure, 3 = so so, 5 = impressive success), after confirming these two measures are not correlated. I then took the residual and used it as a relative importance measure to replicate the analysis in the Table 3. This transformation did not change the results, suggesting that the perceived success does not affect the relative importance of the two motives.[7]

Another potential bias is the so-called 'social desirability bias.' One might give a high score to the question which implies that smart people or a good firm will respond with a high score. For example, one might expect that responding with higher scores to skill-sharing motives will lead him/her to be better perceived than if he/she responds with a high score to the catching-up-with-overseas-competitors motive. There is evidence, however, that this bias is under control in two respects. First, the construction of the RELATIVE measure, and the analysis of the association of this measure with the difference in capability heterogeneity of consortia, eliminates the effect of this bias, which might appear on the difference of the 'level' of two questionnaire responses, if any. Second, it is confirmed that the perceived success score mentioned above does not increase over time, while the motive of catching up with advanced overseas competitors decreases over time, suggesting the respondents are 'rational.'[8]

The provision of government subsidies is another source of potential bias. In projects where the government finances a significant proportion of the budget, the cost-sharing motive may be less important, since the government contribution will ease the financial burden on participants. To account for this potential bias, I split the sample into two according to the extent of government financing, and carried out the analysis on the subsample with a low degree of government involvement.[9] If this bias is significant, then the level of the cost-sharing motive in this subsample would be expected to be higher than the case of the whole sample. This subsample yielded virtually the same results as ones in Table 3, confirming that the relative importance of two

[6] In the case where the sample is split according to the questionnaire response, the average score assigned to the skill-sharing motive is higher in the 'heterogeneous' subgroup than in the 'homogeneous' subgroup, while the average score assigned to the cost-sharing motive has the reverse pattern. These patterns hold for the cost-sharing motive when the sample is split by using any of the diversity measures, but the patterns for the scores assigned to the skill-sharing motive vary depending on the diversity measure used.

[7] On a related note, firms' motives for cooperation may also change over a project's lifetime (Doz, 1996). This evolution of motivations could be assessed through a time-series analysis of R&D consortia. Such an approach, however, would be empirically limited to ongoing projects. Additionally, management concerns that government decisions relating to these projects could be adversely impacted by negative responses potentially adds an alternative bias.

[8] This test is conducted by splitting the sample into three by decades of the starting year of the project and testing if the difference of means of these subsamples are statistically significant or not.

[9] This subsample of projects includes the ones whose stated coverage by the government is less than 100 percent. This split, and the detailed explanation of the effect of the government financing, is found in the section entitled Analysis: Effects of cooperative R&D on R&D spending.

motives is not affected by the extent of government financing.

Relationship between the project size and the importance of the cost-sharing motive

Regression models were estimated to examine the relationship between the project size and the cost-sharing motive as a test of Hypothesis 2. I use the following specification:

$$\text{COSTSHARING}_{ij} = a + b_1 \text{ PJTSIZE}_j + b_2 \text{ HETEROGENEITY}_j + \Sigma b_m \text{ COMPANY}_m + e_{ij}$$

The dependent variable, COSTSHARING_{ij}, is the average of Likert-scale scores on the importance of the two cost-sharing motives mentioned before, taken from firm *i*'s questionnaire response with respect to project *j*. I include several independent variables; PJTSIZE_j is the total project budget, in real terms as of the project's first year, for project *j*; HETEROGENEITY_j refers to capability heterogeneity measures used in the previous analysis, and they are included in some regressions to control for the effects of capability heterogeneity on the importance of the cost-sharing motive as outlined in Hypothesis 1; COMPANY_m are company dummy variables included to control for firm-specific effects such as the ease of R&D financing and other characteristics of the firms' industries. Hypothesis 3 predicts b_1 to be positive.

Table 4 shows the results of ordinary least-square estimations. Regression 1 shows that the coefficient on the project size variable is positive and significant at the 5 percent level, supporting Hypothesis 2. Regression 2 is conducted to control for the consortia capability heterogeneity effects. The coefficients of the diversity measures are negative and significant at the 1 percent level, consistent with Hypothesis 1. The coefficients on the project size variables remained positive and significant at the 5 percent level. Table 4 reports the case when the Montgomery 3-digit SIC diversity measure is used. Other diversity measures yield similar results.

Regression 3 shows these basic results do not change when company dummy variables are included. The *F*-test on the results of regressions 2 and 3 shows that the hypothesis that the company dummy variables are jointly significant is rejected at the 5 percent level,[10] suggesting the robustness of the project size and heterogeneity variables.

Since the dependent variable is a discrete variable which takes a value from 1 to 5 with 0.5 intervals, ordered probit is a preferred way for this estimation. Because of the computer software constraint, however, I could not conduct the ordered probit estimation with 66 company dummy variables. I conducted ordered probit estimations for the specifications without company dummy variables, and obtained essentially similar results.

Effects of cooperative R&D on R&D spending

To see how the R&D consortia have affected R&D spending, companies were asked how much of their own money was spent on R&D related to the consortia project. Project-related R&D spending is a firm's R&D spending in project-related areas including its outlays in the R&D consortium and additional R&D conducted at the firm's labs. R&D spending is measured here as a percentage of the government outlay per firm on the project.[11] Earlier discussions with companies indicated that firms would generally be willing and able to provide such percentage figures, whereas they would not be willing to disclose absolute expenditures for each R&D activity. In a consortium, the government precommits its contribution to the project as a percentage of the total project budget. The total scale of the project is also typically precommitted by the government, but it is changeable as the project proceeds. Firms pay the rest of the project's expenditure, and they optimize in-house R&D spending related to the consortium. Table 5 shows the results of the responses to the question. On average, firms undertook private R&D spending equal to more than 87 percent of the government's budget allocated to that firm. Table 5 suggests that government-sponsored cooperative R&D does not necessarily 'crowd out' private R&D.

In order to test Hypothesis 3, the relationship between the relative importance of the skill-sharing motive *vis-à-vis* the cost-sharing motive

[10] The *F*-statistic is 1.14, which does not exceed the critical value of $F_{66,\ 264} = 1.32$ at the 5 percent level.

[11] This way of measuring private R&D spending might sound odd to U.S. readers, but this is a standard way of communicating with Japanese R&D managers. In government-sponsored R&D consortia in Japan, government funding is typically allocated to each participant. A firm measures its R&D investment as a percentage of this allocated fund.

Table 4. Association between the size of the project and the cost-sharing motive (OLS, standard errors in parentheses)

Dependent variables: the cost-sharing motive[a]

Explanatory variables	Regression 1	Regression 2	Regression 3
Project size (billion yen)	0.00180** (0.000776)	0.00180** (0.000761)	0.00218*** (0.000819)
Montgomery 3-digit diversity measure		–1.151*** (0.303)	–0.842** (0.391)
Company dummies	No	No	Yes
Constant	2.994*** (0.0576)	3.905*** (0.246)	4.278*** (1.030)
Number of observations	333	333	333
R^2	0.016	0.057	0.266
Adjusted R^2	0.013	0.051	0.077

Note: ***significant at the 1% level, **significant at the 5% level, *significant at the 10% level, using a two-tailed *t*-test.
[a]The dependent variable is the average response to the questions 'to share fixed costs among participants and realize economies of scale in R&D' and 'to avoid wasteful duplication of research by dividing the tasks among participants' (range: 1 = not important; 5 = very important).

Table 5. Private R&D spending on R&D consortia related R&D (as percentage of government budget)

Question: How much did your company spend your own money on this project related R&D?

Overall sample means	Frequency distributions: ( ) are Likert scales assigned to each answer				
2.74 (0.06)	Didn't spend at all[a] (=1)	50% of government budget (=2)	Same amount as government budget (=3)	Twice as much as government budget (=4)	More than twice (=5)
	45	141	120	32	47

Source: Author's calculations from 385 responses. Standard errors in parentheses.
[a]Including 12 answers which said they spent less than 50% of government budget.

and R&D spending is examined by estimating regression models. In government-sponsored projects, R&D consortia exert two effects on R&D spending: one is the effect of the government budget on the consortia, and the other is the effect of cooperation on R&D. Though it is difficult to separate these two effects, I chose a subsample of firms that conducted cooperative R&D on a consignment basis; i.e., their R&D costs in the consortia were supposed to be 100% covered by the government, in order to control for the effect of government subsidies. For this type of project, firms have to spend their own money on the project, because the government budget does not cover all expenses, and firms also typically choose to make in-house R&D investments that, in their judgment, are closely related to the cooperative projects. This R&D investment occurs because the activities of the R&D consortia are only a part of the firm's entire R&D program, and private R&D competition typically proceeds behind the cooperative R&D projects.

I assume that the effects of the government budget are the same among firms in this subsample, and investigate how the relative importance of the two motives affected the firms' own R&D spending. The regression equations have the following specification:

$$\text{PROJECTR\&D}_{ij} = a + b_1 \text{ RELATIVE}_{ij} + b_2 \text{ FIRMR\&D}_{ij} + \Sigma b_n \text{ CLUSTER}_n + \epsilon_{ij}$$

The dependent variable, PROJECTR&D$_{ij}$, is the Likert scale score on the response to project-related R&D spending, as a percentage of government budget per firm *i* on project *j*, as reported in Table 5. I include the following independent variables: RELATIVE$_{ij}$, the relative importance of the skill-sharing motive *vis-à-vis* the cost-sharing motive; FIRMR&D$_{ij}$, firm *i*'s total R&D expenditure, in real terms as of project *j*'s first year; CLUSTER$_n$, are the cluster dummies used in Table 2. These CLUSTER dummies are included in some specifications to control for industry effects which might not be explained by the relative importance of two motives on firm R&D spending.

RELATIVE$_{ij}$ as used in Table 3 represents the relative importance of the skill-sharing motive *vis-à-vis* the cost-sharing motive. From Hypothesis 3, the sign of this coefficient is expected to be positive. FIRMR&D$_{ij}$ proxies for the ease of R&D financing by firm *i*, thus b_2 is expected to be positive. Consortia-based private R&D is very small relative to the firms' total R&D, and so this explanatory variable is exogenous to the left-hand side variable. Firm-level R&D expenditure data are drawn from the Japan Development Bank Corporate Finance Database.

Table 6 reports the results of an ordered probit estimation. The signs of coefficients are found to be as predicted. The relative importance variable is significant at the 5 percent level, supporting Hypothesis 3. Application of the likelihood ratio test to regressions 2 and 3 finds that the hypothesis that the cluster dummy variables are significant is rejected at the 5 percent level.[12] The inclusion of these dummies does not change the basic results, confirming that the effect of the relative importance variable is robust.

I conducted the same analysis by creating dummy variables to account for the relative importance of the two motives for consortia participation. The dummies were created by bifurcating the response scores to the associated questions by their means, and assigning 0 to the responses smaller than the mean and 1 to the responses larger than the mean. This conversion is conducted to obtain robust results from the use of questionnaire responses as an independent variable, and I obtained essentially the same results as Table 6. I also conducted an OLS analysis by converting the dependent variable to the implied percentage value, and obtained essentially the same result.[13]

[12] The likelihood ratio statistic is 1.99, which does not exceed the critical chi-squared value of 19.7 (11 d.f.) required to accept the significant cluster dummies hypothesis at the 5 percent level.

[13] I also conducted regressions by adding the project size variable as an explanatory variable. The addition did not change the basic findings reported in Table 6.

Table 6. The effects of cooperative R&D on private R&D spending after controlling for the governmental budget effect (ordered probit, standard errors in parentheses)

Dependent variables: Project-related private R&D as percentage of government budget per firm on a project

Explanatory variables	Regression 1	Regression 2	Regression 3
Relative importance of skill vs. cost-sharing motive	0.159**	0.161**	0.171**
	(0.0676)	(0.0687)	(0.0697)
Firm R&D expenditure (billion yen)		0.00237	0.00257
		(0.00380)	(0.00291)
Cluster dummies	No	No	Yes
Constant	0.927***	0.877***	1.089***
	(0.136)	(0.140)	(0.371)
Number of observations	138	138	138
Log likelihood	–179.87	–179.44	–178.45

Note: ***significant at the 1% level, **significant at the 5% level, *significant at the 10% level, using a two-tailed *t*-test.

CONCLUSIONS AND IMPLICATIONS

Economic theory suggests that cooperative R&D projects are a means for firms with homogeneous capabilities to set cost-sharing rules. Organizational theory suggests cooperative R&D is a vehicle for firms with heterogeneous capabilities to learn skills and capabilities from other consortia participants. These different perspectives emphasize two competing motives for participating in cooperative R&D: cost-sharing vs. skill-sharing.

Past research into the underlying conditions which induce R&D cooperation focuses on transaction costs and appropriability conditions. These conditions, however, only address cost-economizing motives for cooperative R&D, and only view R&D cooperation as a means for transferring or exchanging knowledge. In this article, I propose that heterogeneity in the participating firms' capabilities is an alternative condition which leads firms to cooperate in R&D. This condition can distinguish a relative importance of scale-based, or cost-sharing motive *vis-à-vis* a learning-based, or skill-sharing motive for cooperative R&D, and views R&D cooperation as a means of knowledge creation, as well as knowledge transfer. I suggest that the relative importance of the cost-sharing motive in R&D consortia increases when participants' capabilities are homogeneous or projects are large, while the relative importance of the skill-sharing motive in R&D cooperation increases with heterogeneous capabilities.

These two competing motives have different implications for a participating firm's R&D spending. I suggest that when the skill-sharing motive for participating in cooperative R&D becomes relatively more important than the cost-sharing motive, a firm's R&D spending is likely to increase, while increased relative importance of the cost-sharing motive tends to decrease a firm's R&D spending. In order to test these hypotheses, I administered questionnaires to high-level corporate R&D managers who have participated in government-sponsored R&D consortia in Japan. An analysis of the 398 responses overall confirmed the above hypotheses.

The association between the relative importance of the skill-sharing motive and the capability heterogeneity in R&D consortia is consistent with the resource-based view's notion that an R&D consortium may be a practical alternative to acquire another firm's specific capabilities. In this article, I suggest the use of industry heterogeneity of firms as a possible measure of capability heterogeneity. This article thus contributes to the resource-based view literature by suggesting a possible direction for empirical tests to identify and measure capabilities in a cooperative venture.

In this article, it was revealed that, though the relative importance of the skill-sharing motive is greater in consortia with heterogeneous capabilities, firms found that skill sharing is the dominant motivation *vis-à-vis* cost-sharing in R&D consortia. There are two possible interpretations for this finding. One is that when firms cooperate in R&D, reasons other than simple cost-sharing are required. The costs associated with managing cooperative ventures, which can be quite significant, will not be justified without the possibility that R&D cooperation will yield critical accomplishments that would otherwise be very difficult to obtain. For example, firms facing capability constraints might find that cooperation is the only way to enter a new technological area.

An alternative explanation relates to government subsidies. In this article, all the R&D consortia received varying degrees of government subsidies. Though it was shown that the association between the relative importance of the skill-sharing motive and the degree of capability heterogeneity in R&D consortia does not change with variation in subsidy levels, it is possible that the level of the importance of the cost-sharing motive is reduced due to the presence of government subsidy in the sample.

This article has an important implication for managers. When the new technology increases in complexity, its development requires more heterogeneous capabilities than before. The attention and the organization of R&D cooperation should be more directed to skill-sharing consortia. The possibility of increase in R&D spending associated with the skill-sharing motive to participate in R&D consortia implies that managers should take the increased R&D cost as an additional consideration in the decision of R&D consortia participation. This consideration is worth noting as the number of 'strategic' alliances, and R&D consortia in particular, are increasing rapidly.

There is a policy debate in which some participants claim that Japanese R&D consortia are only feasible because of weak antitrust enforcement, and use this argument as a foundation of asking further relaxation of the U.S. antitrust law. This article showed that many R&D consortia can be 'interindustry' in nature. The application of antitrust law is less relevant for these types of projects than for those motivated by cost-sharing concerns because of the low concentration of participation by firms in a single industry. This article also showed that skill-sharing R&D cooperation is likely to be competition-enhancing, because it tends to increase private, competitive R&D spending in the target technology. Moreover, if this form of R&D cooperation entices new entry into a line of business, this scheme is even more procompetitive.

There are limitations to this analysis. I used the breadth of industry participation as a proxy for the capability heterogeneity of R&D consortia participants. There is a possibility that this proxy picked up an alternative aspect of participant variation: whether or not the firms are currently direct competitors in product market, rather than if their capabilities are homogeneous or heterogeneous. While the participants become direct competitors in the target product market of R&D consortia in either case, being current direct competitors may favor cost-sharing motives. Current direct competitors might be unwilling to share skills because of the potentially lasting effect this sharing would have on competitors' capabilities, which implies that skill-sharing may have a negative effect on a firm's current competitive position. In contrast, cost-sharing is a one-time gain for all the participants, which might make current competitors more agreeable to sharing costs than to sharing skills.

A more precise proxy of capability heterogeneity such as the sum of each participant's technological portfolio could also be used. This can be calculated from the patent data, for example, by constructing the R&D stock of each firm. Unfortunately, for the Japanese firms, only very recent data on domestic patents is electronically available, but this calculation can be done for the U.S. firms in the analysis of U.S. R&D consortia.

Another limitation might come from the use of questionnaire results. Even though the questionnaire methodology is the only way to collect a large sample of qualitative data, these data have limitations due to the subjective nature of the results.

More empirical research on cooperative R&D is necessary and should be encouraged. This paper illustrated the usefulness of using questionnaire results to answer economic questions, such as the relationship between motives for participation and R&D spending. This article also highlighted the value of collecting original, comprehensive data in order to understand a large population of cooperative R&D projects. The future direction of the research includes further analysis at the project level, including the outcomes of the projects and determinants of these outcomes. Firm-level analyses, such as the effects of R&D cooperation on firm-level R&D spending, R&D productivity, and the spillovers among R&D consortia participants and to nonparticipants, would be also important to evaluate the whole effect of firms' participation in cooperative R&D.

ACKNOWLEDGEMENTS

This article is based on my Harvard dissertation. I would like to thank Joel Baum, Richard Caves, Gary Chamberlain, Glenn Ellison, Drew Fudenberg, Zvi Griliches, Adam Jaffe, Tarun Khanna, Marvin Lieberman, Michael Porter, Yishay Yafeh, Hideki Yamawaki and seminar participants at Harvard, UCLA and MIT for this *Special Issue* for helpful suggestions on earlier versions of this paper. I would also like to thank the guest editors and two anonymous referees for their detailed comments that considerably improved this paper. Ken Serwin, Aya Chacar, and Rajesh Chakrabarti provided valuable research assistance. I am also grateful to the Japan Research Industries Association, especially Toyoharu Sumikama and Akira Numata, for their help in managing the survey. I would also like to express my appreciation to Chihiro Watanabe and Toshihide Kasutani at the Ministry of International Trade and Industry, Japan for the coordination and helpful suggestions for the survey. I also wish to thank the 398 R&D managers who responded to my survey. Financial support from the Harvard Business School Division of Research and the Center for International Business Education and Research at the UCLA Anderson Graduate School of Management is gratefully acknowledged. This research was partly conducted when the author was a Special Researcher at the National Institute of

Science and Technology Policy, Science and Technology Agency, Japan. Any remaining errors are my own.

REFERENCES

Aldrich H. E. and T. Sasaki (1995). 'R&D consortia in the United States and Japan', *Research Policy*, **24**(2), pp. 301–316.

Arrow, K. J. (1962). 'Economic welfare and the allocation of resources for invention'. In R. R. Nelson (ed.), *The Rate and Direction of Inventive Activity: Economic and Social Factors*. Princeton University Press, Princeton, NJ, pp. 609–626.

Barney, J. (1991). 'Firm resources and sustained competitive advantage', *Journal of Management*, **17**(1), pp. 99–120.

Borys, B. and D. B. Jemison (1989). 'Hybrid arrangements as strategic alliances: Theoretical issues in organizational combinations', *Academy of Management Review*, **14**(2), pp. 234–249.

Brockhoff, K., A. K. Gupta and C. Rotering (1991). 'Inter-firm R&D co-operations in Germany', *Technovation*, **11**(4), pp. 219–229.

Choi, J. P. (1990). 'Essays in the theory of dynamic R&D competition', unpublished Ph.D. thesis, Harvard University, Cambridge, MA.

Cockburn, I. and Z. Griliches (1987). 'Industry effects and appropriability measures in the stock market's valuation of R&D and patents', Discussion Paper No. 1360, Harvard Institute of Economic Research, Cambridge, MA.

Cockburn, I. and R. Henderson (1994). 'Racing to invest? The dynamics of competition in ethical drug discovery', *Journal of Economics and Management Strategy*, **3**(3), pp. 481–519.

Cohen, W. M. and D. A. Levinthal (1989). 'Innovation and learning: The two faces of R&D', *Economic Journal*, **99**(397), pp. 569–610.

Contractor, F. J. and P. Lorange (1988). 'Why should firms cooperate? The strategy and economics basis for cooperative ventures'. In F. J. Contractor and P. Lorange (eds.), *Cooperative Strategies in International Business*. Lexington Books, Lexington, MA, pp. 3–31.

D'Aspremont, C. and A. Jacquemin (1988). 'Cooperative and noncooperative R&D in duopoly with spillovers', *American Economic Review*, **78**(5), pp. 1133–1137.

Dierickx, I. and K. Cool (1989). 'Asset stock accumulation and sustainability of competitive advantage', *Management Science*, **35**(12), pp. 1504–1511.

Doz, Y. L. (1987). 'Technology partnerships between larger and smaller firms: some critical issues', *International Studies of Management and Organization* **17**(4), pp. 31–57.

Doz, Y. L. (1996). 'The evolution of cooperation in strategic alliances: Initial conditions or learning processes?', *Strategic Management Journal*, Summer Special Issue, **17**, pp. 55–83.

Dunning, J. H. and P. Robson (eds.) (1988). *Multinationals and the European Community*. Basil Blackwell, New York.

Fransman, M. (1990). *The Market and Beyond: Cooperation and Competition in Information Technology Development in the Japanese System*. Cambridge University Press, Cambridge, U.K.

Geroski, P. A. (1993). 'Antitrust policy towards cooperative R&D ventures', *Oxford Review of Economic Policy*, **9**(2), pp. 58–71.

Griliches, Z. (1992). 'The search for R&D spillovers', *Scandinavian Journal of Economics*, **94** (Suppl.), pp. 29–47.

Hagedoorn, J. (1993). 'Understanding the rationale of strategic technology partnering: Interorganizational modes of cooperation and sectoral differences', *Strategic Management Journal*, **14**(5), pp. 371–385.

Hagedoorn, J. (1995). 'A note on international market leaders and networks of strategic technology partnering', *Strategic Management Journal*, **16**(3), pp. 241–250.

Hagedoorn, J. and J. Schakenraad (1990). 'Inter-firm partnerships and co-operative strategies in core technologies'. In C. Freeman and L. Soete (eds.), *New Explorations in the Economics of Technical Change*. Pinter, London, pp. 3–28.

Hamel, G. (1991). 'Competition for competence and inter-partner learning within international strategic alliances', *Strategic Management Journal*, Summer Special Issue, **12**, pp. 83–103.

Harrigan, K. R. (1985). *Strategies for Joint Ventures*. Lexington Books, Lexington, MA.

Harrigan, K. R. (1986). *Managing for Joint Venture Success*. Lexington Books, Lexington, MA.

Hennart, J. (1988). 'A transaction costs theory of equity joint ventures', *Strategic Management Journal*, **9**(4), pp. 361–374.

Hergert, M. and D. Morris (1988). 'Trends in international collaborative agreements'. In F. J. Contractor and P. Lorange (eds.), *Cooperative Strategies in International Business*. Lexington Books, Lexington, MA, pp. 99–109.

Hladik, K. J. (1988). 'R&D and international joint ventures'. In F. J. Contractor and P. Lorange (eds.), *Cooperative Strategies in International Business*. Lexington Books, Lexington, MA, pp. 187–205.

Jorde, T. M. and D. J. Teece (1990). 'Innovation and cooperation: Implications for competition and antitrust', *Journal of Economic Perspectives*, **4**, pp. 75–96.

Katz, M. L. (1986). 'An analysis of cooperative research and development', *RAND Journal of Economics*, **17**(4), pp. 527–543.

Katz, M. L. (1993). 'Research joint ventures as a means of assembling complementary inputs', working paper, University of California, Berkeley, CA.

Katz, M. L. and J. A. Ordover (1990). 'R&D cooperation and competition', *Brookings Papers on Economic Activity: Microeconomics*, pp. 137–203.

Killing, J. P. (1983). *Strategies for Joint Venture Success*. Praeger, New York.

Kleinknecht, A. and J. O. N. Reijnen (1992). 'Why do firms cooperate on R&D? An empirical study', *Research Policy*, **21**(4), pp. 347–360.

Kodama, F. (1992). 'Technology fusion and the new R&D', *Harvard Business Review*, **70**(4), pp. 70–78.

Kodama, F. (1991). *Analyzing Japanese High Technologies: The Techno-Paradigm Shift*. Pinter, New York.

Kogut, B. (1988). 'Joint ventures: Theoretical and empirical perspectives', *Strategic Management Journal*, **9**(4), pp. 319–332.

Kogut, B. and H. Singh (1988). 'Entering the United States by joint venture: Competitive rivalry and industry structure'. In F. J. Contractor and P. Lorange (eds.), *Cooperative Strategies in International Business*. Lexington Books, Lexington, MA, pp. 241–251.

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

Levin, R. C., A. K. Klevorick, R. R. Nelson and S. G. Winter (1987). 'Appropriating the returns from industrial research and development', *Brookings Papers on Economic Activity*, **3**, pp. 783–820.

Link, A. N. and L. L. Bauer (1987). 'An economic analysis of cooperative research', *Technovation*, **6**(4), pp. 247–260.

Milgrom, P. and J. Roberts (1990). 'The economics of modern manufacturing: Technology, strategy, and organization', *American Economic Review*, **80**(3), pp. 511–528.

Milliken, F. J. and T. K. Lant (1991). 'The effect of and organization's recent performance history on strategic persistence and change: The role of managerial interpretations'. In P. Shrivastava, A. Huff and J. Dutton (eds.), *Advances in Strategic Management*, Vol. 7. JAI Press, Greenwich, CT, pp. 129–156.

Montgomery, C. A. (1982). 'The measurement of firm diversification: Some new empirical evidence', *Academy of Management Journal*, **25**(2), pp. 299–307.

Motta, M. (1992). 'Cooperative R&D and vertical product differentiation', *International Journal of Industrial Organization*, **10**(4), pp. 643–661.

Murphy, W. J. (1991). *R&D Cooperation among Marketplace Competitors*. Quorum Books, Westpoint, CT.

Osborn, R. N. and C. C. Baughn (1990). 'Forms of interorganizational governance for multinational alliances', *Academy of Management Journal*, **33**(3), pp. 503–519.

Ouchi, W. G. and M. K. Bolton (1988). 'The logic of joint research and development', *California Management Review*, **30**(3), pp. 9–33.

Palepu, K. (1985). 'Diversification strategy, profit performance and the entropy measure', *Strategic Management Journal*, **6**(3), pp. 239–255.

Pisano, G. P. (1991). 'The governance of innovation: Vertical integration and collaborative arrangements in the biotechnology industry', *Research Policy*, **20**, pp. 237–249.

Polanyi, M. (1958). *Personal Knowledge: Towards a Post-critical Philosophy*. University of Chicago Press, Chicago, IL.

Porter, M. E. (1990). *The Competitive Advantage of Nations*. Free Press, New York.

Porter, M. E., H. Takeuchi with M. Sakakibara (forthcoming). *The Two Japans: Reexamining the 'Japanese Model' of Competitiveness*.

Prahalad, C. K. and G. Hamel (1990). 'The core competence and the corporation', *Harvard Business Review*, **68**(3), pp. 71–91.

Pucik, V. (1988). 'Strategic alliances, organizational learning, and competitive advantage: The HRM agenda', *Human Resource Management*, **27**(1), pp. 77–93.

Randor, M. (1991). 'Technological acquisition strategies and processes: A reconsideration of the make versus buy decision', *International Journal of Technology Management*, **6**, pp. 113–135.

Reinganum, J. F. (1989). 'The timing of innovation: Research, development and diffusion'. In R. Schmalensee and R. D. Willig (eds.), *Handbook of Industrial Organization*, Vol. 1, North Holland, Amsterdam, pp. 849–908.

Sakakibara, M. (1997). 'Evaluating government sponsored R&D consortia in Japan: Who benefits and how?', *Research Policy*, forthcoming.

Scott, J. T. (1988). 'Diversification versus co-operation in R&D investment', *Managerial and Decision Economics*, **9**(3), pp. 173–186.

Shirai, I. and F. Kodama (1989). *Analysis on the Participants of R&D Consortia* (in Japanese). National Institute of Science and Technology Policy, Report No. 5, Science and Technology Agency of Japan.

Sinha, D. K. and M. A. Cusumano (1991). 'Complementary resources and cooperative research: A model of research joint ventures among competitors', *Management Science*, **37**(9), pp. 1091–1106.

Smith, K. G., S. J. Carroll and S. J. Ashford (1995). 'Intra- and interorganizational cooperation: Toward a research agenda', *Academy of Management Journal*, **38**(1), pp. 7–23.

Spence, M. (1984). 'Cost reduction, competition and industry performance', *Econometrica*, **52**(1), pp. 101–121.

Teece, D. J. (1986). 'Profiting from technological innovation', *Research Policy*, **15**(6), pp. 286–305.

Teece, D. J. (1992). 'Competition, cooperation and innovation: Organizational arrangements for regimes of rapid technological progress', *Journal of Economic Behavior and Organization*, **18**(1), pp. 1–25.

Tyler, B. B. and H. K. Steensma (1995). 'Evaluating technological collaborative opportunities: A cognitive modeling perspective', *Strategic Management Journal*, Summer Special Issue, **16**, pp. 44–70.

Westney, D. E. (1988). 'Domestic and foreign learning curves in managing international cooperative strategies'. In F. J. Contractor and P. Lorange (eds.), *Cooperative Strategies in International Business*. Lexington Books, Lexington, MA, pp. 339–346.

Williamson, O. E. (1991). 'Comparative economic organization: The analysis of discrete structural alternatives', *Administrative Science Quarterly*, **36**(2), pp. 269–296.

APPENDIX 1: Government-sponsored R&D consortia data

This sample includes cooperative R&D projects sponsored by the Ministry of International Trade and Industry (MITI), the Ministry of Transportation, the Ministry of Agriculture, Forestry and Fisheries, the Ministry of Post and Telecommunications, and the Ministry of Health and Welfare. This sample was collected from each ministry through direct contacts after examining a wide range of government White Papers and other government publications. MITI-related projects were especially well documented through personal contact with all the project-related divisions at MITI. I might have missed a very small number of projects which were not reported in official publications, especially in defense, forest products, transportation, telecommunications, and health care. Based on the available information, R&D promotion in these industries other than what was covered in my data set took the form of government funding of individual companies and government procurement, not the promotion of cooperative R&D. Therefore, I think my data set is a quite comprehensive representation of all government-sponsored R&D consortia.

Government-sponsored R&D consortia in the sample include all significant company-to-company cooperative R&D projects formed with a degree of government involvement. A principal criterion in the sample selection is that the projects of the R&D consortia involved cooperation among private companies. Projects organized not as cooperation among companies but as governmental projects without companies' expenditure were excluded. An example of this type of project is the Exploratory Research for Advanced Technology Project, sponsored by the Science and Technology Agency.

Various types of R&D consortia are included in this sample. One way to classify them is by their organizational forms, which are associated with different tax benefits. A typical type is the one designated as Technological Research Associations. This scheme, introduced to Japan in 1961, and modeled after British research associations, was intended to promote R&D consortia as a means of coping with trade liberalization and to enhance the productivity of Japanese industries. At that time, Japan faced the task of abolishing domestic industry protection following the domestic industry's recovery from the devastation of the Second World War. Under this scheme, participating companies enjoyed several tax benefits on their research expenses. Typical tax benefits include accelerated depreciation for expenses on machinery and equipment, instant depreciation of fixed assets for R&D, and discounts of property taxes on fixed assets used for R&D. In my data set, 134 Technological Research Associations are documented. Other organizational forms for R&D consortia include foundations and corporations. These forms are chosen by participants on the basis of each form's financial and organizational benefits.

Also, there have been various types distinguished by the sort of R&D and the presence of political goals. They include the Sunshine Project to promote petroleum-alternative energy source development, the Moonlight Project to promote energy conservation technology, and the Large Scale Project to promote large-scale, state-of-the-art R&D projects which the private sector itself could not initiate. Others include the Next Generation Technology Development Project and the Key Technology Development Project.

Government involvement in funding R&D varies with the type of promotional scheme. For example, the Large Scale Project, the Next Generation Technology Development Project, the Sunshine Project, and the Moonlight Project were 100 percent funded by the government. However, government funding customarily does not cover all project expenses, and so consortia participants have to pay the rest. In my data set, as far as I can ascertain, these private expenses are included. The Key Technology Development Project was 70 percent funded by the government. Projects of different project types can use the Technological Research Association framework, and so a project can be classified by both project type and organizational form.

Data collected for the sample include a description of each project, its period of operation, the total budget, the amount of government subsidy, and the names of participating firms. Sources of the data include *The 30 Year History of the Mining and Industry Technology Research Associations* by the Council of the Mining and Industry Technology Research Association, 1991, brochures of each project type, issued by MITI and its affiliated organizations, and hearings from each governmental organization. The sample starts in 1959. Before 1959, the typical method of promoting R&D by the Japanese government, especially MITI, was subsidies to individual companies.

APPENDIX 2: Correlation matrix

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Complementary knowledge sharing/skill-sharing motive	–															
2	Entering new business	–0.02	–														
3	Avoiding wasteful duplication	0.44	–0.04	–													
4	Catching up with overseas competitors	0.06	0.00	0.21	–												
5	Sharing of fixed costs	0.37	0.04	0.44	0.20	–											
6	Catching up with domestic nonparticipants	0.01	0.09	0.04	0.18	0.01	–										
7	Cost-sharing motive	0.48	–0.00	0.85	0.24	0.85	0.03	–									
8	Relative importance of skill vs. cost-sharing motives	0.51	–0.02	–0.39	–0.18	–0.47	–0.02	–0.51	–								
9	Breadth of industry participation (questionnaire)	0.13	0.02	0.02	–0.28	–0.08	0.09	–0.04	0.16	–							
10	Palepu total entropy measure	0.06	–0.01	–0.13	–0.31	–0.17	0.21	–0.18	0.23	0.51	–						
11	Palepu unrelated entropy measure	0.06	–0.04	–0.10	–0.32	–0.17	0.20	–0.16	0.22	0.56	0.93	–					
12	Montgomery 2-digit measure	0.06	0.00	–0.08	–0.29	–0.15	0.18	–0.14	0.20	0.57	0.88	0.95	–				
13	Montgomery 3-digit measure	0.05	0.06	–0.13	–0.26	–0.15	0.18	–0.17	0.21	0.44	0.93	0.76	0.78	–			
14	Project size	0.09	–0.15	0.06	0.25	0.15	–0.06	0.13	–0.03	–0.23	–0.05	–0.16	–0.15	0.01	–		
15	Project-related private R&D spending (questionnaire)	0.01	0.08	–0.04	–0.04	–0.10	–0.04	–0.08	0.09	–0.11	–0.03	–0.10	–0.04	0.06	0.14	–	
16	Firm R&D expenditure	–0.11	–0.07	–0.10	–0.05	0.07	–0.04	–0.02	–0.10	0.05	0.15	0.12	0.09	0.12	–0.02	–0.07	–
17	Overall evaluation of the project	0.03	0.11	–0.01	0.12	0.06	–0.03	0.03	–0.00	–0.13	–0.19	–0.21	–0.19	–0.16	0.12	0.04	0.06

APPENDIX 3: Diversity measures

Identification of firms' main businesses

In order to obtain an objective measure to identify the primary industry of participating firms, I used *Kaisha Kigyo Meikan* (Company Almanac) edited by the Statistics Bureau of the Management and Coordination Agency Japan. This source is a list of companies that are covered by the Census of Establishments, an official census by the Japanese Government. In the Company Almanac, each company reports the SIC 3-digit level industry codes to which its establishments belong. I used the SIC code the firm reported as the primary industry for its headquarters to identify each company's main business. When the firm reports the function of headquarters (such as wholesaling) instead of the industry, I used the industry to which the largest factory of the firm was assigned as the primary industry. Many companies have been assigned to different industries at different times as they change their primary industries. I used the SIC code of a firm at the time the firm joined the project. I used 1963 data for the analysis of the data in the 1960s and earlier, 1972 data for the 1970s, and 1986 data for the 1980s, due to the availability of the source.

Calculation of diversity measures

Palepu entropy measures

Total diversity:

$$\mathrm{DT} = \sum_{i=1}^{n} P_i \ln(1/P_i)$$

where

P_i = share of firms in the ith industry at the 3-digit SIC level
n = number of SIC industries at the 3-digit level

Unrelated diversity:

$$\mathrm{DU} = \sum_{j=1}^{m} P_j \ln(1/P_j)$$

where

P_j = share of firms in the jth industry at the 2-digit SIC level
m = number of SIC industries at the 2-digit level

Montgomery product count measures

$$\text{diversity} = 1 - \frac{\sum \mathrm{m}_j^2}{\left(\sum_j M_j\right)^2}$$

where

m_j = share of firms that are in industry segment j, where j is measured at the 2- and 3-digit SIC code

For the calculation, it is assumed that each firm has an equal share in an R&D consortium.