ELSEVIER

Research Policy 27 (1998) 111–126

research policy

Optimal scale for research and development in foreign environments—an investigation into size and performance of research and development laboratories abroad

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Received 20 April 1997; revised 5 June 1997; accepted 10 February 1998

Abstract

This paper examines the relationship between performance and size of R&D laboratories operated abroad. Based on a theoretical argument, the paper proposes a concave relationship between laboratory size and performance, as well as a linear relationship between firm learning and laboratory performance. Empirical tests with 129 laboratories established by 27 multinational companies in the pharmaceuticals and electronics industries support these conjectures.

Keywords: Optimal size of R&D sites; Performance of R&D sites; International R&D management; Research vs. development

1. Introduction

Studying productivity of firm research and development (R&D) is a challenging task. Corporations in the US, Japan, Germany, France and the UK spent on average 1.7% of their respective country's gross domestic product on R&D (OECD, 1993). Yet, while a considerable number of researchers have measured R&D productivity at the industry, firm, or product line level, evidence on productivity and spillovers of R&D at the laboratory site level is limited (Brockhoff, 1994; Brockhoff and Schmaul, 1996; Coombs et al., 1996; Falk, 1982; Freeman, 1987; Jaffe, 1989b).

However, studying productivity of firm R&D at the laboratory site level is also a potentially very rewarding task (Allen, 1977), for at least three reasons. First, little is known about the relationship between performance of R&D sites and other variables, particularly the size of R&D sites. It seems fruitful to explore, on a theoretical level, how organizational and cognitive phenomena that have been documented in the R&D literature inhibit or stimulate scientific and engineering productivity at the site level. This effort leads to testable hypotheses and answers the question whether there is an optimal size of R&D sites. Second, results from such an inquiry could potentially be useful to academics outside of the field of research management as well, namely to organization scientists (Kimberly, 1976). Third, this research contributes to the discussion about alternative measures of performance of R&D at the laboratory site level.

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0048-7333/98/$19.00
PII S0048-7333(98)00030-4

This paper explores the relationship between laboratory size, laboratory performance, and firm learning. Based on existing research, the paper develops a number of hypotheses. A survey-based measure, as well as a patent-based measure are used to evaluate laboratory performance. Section 2 reviews the relevant literature and investigates the research question from a theoretical perspective. Section 3 develops a model and describes an empirical test. Section 4 analyzes and evaluates results. Section 5, the conclusion, also suggests how this research can be extended.

2. Literature and research hypotheses

A number of researchers have studied the question of R&D management and R&D planning in private industry. A large part of this work has focused on the organization of R&D activities within laboratories (Allen, 1977; Bergen, 1990; Heyel, 1968; Hughes, 1974; Smith et al., 1982), and on the management of spillovers from publicly funded R&D (Jaffe, 1989a; Jaffe, 1989b). This stream of research has shown that the management of firm R&D is a complex activity that requires outstanding managerial skills covering a wide range of activities. Successful R&D managers excel in coordinating R&D activities with the firm's long-term strategy, as well as in making the right choices concerning micro-level issues, such as determining the optimal layout of a laboratory working space, selecting an appropriate communication system and forming and dissolving teams at the right time. For example, Katz and Allen (1982) examined the link between performance of R&D project teams and the tenure of these teams and found a concave relationship: performance increases up to 1.5 years tenure of a R&D project team, is steady for some time, but declines noticeably beyond 5 years tenure.

Insufficient research has been carried out concerning the link between size and productivity of R&D sites, however (Perrino and Tipping, 1989). This seems to be at least partially due to the difficulties associated with measuring R&D performance of laboratory sites. Past research has focused either on the firm level or on the project level. Those studies that looked at the project level frequently chose development projects rather than research projects as a unit of analysis, partially because the outcome of these development projects was easier to identify and because comprehensive data could be gathered more easily (Clark and Fujimoto, 1989).

More recently, a number of researchers have studied the international dispersion of corporate R&D activities (Brockhoff and Von Boehmer, 1993; Kuemmerle, 1997; Patel, 1996; Pearson et al., 1993). With the exception of Patel, these studies conclude that the internationalization of R&D is an increasing trend, and that the two most important drivers of R&D internationalization are sourcing of technology and market adaptation.

The geographical dispersion of firm R&D activities depends on, among other things, knowledge about the optimal size of an R&D site. An improved understanding about the optimal size of a *site* would complement research about overall industry and firm R&D productivity as measured by patent data and citations, and about the performance of R&D at the project level as measured by detailed empirical studies (Amabile et al., 1994; Griliches, 1990; Jaffe et al., 1993; Mansfield, 1984; Mansfield et al., 1977).

Interestingly, there is not much evidence on the optimal size of a laboratory site. Allen (1977) discusses the issue of laboratory size and mentions a concrete number for the optimal size of a domestic laboratory site: 1000 employees. However, while Allen argues that there might be some minimum efficient scale, he also states explicitly that the number, 1000 employees, is based purely on anecdotal evidence and has never been confirmed empirically. Brockhoff (1994) mentions that (domestic) laboratory sites in the chemical and pharmaceutical industry should not be expanded beyond a size of 1000 to 1300 employees. Perrino and Tipping (1989), in an interview-based survey of 16 multinational firms, find anecdotal evidence that 'for some degree of effectiveness (of a laboratory site)' 50–100 employees are needed. They also find that some of the managers interviewed believed that laboratories begin to lose productivity when they grow beyond 250 to 300 employees.

Firm R&D activities generally have an aim or product of commercial value in view. The organization of firm R&D in general and of a firm's R&D

sites in particular must therefore be geared towards achieving this goal. R&D activities are normally organized in projects covered by a number of working groups of scientists, usually comprising between 5 and 10 researchers. The working group leader generally is a senior scientist or engineer with an advanced degree; members include a number of junior scientists and engineers, as well as support specialists such as computer administrators or laboratory assistants. Typically, the working group leader reports the progress of R&D activities to the overall coordinator of the research project. The working group leader also interacts with an administrative unit that provides materials and infrastructure for R&D and manages the payroll for researchers. If there are no requirements for a larger minimum scale because of technical equipment, one could argue that the minimum scale of an R&D site is *one* working group of researchers plus the administrative support staff. This number could be as low as 10 employees for a laboratory site.

Larger sites do provide potential benefits, however. Firm R&D essentially takes place in a hierarchical structure. Junior researchers carry out experiments and other scientific work based on directions from senior researchers, then report results back to senior researchers. In that sense, R&D is not different from other firm functions. R&D *is* different from other firms functions, however, in that the outcomes of R&D activity and the means to achieve them are not well-defined before the start of an R&D project. It is difficult to forecast when researchers will have 'good ideas'—and what kind of good ideas. Furthermore, it is not entirely clear how the creative process can be optimally supported. However, a number of researchers have found that lateral spillovers between different R&D teams are important contributors to the success of an R&D project (Amabile, 1987; Bergen, 1990; Clark and Fujimoto, 1989; Hughes, 1974). Thus, in addition to the formal hierarchical flow of research results upwards and feedback downwards, successful R&D seems to require a strong lateral network of communication among R&D employees within the firm. A problem in the design of a scientific experiment, for example, can often be solved much more quickly if there is an R&D team with related knowledge and skills next-door, rather than if the researchers must communicate with other researchers over large geographical distances in order to find a potential solution (Allen, 1977).

Immediate geographical proximity to other researchers is conducive to successful R&D not only because it is difficult to forecast at what point in time during an investigative effort problems will occur and advice is needed, but also because these problems are often difficult to codify in formal language. Explaining the problems of a prototype test over e-mail or in a telephone conversation is considerably more time-consuming than if the researcher who might be able to provide help is working close by and can 'grasp' the problem by inspecting the prototype and the testing site personally.

Another advantage of geographical proximity to other researchers is agglomeration economies at the micro level. Researchers working on partially related or unrelated projects in close geographical proximity communicate informally beyond their current projects. This form of communication, which generally occurs in hallways, during coffee breaks, or over lunch, can provide good ideas for future research projects and new personal ties with other researchers. In addition, because firms continuously start new research projects, they benefit from a large and diverse stock of current projects. Experience from ongoing projects enables managers to select research team members who not only have relevant knowledge and skills, but who also are able to work together well as a team. Informal communication provides an opportunity for researchers to get acquainted with each other. This will generally be conducive to the formation of effective teams.

In summary, a laboratory site that exceeds the minimum scale has three advantages as far as lateral communication is concerned: quick access to potential support, reduced complexity of communication, and opportunity for informal communication beyond current projects.

An interesting question that follows from the argument above is whether the returns to scale concerning lateral communication are increasing without limit. One could argue that this property obtains for the first two advantages. The more employees a laboratory has, the higher is the probability that somebody at the same site knows the solution to a problem. Furthermore, even at a large site, a re-

searcher can walk or drive to another researcher's laboratory in a matter of minutes to inspect an experiment or to discuss results.

However, laboratory size might have a constant or even negative effect on informal communication beyond a certain threshold. Researchers can only establish informal contacts with a limited number of fellow researchers. These limits are determined by the size of human memory and by the time the individual researcher has available for informal communication. If there are more than a certain number of employees in one site, researchers may not remember informal contacts when they need them most, or they might not have time to maintain personal ties once these have been established. In addition, a very large laboratory site might strongly intimidate a researcher from communicating informally with colleagues in the first place. Thus, while larger R&D sites increase the number of potential ties that a researcher can establish with fellow researchers at a site, many of these ties will be weak. In fact, many of these ties will be too weak to function as support structures for R&D work.

A number of researchers have shown that while weak ties might be useful to a certain degree, strong ties among researchers and managers are a necessary condition for successful R&D (Allen, 1977; Clark and Wheelwright, 1992; Nohria and Eccles, 1992). Strong ties enable researchers to communicate at low cost at critical moments in the R&D process. At large R&D sites, it is more difficult for individuals to meet other researchers and to establish strong ties than at smaller R&D sites (Perrino and Tipping, 1989). As a result, researchers at large sites generally rely on a smaller number of strong ties than researchers at smaller sites. Case-based evidence from our own study confirms Perrino and Tippings' observation. At one site with 240 employees, researchers maintained 13 strong ties on average. At another site with 380 employees (belonging to the same firm) researchers maintained 8 strong ties on average.

At a certain laboratory size, the negative effect of increasing laboratory size on informal communication and quality of ties will eventually outweigh its positive effect on access to potential support and reduced complexity of communication. In other words, geographical concentration of resources is irrelevant for the progress of a research project if individual researchers cannot benefit from potential spillovers in the first place.

Firms can, of course, take measures to facilitate lateral communication within a large laboratory site. Intra-laboratory colloquia, wherein researchers present intermediate results to interested colleagues, electronic communication systems, the layout of dining halls, and the organization of informal meeting platforms after work all offer opportunities for informal communication. These and other measures will enable the researcher to establish ties with other researchers more easily. Also, these measures can help researchers to strengthen existing ties. Nevertheless, we would argue that even with these measures, laboratory performance will decline once a laboratory has grown beyond a certain size.

Beyond the minimum size (one research team and support staff) laboratory performance will also increase because of declining overhead costs per researcher. Overhead generally consists of administrative costs, facilities and equipment costs. However, in addition to negative effects on informal communication, increasing laboratory size will most probably eventually lead to rising overhead costs per researcher.

Furthermore, larger laboratories generally employ additional layers of science managers between bench scientists and laboratory leaders. In larger laboratories, the most accomplished scientists and engineers are often pressured to spend larger amounts of time on administrative matters than if they were working at smaller sites. As a result, the most qualified scientists and engineers have less time for coaching of younger scientists and for their own research (Patterson, 1993).

It is quite challenging to empirically separate the initially positive effects of overhead sharing and the subsequently negative effects on lengthy decision routines from the initially positive, but subsequently negative effects that laboratory size has on lateral communication. We will not be able to do so in the following model. However, we can summarize our theoretical argument in the following set of hypotheses.

H1a: At small laboratory scales, laboratory performance is increasing.

Beyond the minimum size of one research team and support staff laboratory performance increases

because of a combination of the positive effects of quick access to potential support from other researchers at the same site and increasing opportunities for informal communication. H1a would be falsified if we did not find increasing laboratory performance at small laboratory scales.

H1b: At large laboratory scales, laboratory performance is decreasing.

With the growing size of the laboratory site, the overall amount of meaningful informal communication at the laboratory site decreases because individual researchers become increasingly isolated. This leads to lower performance of the site.

Based on our field research, we think that the downward sloping part of the laboratory performance curve is caused by additional administrative tasks imposed on highly qualified scientists and by a relatively greater share of weak rather than strong ties between researchers. However, the downward slope in performance could also be caused by at least three other phenomena.

First, at a certain size, laboratories might become engaged in more than one field of technology. In each of these fields, operations can be small enough to support efficient communication. It is possible that the true reason for declining performance of larger laboratories is poor management of the laboratory's technology portfolio and a lack of focus.

Second, technology cycles might be responsible for the decline in performance of larger sites. When an important technology has reached maturity, and the site becomes oversized for the remaining technological potential, performance in terms of output/input terms is likely to suffer. There could be a period of temporary decline in performance and a subsequent adjustment of size.

A third alternative explanation for lower performance of larger sites could be power struggles, which are part of international expansion and growth (Doz and Prahalad, 1991). One could argue that as laboratory sites abroad grow beyond a certain threshold size, managers at the home base or at other sites abroad grow envious and seek to hamper further expansion of the site in question. These managers might seek to influence the resource allocation and budgeting process in a way that makes it harder for the site to receive additional resources. Thus, power struggles might consume an increasing amount of management capacity at the site and reduce the amount of time available for R&D.

In the empirical analysis below, we will test whether there is a negative relationship between laboratory size and performance. The test does not allow us to identify to what degree the four phenomena listed here contribute to declining performance.

3. Learning and performance of R&D sites

While the main focus in this paper is the relationship between laboratory size and performance, we also reflected on how laboratory site performance will differ for different stocks of R&D management knowledge at the laboratory site level and at the firm level.

We expect that over time, the organization of R&D activity within a laboratory site improves. Through a trial-and-error process senior R&D management learns how to better manage informal communication within the laboratory, how to absorb more spillovers from other research organizations in close geographical proximity, and how to identify the best researchers for recruitment. Also, over time laboratory employees learn how to communicate better with other parts of the firm regardless of lab size. Therefore, we expect a higher performance for laboratories that have been operating for a longer time.

Furthermore, we expect that firms learn how to improve the startup process and management of R&D at a new laboratory site with each additional site they establish. The firm's initial choices for a new laboratory site, such as how to organize the flow of information, how to select and hire appropriate researchers, and how to integrate the new laboratory into the firm's existing R&D network, are crucial to the laboratory's success (Kuemmerle, 1997). We hypothesize that the more often the firm has gone through the process of establishing and starting up a new laboratory site, the higher the performance of the next new site will be.

We summarize our expectations in the following two hypotheses.

H2: Performance of a laboratory sites increases with the age of the site.

H3: Performance of a given laboratory site increases with the number of sites that the firm has established prior to establishing the site in question.

Other researchers have found that team performance increases with team tenure, reaches a plateau and declines thereafter (Katz and Allen, 1982). If we found support for hypothesis 2, this earlier finding would be contradicted (albeit at the laboratory site as opposed to the team level) unless the firm had changed the composition of teams at the site over time, and thus kept teams performing at their optimum level. This is in fact the case. Reorganization and staffing changes of teams occurred at all sites we studied. Teams within the site were formed for specific research projects that lasted anywhere from a couple of months to several years. Furthermore, natural fluctuation of employment at the site lead to recomposition of teams and to changes of site employment. Finally, scientists and engineers from other sites were transferred to the site in question either temporarily or permanently.

4. Data and model

In order to test our conjectures, we use data on laboratory sites abroad from an extensive survey about the geographical dispersion of R&D activities by multinational enterprises (Kuemmerle, 1997). Using data on laboratory sites abroad rather than laboratory sites in the firm's home country offers two advantages. First, the potential sample of sites is larger. Firms in the sample operated approximately twice as many sites abroad than in their home country. Second, as will be discussed below, we expect a smaller upward bias of the perception-based performance measure for sites located abroad.

The survey covered all laboratory investments by 32 US, Japanese and European pharmaceutical and electronics firms. Twenty-seven out of 32 firms provided data on laboratory performance. Thirteen out of 27 firms are Fortune Global 50 firms, while 24 out of 27 firms are Fortune Global 500 firms (Fortune, 1995). Of the 27 firms, 7 are domiciled in the US, 12 in Japan, and 8 in Europe; 10 are pharmaceutical firms and 17 electronics firms. While the main objective of the survey was to examine competitive interaction in technologically intensive industries [1] and to analyze motives for foreign direct investment in R&D, we also collected a simple performance measure for all foreign laboratories of 27 of these firms. The data collection effort included archival research, a detailed questionnaire, and at least one interview (normally two or three) with senior managers in R&D and top line managers at each company. We estimate that our sample comprises almost all laboratory sites these firms operate abroad and most of the R&D sites operated in their respective home countries (Fig. 1).

Electronics firms	19	60%
Pharmaceutical firms	13	40%
Total number of firms	32	100%
Research sites	76	49%
Development sites	78	51%
Total number of sites	154	100%
Average number of sites per firm	4.81	
Average number of employees per site	86	

Fig. 1. Summary of information on R&D sites abroad in sample.

4.1. Dependent variables

We considered a number of possibilities for measuring laboratory performance and eventually decided on a perception-based measure as well as a patent-based measure. We had initially intended to measure laboratory performance exclusively by using patenting activity at the laboratory level. Although we collected such data for a number of laboratory sites, for a large number of sites, patenting data was nonexistent. Furthermore, most managers we interviewed discouraged us from using patent data because patents are not always filed in the country of inventive activity; also, joint inventive efforts across sites make attribution of patents to specific sites difficult, and in a very productive research environment patents are sometimes not filed at all since they bind resources that can be deployed more productively for other R&D tasks.

We also considered the number of scientific publications as a dependent variable, but decided not to

[1] Mean R&D/Sales ratio in the sample: pharmaceuticals: 8.4, electronics: 6.5%.

use this measure because incentives to publish differ across firms and because our sample includes 78 development laboratories (51% of the total sample) that, given the nature of their work, produce only a few publications.

Finally, we considered measuring the contribution of each laboratory site to the firm's current sales. The contribution could be measured by attributing sales figures for each product the firm currently sells or sold within a given period to the R&D laboratory site where the primary R&D activity was carried out. To our knowledge, such a performance measure has so far not been used in empirical investigations. However, there are formidable challenges associated with data collection for this measure, particularly in regards to the contribution of research laboratory sites to current sales.

Instead, we decided to measure perceived laboratory performance through interviews with senior R&D executives in charge of global R&D management or technology management. We also use a patent-based measure for a smaller sample of sites as an alternative dependent variable. The interviews were prepared based on a questionnaire survey. Our method of measuring laboratory performance via perception-based measures is comparable to that used by Brockhoff and Schmaul (1996), although these authors relied exclusively on questionnaires. Typically, the executives we interviewed had a science and engineering background and had worked in R&D for a number of years, often for some time as the leader of a laboratory site, before moving into a coordinating management function. Through both preliminary interviews and contacts with the manager who introduced us to the firm, we sought to identify in each company the individual who had the best comparative understanding of all laboratory sites. A staff member in this individual's office would generally complete a detailed questionnaire with data about all laboratory sites.

Once the questionnaire had been mailed back to us, we scheduled an interview with the executive. We sought an evaluation of laboratory sites on a five-point scale with the following characteristics: 1 = Overall performance of the laboratory since establishment was strongly below expectations, 2 = ... below expectations, 3 = ... according to expectations, 4 = ... above expectations, 5 = ... highly above expectations. [2] Our measure of laboratory performance measures the level of satisfaction expressed by the most knowledgeable R&D managers in regards to the performance of each of their firms' R&D sites abroad.

We cannot exclude the possibility that responding managers' expectations concerning laboratory performance were conditioned positively or negatively by specific host country factors. However, we are quite confident that the respondents' evaluation of lab performance were not influenced by prior knowledge about optimal laboratory *size*. Results from a pilot study (which included interviews in three of the firms in the sample and interviews with R&D consultants) led us to conclude that there is no widely accepted optimal laboratory size. We made sure in our interview during the main study not to mention explicitly our intention to examine the relationship between size and performance of R&D sites. Thus, only very few, if any, executives in our sample were biased towards a specific size in their evaluation of laboratory site performance. [3]

We obtained evaluations for 139 laboratories operated abroad by 27 companies. In some cases, evaluations were not available because the executive did not know the site very well. Where we could interview two or three senior R&D executives (in about 70% of the labs), we checked responses across interviews. In cases of strong deviations, we discussed these deviations with all the managers concerned and used the resulting value. The variance of laboratory performance across multiple responses for the same laboratory location was significantly smaller (5% level) than the variance across the whole sample. We

[2] The exact wording for the question was as follows: Please evaluate the overall performance of each laboratory site that you described in the questionnaire on the following five-point scale: 1 = Overall performance of the laboratory site since establishment was strongly below expectations, 2 = ... below expectations, 3 = ... according to expectations, 4 = ... above expectations, 5 = highly above expectations.

[3] It is, in fact, important for our research design that the state of managers' information be exactly as described in this paragraph. If the respondents knew the intrinsic 'frontier' between performance and efficiency, their responses would indicate deviations of actual performance from efficient performance (or mean performance) for that scale, and we would learn nothing about true scale economies.

think that corporate and political considerations shaped the performance measure only little. Most respondents had no particularly strong formal affiliation with any of the laboratory sites abroad. Furthermore, we checked responses concerning laboratory performance with qualitative responses from the interviews concerning history, focus, and operations of the laboratories in order to catch possible contradictions.

The variable for laboratory performance (LABPERF) has a mean of 3.2 and responses were approximately normally distributed (S.D. = 0.97, n = 139). The mean responses and standard deviations for research sites and development sites differed only minimally (research sites: mean: 3.32, S.D.: 1.01; development sites: mean: 3.11, S.D.: 0.89). The null-hypothesis of identical means could be rejected at the 1% significance level.

Obviously, our perception-based performance measure represents two or three persons' opinions about a number of laboratory sites, which are quite complex organizational units. Except for cross-validation across two or three responses where applicable, and inspection whether responses satisfied a normal statistical distribution, we could only validate the accuracy of responses through qualitative statements from interviews. Furthermore, while the mean age of laboratories was about 11 years (base year: 1994) some laboratories had been established much earlier, up to 37 years ago. The executives that participated in our survey had generally been with the firm for over 10 years and were arguably among the most knowledgeable concerning the laboratory sites' performance.

We also collected data on average patent output per year for 88 electronics laboratories in the sample. PATENT measures the number of patents that were issued per year for research that was carried out at a site. This measure was provided by senior R&D managers, who in most cases, checked archival records. On average, each of the 88 sites obtained 4.3 patents per year (S.D. = 5.0). The patent-based measure of site performance is correlated with the perception-based performance measure (correlation coefficient 0.59, significant at 1% level). On average, each site produced 0.06 patents per employee and year. Research sites produced about twice as many patents as development sites. In a study of inventive productivity in four companies, Narin et al. find that inventors received 0.17 patents per year (Narin and Breitzman, 1995). This figure is about 3 times as high as our figure. One probable reason for this difference is that Narin examined patents per inventor (where inventor is defined as recipient of at least one fractional patent), while we examine patents per R&D site employee (which includes researchers who did not receive any patents and support staff).

4.2. Independent variables

The first independent variable (LABSFIN) is the 1994 size of the laboratory site in terms of total number of full-time equivalent employees. We used this measure instead of only the number of scientific employees because support staff, such as computer experts or experimental design assistants, make an increasingly important contribution to laboratory performance. While these employees might not be as unique as scientists in their specific skills, they are an important part of the laboratory structure. The range of laboratory size is 4 to 540, with a mean of 86. This range does not include two large development sites that employ 1200 and 1300 people, respectively. These two sites can be considered outliers, both in terms of their historical development and their size. We excluded them from the analysis. [4]

The laboratory size variable is corrected for short-term fluctuations and is representative for the laboratory size between 1993 and 1994. When they were established, many of the laboratory sites were originally designed for about 60% of their 1994 size, but were enlarged after about five years of operations and enlarged again somewhat later to reach their 1994 size. Since we expect a concave relationship between laboratory performance and size, we also included the square of laboratory size (LABSFISQ). We expect the laboratory size variable to

[4] Inclusion of these two outliers did not substantially change the results of our analysis. Specifically, all the coefficients had the hypothesized sign and were significant mostly at the 1% significance level or at least at the 5% level. The overall regressions remained significant at the 0.1% significance level. As one would expect, the estimated optimal size of a laboratory increases when the two large laboratories are included.

have a positive coefficient and the square of laboratory size to have a negative coefficient. [5]

The third independent variable is a control variable for two categories of laboratories. RESEARCH takes the value 1 if the laboratory is a research laboratory and 0 if the laboratory is a development laboratory. In the survey, we used OECD definitions (OECD, 1981) to distinguish research and development. The fourth independent variable is an industry control variable. PHARMA takes the value 1 for pharmaceutical laboratories and 0 for electronics laboratories.

The fifth independent variable, LABAGE, is the number of years since the laboratory was established (base year 1994). We expect this coefficient to be positive since a laboratory's performance will improve over time due to organizational learning. There was only a minimal survivorship bias in our sample. We surveyed all the laboratory sites abroad that the firms in our sample ever operated, and only two out of 154 laboratories had been closed.

The sixth independent variable, NUMLABS, is the number of laboratory sites the company operates abroad at the time the laboratory in question was established. We expect this coefficient to be positive, as firms will draw from the establishment experience of each laboratory when setting up a subsequent site. The managers interviewed were primarily corporate R&D managers who had in most cases been working for the company in question for more than 10 years. For 131 out of 154 laboratory investments abroad (81%), we could interview at least one manager who had been directly involved in the investment decision process.

We also included two regional dummies, EUROPE and JAPAN, in one specification of the regression in order to control for response differences among European, US, and Japanese managers. In the other specification, we substituted industry dummies and regional dummies through firm dummies. Finally, we included interaction terms of Japan and laboratory age, as well as Japan and number of laboratories in operation because over 40% of Japanese laboratory sites were established during the five years prior to 1994. [6]

5. Results

Figs. 2 and 3 present descriptive statistics and correlation coefficients. Fig. 4 shows regression results from an ordinary least squares regression. [7] In all models, laboratory size and the square of laboratory size have the expected coefficients and are highly significant. These results suggest that there is indeed a unique size at which laboratory performance is optimal.

The industry dummy for the pharmaceutical industry included in model 1 is not significant. Laboratory performance evaluations did not differ across the pharmaceutical and electronics industry. The coefficient for research is positive, but not significant at the 10% significance level in model 1, and significant at the 10% significance level in model 2. This represents weak evidence that the perceived performance for research activities in our sample was somewhat higher than for development activities.

In model 1, the coefficients for age of laboratory and number of laboratories established abroad prior

[5] The simple correlation between performance and square of laboratory size is positive but not significant at the 10% level. The correlation between patents and square of laboratory size is positive and significant at the 10% level. The sign of these correlation coefficients is unexpected. However, in the OLS regressions the square of laboratory size has the expected negative sign and is significant at the 1% level. Only once one controls for size can the concave relationship between performance and laboratory size be identified.

[6] We also tested interaction effects between LABAGE and NUMLABS and RESEARCH and PHARMA but did not find the inclusion of these interaction terms to significantly improve the regression results.

[7] We made an effort to select a suitable regression technique and decided for OLS. OLS requires the distribution of regression residuals to be homoskedastic. Inspection of Q–Q plots for models 1, 2 and 3 revealed no serious deviation from this condition. Furthermore, we carried out nonparametric tests that do not require a normal distribution (Kruskal–Wallis ANOVA). These tests support our findings from the OLS regression. Finally, while the dependent variable for models 1 and 2 represents only 5 ranked categories and is not continuous, it was pointed out to respondents that differences between response categories should be treated as equal.

Variable	Mean	Std Dev	Minimum	Maximum	Valid N
LABPERF	3.18	.97	1.00	5.00	139
PATENT	4.27	4.96	.00	30.00	88
LABSFIN	85.61	99.08	.00	540.00	150
LABSFISQ	17079.31	37915.07	.00	291600.0	150
JAPAN	.45	.50	.00	1.00	154
EUROPE	.21	.41	.00	1.00	154
PHARMA	.37	.48	.00	1.00	154
RESEARCH	.49	.50	.00	1.00	154
LABAGE	11.16	9.64	.00	37.00	153
NUMLABS	2.59	2.53	.00	12.00	154

Fig. 2. Descriptive statistics.

to the laboratory in question are both positive as expected and significant: at the 10% level for the number of labs in operation, and at the 5% level for the number of years the laboratory has been in operation. In model 2, the laboratory age variable is positive and significant at the 1% level, and the variable for the number of laboratories in operation is positive and significant at the 5% level. These results suggest that there is in fact a learning effect both within a laboratory site once the site is established, and across laboratory sites within the same firm. While the dependent variable does not have natural units, we attempted to interpret the magnitude of these results. For model 2, these results imply that a difference in laboratory age of one year leads to an increase in performance of 0.1 on a 5-point scale. The existence of one additional laboratory site by the time a new laboratory site is estab-

	LABPERF	PATENT	LABSFIN	LABSFISQ	EUROPE	JAPAN	PROCESS
LABPERF	1.0000						
PATENT	0.5871***	1.0000					
LABSFIN	0.2690**	0.5671***	1.0000				
LABSFISQ	0.1278	0.4378***	0.9332***	1.0000			
EUROPE	0.1072	0.2387**	0.1667*	0.1004	1.0000		
JAPAN	-0.0014	-0.4005***	-0.4071***	-0.2887***	-0.5059***	1.0000	
PROCESS	0.0412	0.0000	0.0708	-0.0053	0.3809	-0.2049**	1.0000
RESEARCH	0.0760	0.1620	0.0082	-0.0515	0.2547***	-0.1654*	0.1741**
LABAGE	0.1077	0.4636***	0.3840***	0.3498***	0.1896**	-0.5406***	-0.0064
NUMLABS	-0.0362	-0.2138**	-0.2492***	-0.2320***	-0.1177	0.1290	-0.1432*

	RESEARCH	LABAGE	NUMLAB	
RESEARCH	1.0000			
LABAGE	-0.0943	1.0000		
NUMLABS	0.0828	-0.3570***	1.0000	1.0000

* - Signif. .10 ** - Signif. .05 *** - Signif. .01 (2-tailed)

Fig. 3. Correlation coefficients.

	Predicted Sign	Model 1 Coefficients	Model 2 Coefficients	Model 3 Coefficients
Dependent Variable		LABPERF	LABPERF	PATENT
Independent Variables				
Intercept		1.363***	2.126***	-3.146*
LABSFIN	+	0.013***	0.012***	0.047***
LABSFISQ	-	-0.000026***	-0.000024***	-0.0000625**
PHARMA		-0.161		(electronics only)
RESEARCH		0.084	0.336*	2.013**
LABAGE	+	0.028**	0.085***	0.164***
NUMLABS	+	0.112*	0.252*	0.476
JAPAN		1.496***		3.999*
EUROPE		0.546**		2.313
Firm dummies			included	
LABAGE*JAPAN		-0.038	-0.070	-0.207
NUMLABS*JAPAN		-0.123	-0.217	-0.559
F Statistic		5.39***	2.49***	8.52***
R^2		0.31	0.45	0.51
Adjusted R^2		0.25	0.27	0.45
n		134	134	84

* Denotes level of significance p <= 10%; ** denotes level of significance p<= 5%;
*** denotes level of significance p<= 1%.

Fig. 4. Regression models, LABPERF (laboratory performance) and PATENT (patent output) as dependent variables.

lished leads to a performance increase of about 0.3 on a 5-point scale. [8]

When firm dummies are dropped in model 2, the *t*-value for the laboratory age variable falls from 2.67 to 0.44, and the *t*-value for the number of laboratories variable falls from 2.0 to −0.25. These results suggest that laboratory age and the number of laboratories in operation do not proxy firm effects. Exclusion of interaction effects between the Japan variable and the laboratory age and number of laboratories variables reduced the significance of laboratory age and number of laboratories to the 8% significance level and 28% significance level, respectively, in model 1; and to the 6% significance level and 2% significance level, respectively, in model 2. This suggests that the relatively recent establishment of Japanese labs has an influence on regression results.

Finally, in model 1, the Japan dummy was positive and significant at the 1% level, while the Europe dummy was positive and significant at the 5% level. Japanese managers evaluated the performance of their laboratories more highly than their US and European counterparts. While it could well be the case that Japanese laboratories abroad performed better on average than US laboratories abroad, there might also be a certain positive response bias among Japanese managers, whose cultural values keep them from expressing negative evaluations explicitly.

Alternatively, it could be that Japanese laboratories that were established more recently than laboratories by other companies are still growing in size and will eventually reach similar sizes as the laboratory sites of European and US firms, but without necessarily achieving higher performance ratings in the future because respondents already integrated future projected performance in their evaluations. This finding could imply that our results for the optimal size of Japanese laboratories represent a local optimum and that, over time, the optimal size of Japanese sites will increase and approach the size of non-Japanese sites abroad. (The mean ages of Japanese laboratories and other laboratories are 6 years and 15 years, respectively). The optimal size of

[8] We also tested the hypothesis of a concave relationship between laboratory performance and laboratory age. Support for this hypothesis would indicate that there is an optimal life span for laboratories. However, we did not find any support for this hypothesis. One reason could be that team composition within laboratories changes frequently. Limiting the life span of teams is probably conducive to increasing the overall laboratory performance over time.

the 68 Japanese laboratories in our sample was 211 employees (significant at 1% significance level). This is about 24 employees less than the optimal size for the overall sample.

Model 3 uses patent output as dependent variable and is otherwise identical with model 1. All variables in model 3 have the predicted sign. In contrast to models 1 and 2, however, the number of laboratories is not a significant predictor for laboratory performance at the 10% level.

The overall explanatory power of the models is 0.25, 0.27 and 0.45 for models 1, 2 and 3 respectively. [9] For models 1 and 2, we also tried a linear specification for the independent variable of laboratory size. We found the coefficient for laboratory size to be positive and significant at the 1% level in the equivalent of model 1, and positive and significant at the 5% level in the equivalent of model 2. However, the adjusted R^2 value was 0.12 and 0.17 for the equivalent models to model 1 and model 2, respectively. An *F*-test revealed that the quadratic term adds significantly (1% significance level) to the explanatory power of the model. This finding suggests that a concave specification fits the data considerably better than a linear specification in which laboratory performance changes monotonically with size.

The laboratory performance measure picks up *average* laboratory performance over the years the laboratory existed. In the survey, we made sure that respondents understood this issue. However, it is possible that respondents assigned more weight to recent performance of sites. If this was the case, recent events would influence performance evaluations of older sites more strongly than they should. This influence could be either positive or negative, and could increase the variance of measured performance of older sites. Thus, the statistical significance of our estimates would be lower than it should be. If we still found support for hypothesis 2 (which we do) our estimates probably err on the conservative side. Also, regarding hypothesis 3, if respondents assigned more weight to recent performance sites that were established when few other sites existed within the firm will be perceived too positively. Thus, the relationship between number of sites and performance would have a smaller slope coefficient than it should have. Since we still find a positive relationship (significant at the 10% level), our estimates probably err on the conservative side.

An interesting question emerging from this analysis concerns the optimal size of a laboratory. Based on model 1, we calculated an optimal size of 250 full-time equivalent employees; based on model 2, the optimal size is also 250 full-time equivalent employees. At these employment levels, we calculated a laboratory performance level of approximately 3.0 for a the base case (a US electronics development laboratory built in 1994 as the firm's first laboratory site abroad). If the same laboratory had an employment level of 125 or 62.5 employees, the calculated performance would have been 2.59 and 2.08, respectively. For a US electronics development laboratory with 250 employees, and which was established in 1984 by a firm that already had five laboratory sites abroad, we calculated a performance level of 3.8. The finding of an optimal laboratory site size of 250 employees is approximately in line with the anecdotal evidence from Perrino and Tipping (1989).

We also examined how optimal scales differ for young and mature laboratory sites. We found that younger laboratories generally have a smaller optimal size than older laboratories. When the whole sample was split into two equal-sized subgroups according to increasing laboratory age, we still found support for a concave relationship between laboratory performance and size for each of the two subgroups. The calculated optimal size of the group of laboratories that were 9 years old or less was 152 employees, and the optimal size for laboratories older than 13 years was 253 employees. [10]

[9] We also carried out diagnostic statistics for all models. None of the standardized residuals in any of the two models was an outlier in a sense that it exceeded 3 standard deviations. An inspection of normal probability plots revealed no serious deviation from normality. Inspection of a Q/Q plot revealed that the dependent variable satisfies the normality assumption for OLS regression quite well.

[10] When performing the same analysis with five equal-sized subgroups, we obtained similar results.

It is important to reiterate that the sample consisted only of laboratories abroad. These either carry out focused research projects or support local manufacturing facilities and digest local market information; they are generally more limited in their scope of activity than the company's home laboratories. Therefore, it would not be appropriate to assume that the optimal laboratory size abroad of approximately 250 employees applies for the firm's home laboratories as well. Furthermore, only 10% of the laboratory sites in our sample were above the size of 250 employees. This finding suggests that a more detailed investigation into the descending part of the postulated concave relationship would be useful to further confirm our hypothesis. [11] Furthermore, independent sample *t*-tests confirmed that the mean performance of laboratories in the smallest group (<60) and the laboratories in the largest group (>180) do not differ significantly (5% level). The mean laboratory performance of the middle group (60–180) is significantly higher than in the smallest and largest group (1% level). Given the limited precision of the survey-based performance measure, all our estimates for optimal size have to be viewed as indicative rather than precise. For example, it would be unwise to stick to an optimal size of 250 employees rather than to add 10 additional employees in order to study a promising new field of technology.

The average (not optimal) size of home country laboratories of the companies in our sample was 750 employees. This is close to the figure of 1000 employees for domestic laboratories mentioned by Allen (1977). In addition, the reason why laboratories in our sample are smaller might be attributable not only to their location abroad and their special mission (Ronstadt, 1977) but also to their more recent date of establishment in comparison to domestic laboratories. Domestic labs in the sample had a mean age of 25 years, while labs abroad had a mean age of 11 years. With the growing integration of a multinational firm's activities across borders, sites abroad might increasingly resemble domestic sites (Hakanson and Zander, 1988).

On the other hand, one could argue that even after a long period of time, the optimal size of a foreign site will be smaller than the optimal size of a domestic site. This would imply that the findings of this paper represent a long-term optimum size rather than a temporally optimum size. First, R&D managers at foreign sites might be less capable in managing researchers than R&D managers of domestic sites. The best managers in a foreign country might prefer to work for a domestic firm rather than a foreign firm. Thus, the optimal control span of a foreign manager and, as a result, the overall size of a foreign site might be smaller than that of a domestic site. Second, if new technologies get researched at home labs first and only later at foreign labs, foreign labs might have less time to perform well researching the new technology before it reaches maturity. Third, if resource allocation decisions get made at the home base, domestic R&D managers might have more influence on these decisions than foreign R&D managers (Malnight, 1995). As a result, growth of domestic R&D sites might be curbed more strongly than growth of foreign sites, even in the long range.

Independent of considerations about absolute optimal size levels for foreign and domestic labs, however, we hypothesize that the concave relationship will hold for domestic laboratory sites as well because the basic economic and behavioral patterns of R&D activity described in Section 2 apply to any kind of R&D site.

We also fitted a number of concave (quadratic) specifications for subsets of our data set. In all cases, the dependent variable was laboratory performance, and the independent variable was laboratory size. From this analysis, we computed the optimal laboratory sizes and performance levels displayed in Fig. 5. For all subsets, we also fitted linear specifications, all of which had lower R^2 values than the concave specifications. The optimal size ranges between 167 and 260 employees.

Fig. 5 shows that the optimal size of Japanese laboratories is smaller than optimal size of labs for the overall sample. Also, at their optimal size, research laboratories are smaller than development laboratories, and pharmaceutical R&D sites are smaller

[11] Other statistical tests also suggest a concave relationship between laboratory size and performance. A spline regression with three segments of laboratory size (<60, 60–180, >180) confirmed that the slope of the whole function is not constant, but decreasing across all three segments (significant at the 0.1% level).

Sample	Nationality	Industry	Orientation	Optimal size	n	Significance level	Optimal Performance
1	all	all	all	235	135	1%	3.98
2	Japanese	all	all	211	70	1%	5.00
3	all	pharma	all	167	45	1%	4.49
4	all	electronics	all	256	90	1%	3.86
5	all	all	development	260	66	10%	3.67
6	all	all	research	182	69	1%	4.25

(Dependent variable: LABPERF, independent variables: LABSFIN, LABSFINSQ)

Fig. 5. Fitted curves for optimal laboratory size (quadratic specification).

than electronics R&D sites. We suspect that Japanese laboratories' optimal size (211 employees) is smaller than the optimal size for the overall sample (235 employees) because Japanese laboratory sites have been established more recently than other sites.

However, we guess that other reasons drive the smaller optimal sizes of research laboratories (182 employees) as opposed to development laboratories (260 employees). Research sites may require a higher level of informal interaction between researchers for optimal performance because research activities are not as clearly specified ex ante, while development activities benefit to a greater degree from cost advantages of shared overhead and from more broader, but less deep interactions among a larger number of researchers.

A somewhat different argument could explain the fact that the optimal size of pharmaceutical laboratories is lower than the optimal size of electronics laboratories (167 vs. 256). Pharmaceutical R&D is essentially geared towards the discovery and testing of complex single molecules, while R&D in the electronics industry is geared towards applying basic scientific discoveries to the creation and improvement of products often consisting of numerous parts and modules. If R&D in electronics is more of a combinatory task while R&D in pharmaceuticals is more of a pure discovery task, it might be necessary in electronics to concentrate more researchers in one location.

We also checked for heteroskedasticity in the relation between laboratory performance and laboratory size and laboratory age. One might expect a greater variance for younger and smaller laboratory sites. This pattern is common in studies of firms' profitability in relation to size. A Goldfeld–Quandt test revealed no heteroskedasticity (95% significance level) for the relation between laboratory performance and laboratory size or laboratory age (Greene, 1993). In order to increase the power of the Goldfeld–Quandt test, we omitted one-third of the observations in the middle of the sample (Greene, 1993), but still could not detect any support for the hypothesis that laboratory performance varies more for younger and smaller laboratories.

6. Conclusion

Building on prior research, we hypothesized that there is an optimal size for R&D sites. If R&D sites are too small, there is not enough opportunity for creativity-stimulating communication among research groups. As R&D sites grow larger, the positive effects of increased communication and improved access to scientific support structures are outweighed, among other things, by the difficulties individual researchers face within a larger site when they attempt to establish informal contacts with colleagues. In addition, performance in large R&D sites is reduced due to lengthy decision routines.

We tested our conjectures using a subjective measure and a patent-based measure as proxies for laboratory performance. Some of the most knowledgeable R&D managers in 27 large multinational firms constituted the source of information for our laboratory performance measure. The empirical test found strong support for the conjecture of a concave relationship between size and performance of R&D sites abroad.

Furthermore, we hypothesized that learning at the laboratory level and at the firm level might positively influence laboratory performance. The empirical test found support for this hypothesis. R&D sites that have been operating for a number of years perform better than recently established sites, and as firms operate more R&D sites abroad, the performance of a subsequently established site is higher, most probably because over time, firms learn how to design and manage R&D sites abroad.

While the empirical findings are based on a sample only of foreign laboratories, it seems likely that theoretical arguments about the relationship between laboratory performance, size, and learning apply to all kinds of R&D sites, abroad and in a firm's home country. Firms must strike an appropriate balance between several drivers of laboratory size: Increasing laboratory size initially supports but subsequently hampers lateral communication, particularly informal communication. And, increasing laboratory size initially decreases but subsequently increases overhead costs per researcher. Results from our research are relevant for academics studying R&D management but also for academics studying organizations in general. [12]

Further research should investigate a number of questions. First, it would be valuable to use the same dependent variable for other settings such as R&D sites in a firm's home country, or R&D sites at universities. The same methodology could also be used to study the optimal size of manufacturing sites, particularly in industries where a site's size is not driven by the requirement for lumpy investments in fixed assets, but is primarily dependent on communication requirements among workers. Second, it would be interesting to compare the dependent variables chosen in this study to other dependent variables, such as design awards or sales derived from a R&D site's output.

Beyond these detailed extensions, however, lie two bigger issues that concern the core of R&D management. First, it is important to examine which measures firms should take when they operate an R&D site of sub-optimal size. Questions that need to be answered include: How can a site be expanded in an effective way? Which managers should be involved and over what period of time should the site expansion take place? What factors should trigger the decision to shut down rather than to expand a site that is too small? It also seems rewarding to study questions related to sites that are too large: How can an existing R&D site be 'right-sized'? Is it possible to break up a large site into a number of smaller sites without reducing the number of employees—i.e., can R&D managers create 'Chinese Walls' that simulate geographically separate R&D sites of optimal size within one large location?

Second, it is important to study which factors other than size and existing configuration of R&D sites influence R&D site performance. These factors probably include the quality of employees, the management tools used to connect an R&D site to its local environment, as well to the company's existing R&D network and the leadership style of R&D managers.

In order to answer these questions, further detailed yet rigorous studies of R&D management at the laboratory site level are essential.

[12] In fact, our arguments about optimal size of sites might apply to manufacturing sites as well if there is a pronounced need for intensive yet unstructured communication within the site. The chairman of W.L. Gore and Associates, a manufacturer of special textiles, for example, has intentionally limited the workforce at each manufacturing plant to 200 people to accentuate a close-knit and interpersonal atmosphere that suits the firm's flat management hierarchy and pay-for-performance compensation schemes (Industry-Week, 1983).

Acknowledgements

I would like to thank Richard S. Rosenbloom, Gary Pisano, Marco Iansiti, Kim Clark, Richard E. Caves, Christopher A. Bartlett, Michael E. Porter, as well as seminar participants at MIT for their comments and insights. I would also like to thank three anonymous referees for their comments. The financial support of the Harvard Business School Division of Research is gratefully acknowledged.

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