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INDUSTRY–PUBLIC KNOWLEDGE INFRASTRUCTURE INTERACTION: INTRA- AND INTER-ORGANIZATIONAL EXPLANATIONS OF INTERACTIVE LEARNING

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Owing to rapid technological developments, increased global competition, and shorter product life cycles, firms are confronted with strong pressures to develop new knowledge and to innovate.[1] Many firms decide to acquire knowledge and technology from external sources to complement their internal knowledge bases for innovation purposes. These sources include buyers, suppliers, competitors, research organizations, and universities. Especially research organizations and universities, both part of the public knowledge infrastructure, can have unique potentials for innovating firms. Not only can firms obtain technological knowledge, but they can also recruit students and scientists to serve as employees or consultants. Industry–public knowledge infrastructure interaction represents an evolving trend for advancing new knowledge and technologies (Sakakibara 2002).

Industry–public infrastructure interaction can have different forms and levels of intensity. To set the stage for the focus of this paper, interactive learning between industry and public knowledge infrastructure, we first present two case studies.[2] These will enable us to derive some insights in actual processes of interactive learning and help us to develop our theoretical framework.

The first case concerns a Flexible Assembly and Welding Unit Program, founded in 1987, which was a research consortium in which a faculty of Mechanical Engineering of a Dutch university, an institute part of the Dutch Centre for Applied Research, and a major Dutch automotive company participated. Mid-1988, a research unit of a large Dutch electronics company specialized in computer-aided manufacturing (CAM) joined the programme too. The programme was part of a government-sponsored project, which encouraged industry–university research cooperation in the information sciences.

The main aim of the research programme was to develop a working version of an unmanned flexible manufacturing unit. The unit enabled users to put together and weld families of sheet steel products, which consisted of relatively simple basic units.

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2 For reasons of confidentiality, names of organizations involved are not listed.

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The programme focused on developing new knowledge in three research fields: technologies (bow welding), methods (design, production, assembly, and test methods using CAD/CAM techniques), and control (designing and constructing a central control unit).

The programme was terminated at the end of 1991 and considered a success by the participants. Several observations confirmed this judgement. First, the quality of the design improved considerably, while the same was true for work preparation processes and the production quality of discrete products, which consequently resulted in a reduction of the production time of such a unit. Moreover, the software developed for this unit could be applied in other areas, especially in CAD/CAM milling. Second, the research programme facilitated interactive knowledge transfer between university and industry and it was at the same time possible to train young engineers in dealing with production automation problems derived from industry. Third, participants' contributions to the programme were of a complementary nature, which resulted in commitment of all parties involved. Fourth, the research programme resulted in a large production of (co-authored) papers, dissertations, and master's theses by the research group. In the period 1987–91, 29 scientific papers, 4 dissertations, and 89 Master of Mechanical Engineering theses were published. Given these characteristics, Santoro and Chakrabarti (2002: 1165) would consider this programme as highly interactive, since both elements of knowledge and technology transfer are involved.

For reasons of contrast, the second case study of industry–university interaction can be typified as having low levels of interactivity. The industry–university research project concerned the development of a digital book and the commercialization of the digitization process. It was initiated by a Dutch university that wanted to investigate the possibilities of supplying library books in digital form to their clients. Because of a lack of internal expertise in the fields of scanning and image recognition of extremely large documents, the university contacted the research department of a nearby large organization, which sees document processing technologies as its core competence. Given the possibilities for developing new expertise, both parties decided to start a collaborative project.

The two parties formulated project goals, which in hindsight differed to a certain extent. Both parties saw as the main collective goals of the project developing new knowledge about the digitization and the electronic supply of a very large document on the one hand, and generating a working prototype on the other. On top of these, the university wanted to get insights in the limitations and costs of such a product. Unfortunately, this requirement was communicated to the organization by the university only 5 months after the start of the project. The research department could not provide this information, since the expertise and authority for determining and communicating cost and price information to external parties was allocated to a different department. However, the research department failed to pass on this message to the university, leading to some disappointments on the university side. The frequency of interaction between the two collaborating parties was fairly low (on average once in every 6 weeks, not on a face-to-face basis) and was mainly focused on the exchange of general technical specifications and progress reports.

The project resulted in a prototype of a digitized large document and was regarded as a success from a technical point of view. However, the research department felt that the university was unable to articulate specific technical requirements, which were needed to define design details. The research department concluded from this that the university partner did not have the necessary knowledge level and its contributions to the research project were less than required and expected. Therefore, learning and knowledge development mainly took place on the side of the research department, the information and knowledge exchange between partners was limited, resulting in a low level of interactive learning.

From both case descriptions, some interesting lessons can be derived. First, both cases point at the changing role of universities. Universities are no longer only suppliers of (basic) knowledge, but also act as co-developers or, as in the second case, as the demanding party. This observation fits the Triple Helix III model (Etzkowitz and Leydesdorff 2000) that emphasizes the changing roles of industry and academia. Second, both research projects were highly complex in the sense that completely new artefacts were developed that asked for the creation of new knowledge. Intensive interaction between collaborating parties, lacking in the second case, turned out to be important. Third, the efforts made by collaborating participants seem to be associated with the level of interactive learning. In the first case, the use of complementary resources led to commitment and high levels of interaction, whereas in the second case the collaboration was more asymmetrical with only the research department really investing in the project and low interaction levels.

The cases outlined above show that there are compelling reasons for industrial firms and the public knowledge infrastructure to work together. Benefits to a firm include access to highly trained students, facilities, and faculty as well as a reputation effect when working together with a prominent academic institution (Frombrun 1996). Actors part of the public knowledge infrastructure interact with industry for additional (research) funds, exposure of students and staff to practical problems, job opportunities for their graduates, and access to specific technological areas (Gibbons 2003; Vermeulen 2003).

Geisler (1995) stated that many of the studies on industry-public knowledge infrastructure collaboration are descriptive and do not have a strong theoretical foundation. Most research relies on an open systems perspective, and on the notions of systems integration and differentiation, but these give no clue on the behaviours and the formation of linkages as such. Although some cross-sectional studies have been reported in the literature (Cohen *et al.* 1998; Sakakibara 2001; Santoro and Chakrabarti 2002), the dominant research design has been small-sample case study with a focus on public knowledge infrastructure actors. In this paper, the focus is on a relatively large sample of innovating firms and the question is asked: what drives these firms to go for collaborative R&D and innovation efforts with partners in the public knowledge infrastructure? The purpose of this paper is to contribute to a more complete and theoretical understanding of the *probability* of interactive learning between firms and the knowledge infrastructure in the context of innovation.

Our theoretical explanations are derived from organization theory with its wealth of explanations of firm's interdependencies (for a review see Galaskiewicz 1985; Grandori 1997). We take a resource-based, more specifically a knowledge-based perspective, and an activity-based perspective as our theoretical starting points. We elaborate both approaches by showing their flaws and complementarities. Galli and Teubal's (1997) description of changing roles and functions of actors in National Systems of Innovation is parallel to the arguments of Lundvall (1993) and Nelson (1982), and *implicitly* applies the complementary resources argument. However, the theoretical elaboration is to be found in the literature on inter-organizational relations (Aiken and Hage 1968; Gulati 1995) and alliance formation (e.g. Chung *et al.* 2000). In advancing the complexity of innovative activities, our activity-based argument criticizes the intellectual imperialism or the resource-based approach (Dougherty 1992). Finally, we extend both the resource-based and the activity-based account for interactive learning by including the structuring of innovative activities. On the one hand, the probability of interactive learning is considered to depend on the way in which innovator firms integrate their innovative activities internally (Cohen and Levinthal 1990; Grant 1996; Teece and Pisano 1998). On the other hand the probability of interactive learning is expected to depend on innovator firms' embeddedness in *and* their active utilization of so-called bridging institutions like innovation centres or trade organizations (Edquist 1997; Cooke *et al.* 2000). This yields our research question: to what extent does the complexity of innovative activities, the strength of internal knowledge resources, and the structuring of innovative activities affect the probability of interactive learning of innovator firms with actors in the knowledge infrastructure?

In the debate on systems of innovation, our theoretical effort performs several functions. First, we shift the systems of innovation analysis of collaboration to the level of dyads of individual innovator firm and knowledge producers, and to an intra-organizational explanation. This intra-organizational model explores the complementarities of activity and resource-based organization theories in the explanation of interactive learning. The resource-based organization theories in economics and sociology (Pfeffer and Salançik 1978; Wernerfelt 1984; Håkansson 1987; Barney 1991) are linked with elements of the knowledge-based theories on networks and learning (Cohen and Levinthal 1990; Kogut and Zander 1992; Grant 1996; Hage and Alter 1997; Jin and Stough 1998; Teece and Pisano 1998). Second, whereas much empirical literature focuses on dyadic relations of innovator firms with one external actor, we analyse the innovator firms' interactions with both technical universities and public research organizations. Third, neither network research in the innovation literature, nor the learning literature makes an explicit theoretical argument for the probability of interactive learning with the public knowledge infrastructure (Meeus and Oerlemans 1993).

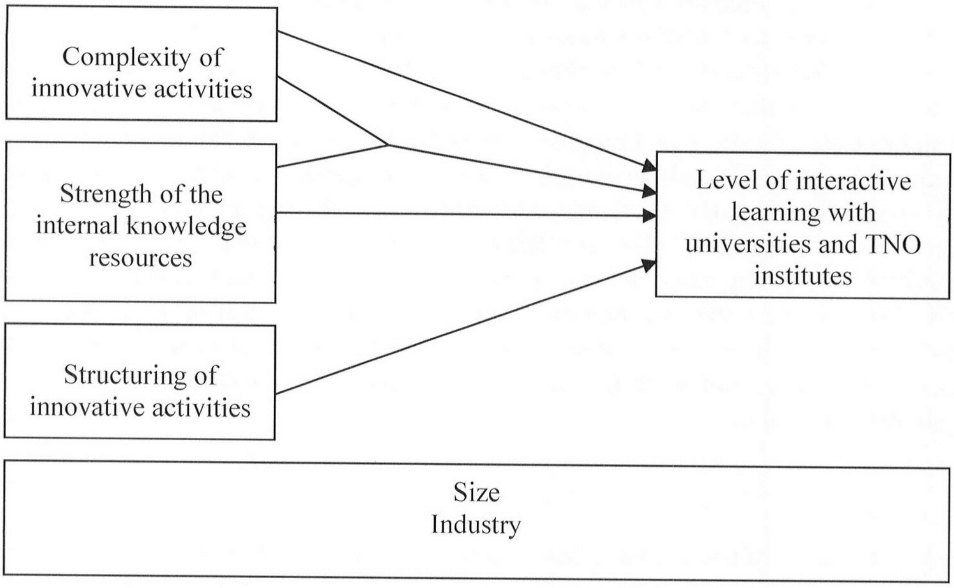
The structure of our paper is as follows. First, we describe the components of our theoretical framework. This yields a research model, a clarification of interactive learning, the complexity of innovative activities, the strength of the internal knowledge resources and the structuring of innovative activities, and a set of testable propositions. The next section describes the research design including the sample and the analytical procedures. Subsequently, our results are described. Finally, we discuss these results and derive some theoretical and policy inferences.

RESEARCH MODEL

Interactive learning

From a theoretical point of view, Lundvall's notion of interactive learning aligns the old resource dependence argument with the innovation process. The basic premise

FIGURE 1: RESEARCH MODEL.



of resource dependence theory is that organizations are open systems. From this it follows that organizations (1) are not self-sufficient; (2) cannot generate all the necessary resources internally; and (3) must mobilize resources from other organizations in their environments if they are to survive. To acquire the necessary resources involves interacting with other organizations that control these critical resources (Pfeffer and Salançik 1978: 25–28).

It was one of Lundvall's (1985) major conceptual contributions to re-work the notion of user–producer interaction, introduced in the 1970s by Von Hippel (1976), Teubal (1976), and others, into the concept of interactive learning. The level of interactive learning between the innovator firms and external actors indicates the extent in which innovator firms can access and apply knowledge from external partners in order to innovate their individual or joint products and/or processes. By engaging in interactive learning, firms expect to enhance their innovative and overall economic performance and create value. This pooling of complementary knowledge allows innovator actors to initiate innovation projects that would have been impossible in a stand-alone mode. On the one hand, the notion of interactive learning relaxes the resource control assumption by adding the assumption of the reciprocity of exchange, which on the other hand implies that the assumption of interdependence is specified. From this description we derive the following definition. The level of interactive learning between the innovating firms and external actors is defined as the frequency that innovator firms acquire knowledge inputs from external actors *and* transfer knowledge to external actors in order to innovate products and/or processes.

The context and nature of innovation processes implies that from the point of view of the individual partners in a dyad, the control assumption has to be relaxed. First, because the non-exclusive nature and transitory nature of technical knowledge

(Cohendet *et al.* 1993) makes the acquisition and protection of information a core competence that enables firms to profit from innovation, and explains innovator firms' inclination to formalize innovative ties. Secondly, the stickiness of technical knowledge (Von Hippel 1987; Senker and Faulkner 1996; Szulanski 1996; Lam 1997), its range and significance is so difficult to assess that any contractual arrangement pursuing a specification of knowledge transactions would become an unworkable straitjacket. Third, the control assumption is also put in perspective by the uncertain outcomes of knowledge exchange and knowledge sharing in innovation projects (Galaskiewicz 1985: 282; Alter and Hage 1993; Saxenian 1994: 148–149; Hage and Alter 1997). Also the reluctance to initiate external knowledge acquisition (Huber 1991: 98), and the enhanced imitation risks diminishing innovation rents (Kogut and Zander 1992), illustrates the limited control possibilities. It is exactly this effect of innovation on the control of resources, which makes interactive learning risky, yet apparently inevitable.

Resources

The central tenet of the resource-based approach is that firms select actions that best capitalize on its unique endowments of resources, and that they focus on the production and maintenance of strategic resources in order to remain competitive (Combs and Ketchen 1999). Performing product or process innovations induces firms to draw on their internal and external environment and forces them to pool all resources conducive to innovation. In innovation races, technical knowledge is the primary strategic resource to be acquired and developed (Cohen and Levinthal 1990; Kogut and Zander 1992; Hage and Alter 1997). Without technical knowledge, new technical opportunities would not be recognized, and hence neither product, nor process innovations could be achieved. The heterogeneity of the resources—specialized skills, facilities, and money—needed in innovation urges firms to monitor actively their resource base as well as their financial position and decide how to solve their resource deficits. The strength of internal knowledge resources determines the ability to cope with this heterogeneity. If resource stocks turn out to be insufficient, a search for complementary resources starts, wherein intensification of existing relationships or the formation of new linkages with other firms, institutional actors like universities, are behavioural alternatives enabling innovation strategies (Aiken and Hage 1968: 930; Håkansson 1987; Combs and Ketchen 1999: 868). Summarizing, interactive learning of innovator firms with actors in the knowledge infrastructure permits firms to share resources and thereby overcome resource-based constraints for innovative activities. This yields the following proposition:

P1: The stronger the innovator firm's internal knowledge resources, the lower the probability of interactive learning with actors in the knowledge infrastructure.

While Proposition 1 suggests a negative monotonic relationship between the level of interactive learning and the innovator firm's internal knowledge base, there are two arguments for alternative propositions. First, Cohen and Levinthal (1990), and Gulati (1995), argue that the ability to evaluate and utilize outside knowledge—firms' absorptive capacity—is largely a function of prior related knowledge. There are few direct tests of the influence of absorptive capacity, but the results of such tests are broadly supportive of this argument (Gambardella 1992; Mowery *et al.* 1996). This yields a competing resource-based hypothesis:

P2: The stronger the innovator firm's internal knowledge resources, the higher the probability of interactive learning with actors in the knowledge infrastructure.

The second argument pertains to the nature of the empirical relation suggested in Propositions 1 and 2. Both suggest a monotonic relationship between the probability of interactive learning and the strength of the internal knowledge base. However, there are additional arguments for a non-monotonic relationship that suggest that a stronger internal knowledge base only leads to a higher probability of interactive learning up to a certain point, after which stronger internal knowledge bases are associated with a lower probability of interactive learning. First, there is the myopia argument, which suggests that firms have limited capabilities to develop and value their internal knowledge base, which makes them blind to the opportunities of external partnering (Miller and Chen 1994). Second, there is the marginal information value argument (Gulati 1995; Chung *et al.* 2000), which suggests that if knowledge resources grow, the probability of diminishing returns of knowledge exchange and knowledge sharing grows, which in turn decreases the probability of interactive learning after a certain maximum. Third, as a result of the continuous monitoring of external actors' knowledge bases, innovator firms simultaneously reassess the value of their internal knowledge resource stock. Especially for firms with stronger internal knowledge bases this reassessment diminishes the potential complementarities of external knowledge, because of the identification of slack resources. This decreases the probability of interactive learning. Therefore we propose:

P3: Innovator firms with knowledge resources of moderate strength have a higher probability of interactive learning with actors in the knowledge infrastructure than innovator firms with weak or strong knowledge resources.

Complexity of innovative activities

A major flaw of the resource-based view of the firm is that resources and activities are simply conflated, as if there is no analytical value in distinctions between organizational behaviours, structures, resources, and activities (Wernerfelt 1984: 172; Barney 1991: 101). Lundvall's original account of interactive learning turns out to be foremost activity-based. In his view, the rate and radicalness of innovations, both indicating a certain complexity of innovative activities of firms, are expected to occasion interactive learning (Lundvall 1988). Therefore, it is theoretically useful to extend the resource-based view of interactive learning.

The complexity of innovative activities is defined as the innovator firm's learning, and problem-solving efforts induced by the implemented innovative activities. Kogut and Zander (1992: 388) define the complexity of a task as the number of operations required to solve a task. Jones *et al.* (1997: 921) stress another dimension of task complexity by referring to the number of specialized inputs needed to complete a product or service. Following these definitions, we discern two complexity dimensions that both significantly enlarge this number of learning and problem-solving operations: first, the heterogeneity and intensity of perceived innovation pressures that compel innovator firms to adapt, and second the actual innovation rate. Innovation pressures are for example: perceived customer needs, competitor behaviour (Lundvall 1993), proliferation of new technical knowledge, new technical findings (Hage and Alter 1997), legal requirements, emergence of new markets, standardization (Anderson and Tushman 1990), need for cost reduction (Duncan 1972). More heterogeneous innovation pressures imply that more divergent, and probably less compatible criteria have to be met in the product or process innovation. This requires additional specialized skills and knowledge (Dewar and Hage 1978; Jones *et al.* 1997), or makes existing competencies obsolete (Leonard-Barton and Doyle 1996). The higher the likelihood of incompatible innovation pressures, the higher the required capacity for problem solving, the more firms must go beyond the incremental improvement of existing competencies associated with learning by doing and learning by using (Windrum 1999: 1539). If innovation pressures are more heterogeneous, the number of innovation opportunities grows and hence this demands more interaction with external actors, primarily buyers and suppliers, but also with the knowledge infrastructure (Freeman and Soete 1997).

The rate of innovation measures the actual innovative behaviour of the innovator firms. The higher the number of implemented product and process innovations, the higher the actual intensity of the problem solving and associated (un)learning (Henderson and Clark 1989; Dodgson 1993; Rosenbloom and Christensen 1998). High innovation rates erase existing communication codes between users and producers (Lundvall 1992: 58), and raise the likelihood of the innovator firm's need for additional specialized skills of third parties like knowledge producers.

In sum, both the heterogeneity of innovation pressures and the rate of innovation demand more coordination and cooperation, the need to build external linkages and control many discrete activities, which in tandem generates a higher complexity of innovative activities (Evan 1993: 230; Hage and Alter 1997). The general proposition derived from the complexity argument is as follows:

P4: Innovator firms performing more complex innovative activities have a higher probability of interactive learning with actors in the knowledge infrastructure.

As was the case with the resource-based propositions, the relation between complexity and interactive learning could be either monotonic or non-monotonic. On the one hand, the argument is that innovative activities with low complexity probably do not require interactive learning, because in that case neither innovation pressures nor innovation rates are high, hence there is no need for complementary knowledge. On the other, innovator firms are more inclined to perform extremely complex innovative activities within organizational boundaries. First, because of unwanted reputation effects of highly complex innovation projects, for both internal R&D teams, and for external partners. R&D teams are inclined to keep complex projects internal, because their reputation might get damaged if one has to report to a CEO that the complexity of the innovative venture was underestimated (Huber 1991). External partners do value complex projects on their own terms, and are in general hesitant to team-up with partners that cannot solve their problems, simply because it is not convincing to join projects that the initiator cannot finish successfully himself. Finally, highly complex projects are more likely to reflect very fundamental core technology problems and opportunities, and hence external collaboration is less obvious.

Second, because the likelihood of finding partners that are able to solve problems associated with highly complex innovative activities decreases after a certain threshold point. Firms initiating innovations with moderate levels of complexity are more likely to detect problems they cannot solve themselves than in the case of low complexity, and simultaneously, the risk of damaging reputations is lower than with extremely high complexity levels. This increases the chance that a moderate complexity of innovative activities induces a comparatively high probability of interactive learning. This yields the following proposition:

P5: Innovator firms performing innovation projects with moderate levels of complexity have a higher probability of interactive learning with actors in the knowledge infrastructure than firms performing innovative activities with low or high levels of complexity.

The interaction between complexity of innovative activities and the strength of the knowledge resources

An additional reason to combine Lundvall's activity-based and the resource-based explanation of interactive learning is that we expect that their effects are complementary. Actually, a synthesis of the resource-based and the activity-based explanation for interactive learning yields a more comprehensive theoretical account of interactive learning. The complexity of the firms' innovative activities determines whether the strength of the internal knowledge resources is sufficient, and therefore, determines the level of interactive learning. More complicated innovative activities draw more heavily on a firm's resource base than routine distribution activities with lower complexity do, hence they reveal resource deficits or shortages and affect the probability of interactive learning. This yields the following proposition:

P6: The effect of the strength of the internal knowledge resources on the probability of interactive learning with actors in the knowledge infrastructure is moderated by the complexity of the innovative activities.

Also for this proposition a non-monotonic version is explored. We expect that moderate levels of complexity and moderate quality of the resource base in tandem are associated with the highest probability of interactive learning. The argument runs parallel with the arguments pertaining to Propositions 3 and 5.

P7: Innovator firms combining moderate levels of complexity of innovative activities with a moderate strength of their knowledge resources are more inclined to interactive learning with actors in the knowledge infrastructure than innovator firms with low or high scores on the interaction term.

Structure of innovative activities

A final extension of the resource-based perspective on interactive learning concerns the conflation of resources and structures. This conflation of resources with the structuring of organizations contrasts strongly with the newer versions of the resource-based theories such as the knowledge-based theory (Cohen and Levinthal 1990; Kogut and Zander 1992; Grant 1996; Teece and Pisano 1998). These authors stress the significance of internal organizational structuring enhancing relationships between knowledge sharing and knowledge diversity across individuals, departments, and plants. The pooling of internal departments' innovative activities becomes more important in case of a higher complexity of innovative activities (Lawrence and Lorsch 1967). It has become generally accepted that complementary functions or departments within organizations (e.g. R&D, sales, marketing, purchase, and production) ought to be tightly interrelated. After all, some amount of redundancy in expertise may be desirable to create what can be called cross-function absorptive capacities (Cohen and Levinthal 1990: 134; Dougherty 1992: 179; Teece and Pisano 1998: 198–200). To the extent that an organization develops a broad and active network of internal relationships, individual awareness of others' capabilities and knowledge will be strengthened. Inward looking (production, engineering) and outward looking (R&D, sales/marketing) departments enable a comparison of the internal and external opportunities for cooperation in innovation projects.

P8: A higher level of integration of internal innovative activities increases the probability of interactive learning with actors in the knowledge infrastructure.

A second aspect of the structuring of innovative activities relates to the external management of innovation. In the systems of innovation literature, the importance of so-called bridging institutions (Midgley *et al.* 1992; Edquist 1997) is emphasized. This may be the central government, but also agents like technology centres responsible for local knowledge transfer, regional development authorities, trade or industrial associations, chambers of commerce, etc. These organizations are interfacing units that link innovating firms to external actors and facilitate information and technology transfer, as well as technological collaboration (Galli and Teubal 1997: 356–357). Because European and Dutch technology policies are geared toward clustering and networking (Cooke *et al.* 2000), in many EU countries technology subsidies are assigned only if the submitted innovation projects induce (international) collaboration (e.g. CRAFT). Many bridging institutions operate in this technology subsidy niche and are rewarded for their "network" activities, which is conducive to their legitimacy. This yields the final proposition:

P9: Stronger links with bridging institutions induce a higher probability of interactive learning with actors in the knowledge infrastructure.

The generality of our claims

The theoretical model we have developed is probably contingent on several factors one would like to control for, because they limit the generality of our claims. The first contingency we control for is firm size, which is often considered as a proxy for resource availability. Empirical research (Santoro and Chakrabarti 2002) shows that firm size has dual effects. On the one hand, the resource availability tends to grow as firms grow. Large firms have qualitatively and quantitatively more comprehensive resource bases and are, therefore, better equipped to innovate successfully and to compete proactively and aggressively. Compared to small- and medium-sized firms, large firms are favoured by the availability of internal funds in a world of capital market imperfections. Cash flow, for instance, a measure of internal financial capabilities is empirically associated with higher levels of R&D intensity (Cohen and Levin 1989: 1072). Simultaneously, slack resources buffer firms from competition and promotes insularity, affording economies of scale that capitalize on inertial routines (Miller and Chen 1994). On the other hand, large firms are more bureaucratic than small- and medium-sized enterprises (SMEs). The rigid rules and routines that so profoundly permeate many larger companies may hamper resource utilization (Miller and Friesen 1982; Tushman and Romanelli 1985).

The second contingency is the enormous difference between sectoral technological dynamics. Pavitt's (1984) research revealed that the technological change between the high-tech and low-tech sectors differs significantly due to higher R&D spending in the former, and strongly distinct sources of innovations, and innovation partners. Sakakibara (2001, 2002) found industry effects on firms' rate of participation in R&D consortia explained by differing sectoral appropriability and competition conditions.

RESEARCH DESIGN

In this research, we combined case study analysis with survey research. We analysed 23 innovation projects in 18 firms. This helped us to develop a questionnaire allowing for a full treatment of theoretical issues related to innovative behaviour in innovation networks, which were left out of the Community Innovation Survey (CIS). Gathering data from a representative sample of firms allows us to generalize our findings.

Sample

A survey was administered to industrial firms with five or more employees in North Brabant (a province in the southern part of the Netherlands). The data gathering took place in the first half of the 1990s.

The data gathering was performed in a region with typical features. This region is one of the most industrialized regions in the Netherlands. In 1992 the total number of jobs in manufacturing was roughly 210,000, i.e. the manufacturing sector share of employment in the region was 28.8 per cent (the Netherlands, 19.5 per cent). The region of North Brabant has features that differ widely from Dutch agricultural regions (Zeeland, Groningen, and Drente), and Dutch service-oriented regions like South and North Holland. Brabant's industrialization started in *c.*1850 and was based on traditional industries like dairy industries, textile and wool industry. The Brabant region has two universities, a number of institutes, which are part of the Dutch Centre for Applied Research, and three innovation centres. A strong group of key players in internationalized industries and its location near important distribution centres like Rotterdam and Antwerpen make this region highly attractive for foreign direct investment. In the Dutch context, this region is considered as a high-tech region housing multinational enterprises such as Philips, DAF trucks, Royal Dutch Shell, Akzo Chemical, DSM, former Fokker (aircrafts), and Fuji. Brabant also accommodates a number of important medium-sized niche international players like ASM Lithography,

TABLE 1: POPULATION AND SAMPLE DIVIDED IN PAVITT SECTORS (OERLEMANS 1996)

Pavitt sector	Population (%, N)	Total sample (%, n)	Sample of innovating respondents
Supplier dominated	33.5% (1.028)	25.7% (149)	22.9% (92)
Scale intensive	41.1% (1.261)	36.1% (209)	34.1% (137)
Specialized suppliers	13.6% (478)	21.4% (124)	22.1% (89)
Science based	11.8% (363)	16.8% (97)	20.1% (84)
Total	100% (3.069)	100% (579)	100% (402)

OCE and Rank Xerox (copiers), ODME (optical discs equipment), Ericsson, EMI (CDs), General Plastics, etc.

The population of firms in the region consists of a mix of small, medium-sized, and large enterprises. About 84 per cent of the responding firms have 100 or less employees. Furthermore, the manufacturing sector has shown a relatively high R&D and export performance (Meeus and Oerlemans 1995).

Our sample is a reliable representation of the population of industrial firms in North Brabant, in which sample strata and population strata deviated within 8 per cent boundaries. The mean deviation between the percentages in the sample and in the response is 6.4 percentage points. The sample of industrial firms is classified according to Pavitt's taxonomy (Table 1).

Measurement

Interactive learning was measured as a multidimensional construct, with a learning dimension, and interaction dimension (for the items see Table 2). The learning dimension of interactive learning was measured in terms of the knowledge exchange that supplements the innovating firm's knowledge base (Dodgson 1993) and augments the range of its potential behaviours (Huber 1991; Jin and Stough 1998). Our indicators measured the extent to which public knowledge infrastructure actors actively contributed to the innovating firms' innovations, either by active participation in or by their contribution of ideas to the innovation process of the innovating firm.

The interaction dimension was measured by asking the innovating firms to rate the contact frequency between the innovating firms and the external actors. Social interaction is defined as a sequence of situations in which the behaviours of one actor are consciously reorganized and influenced by the behaviours of another actor and vice versa (Turner 1988: 14). The measure captures the level of reciprocity between innovating firms and external actors, indicating, on the one hand, the frequency of knowledge transfer initiated by external actors, and, the frequency of knowledge transfer initiated by the innovator firms on the other.

Resources

Scholars have different opinions with regard to the resources involved in innovation. Håkansson (1989) and Smith (1995) defined resources broadly in terms of money enabling investments, a physical and technological infrastructure, a stock of know-

TABLE 2: MEASUREMENT OF THE DEPENDENT VARIABLE "INTERACTIVE LEARNING"

Variable	Indicators
Interactive Learning with universities	Two items were included in this variable: (1) firms were asked if they acquired information and/or knowledge from universities; (2) firms were asked how often universities contributed to their innovation processes by bringing up ideas, or participate actively. Item 1 was coded: (1) No, or (2) Yes. For item 2 answers were coded: (1) never; (2) sometimes; (3) regularly; (4) often; (5) always. A sum score was computed. If the resulting sum score equalled 2, this value was coded 0 indicating no interactive learning between the innovating firm and universities. A resulting sum score higher than 2 was coded 1 indicating interactive learning between universities and the innovating firm.
Interactive Learning with TNO institutes (Dutch Centre for Applied Research)	Two items were included in this variable: (1) firms were asked if they acquired information and/or knowledge from the Dutch Centre for Applied Research (TNO); (2) firms were asked how often the Dutch Centre for Applied Research (TNO) contributed to their innovation processes by bringing up ideas, or participate actively. Item 1 was coded: (1) No, or (2) Yes. For item 2 answers were coded: (1) never; (2) sometimes; (3) regularly; (4) often; (5) always. A sum score was computed. If the resulting sum score equalled 2, this value was coded 0 indicating no interactive learning between the innovating firm and the Dutch Centre for Applied Research (TNO). A resulting sum score higher than 2 was coded 1 indicating interactive learning between the Dutch Centre for Applied Research (TNO) and the innovating firm.

ledge, information and human skills enabling an organization to transform inputs into outputs and decision-making. Cohen and Levinthal (1990) and Hage and Alter (1997) argue that the ability to evaluate and utilize outside knowledge—firms' absorptive capacity—is largely a function of prior related knowledge.

In our research model, we restrict the measurement of the strength of the knowledge resources to three different knowledge-based indicators (see Table 3). First, R&D intensity (Baldwin and Scott 1987; Cohen and Levinthal 1990); second, the percentage of higher educated workforce (Kleinknecht and Reijnen 1992; Jin and Stough 1998); third, the number of problems firms experienced during their innovation projects (Meeus *et al.* 1996). A large number of innovation problems indicate large resource deficits. In order to align the meaning of this indicator with the other indicators the raw scores were recoded. High scores on this indicator represent few innovation problems and hence a high problem-solving capability of the innovator firm.

Complexity of innovative activities

We have distinguished two dimensions of complexity of innovative activities, which were combined in one compound independent variable (for separate items, see Table 3). The first dimension is the heterogeneity and intensity of perceived innovation pressures, which defines the diversity of environmental pressures (Duncan 1972) pushing firms to innovation. The items pertain to customer demands, innovative

TABLE 3: MEASUREMENT OF THE INDEPENDENT AND CONTROL VARIABLES

Variable	*Indicators*	Calculation of scores
Complexity of innovative activities: A sum score was computed using "the percentage of new processes and products" and "heterogeneity of innovative pressures"	*Percentage of new processes and products in a 5-year period*	Firms were asked to indicate to what extent (1) their machines/processes and/or (2) their line of products changed in a 5-year period. Each item was coded: (1) 0–20%; (2) 20–40%; (3) 40–60%; (4) 60–80%; (5) 80–100%. An average score was computed, which was standardized.
	Heterogeneity of innovative pressures	Firms were asked to indicate how often the items mentioned below were pressures to innovate. Items included were: (1) customers asked for specific new product; (2) customers asked for specific operation method; (3) competitor had comparable new product; (4) competitor had comparable machine/process; (5) improvement of product quality; (6) maintain market share; (7) increase market share; (8) reduction of cost price; (9) improved production time; (10) new market need discovered; (11) technical idea/invention; (12) solve technical product deficiencies; (13) solve technical production problems; (14) improve delivery time; (15) react to regulation; (16) technical standardization. Items were coded: (1) never; (2) sometimes; (3) regularly; (4) often; (5) always. An average score was computed, which was standardized.
Strength of the internal knowledge resources: A sum score was computed using "R&D intensity", "percentage of higher educated employees", and "resource deficits"	*R&D intensity*	The percentage of employees working full-time on R&D. The variable was standardized.
	Percentage of higher educated employees	The number of higher educated employees as a percentage of the total workforce of the firm. The variable was standardized.
	Resource deficits	Firms were asked to indicate whether or not the following issues hampered their innovative activities: (1) lack of financial resources; (2) lack of time; (3) lack of skilled workers; (4) lack of technical know-how. If an issue hampered innovative activities it was coded 1, else it was coded 0. A sum score was computed and the resulting variable was recoded and standardized. Low scores indicate high levels of resource deficits, and high scores indicate low levels of resource deficits.
Structuring of innovative activities The separate indicators were used in the estimations	*Level of integration of internal innovative activities*	The sum of the frequency with which the R&D, marketing and sales, purchase, and production function of the firm contributed to the firm's innovation projects. Answers were coded: (1) never; (2) sometimes; (3) regularly; (4) often; (5) always. After the sum score was computed, the variable was standardized.
	The level of support by bridging institutions	The sum of the frequency with which trade associations, innovation centres, and chambers of commerce contributed to the firm's innovation projects. Answers were coded: (1) never; (2) sometimes; (3) regularly; (4) often; (5) always. After the sum score was computed, the variable was standardized.
Pavitt sector Control variable	*Pavitt dummy*	Firms were coded 0 if they belonged to the supplier-dominated or the scale-intensive sector (traditional manufacturing, bulk material, assembly). Firms were coded 1 if they belonged to the specialized suppliers or science-based sector (machinery, instruments, electronics, chemicals).
Size Control variable	*Size dummy*	Firms were coded 0 if they had less than 100 employees. Firms were coded 1 if they had 100 employees or more.

behaviour of competitors, new market needs and technical findings, as well as to institutional developments. Due to these pressures, existing skills and capabilities can become obsolete and shift the locus of technical expertise from industry incumbents to newly formed ventures and firms from other industries (Schumpeter 1975: 83; Tushman and Anderson 1986; Pisano 1989). The second dimension of complexity of innovative activities is the rate of innovation. It is measured by the percentage of products and processes that were innovated between 1988 and 1993. The rate of innovation measures the extent to which the innovator firm has responded to innovation pressures. Jointly, these indicators represent the degree of difficulty of the innovator firms' learning efforts, which is higher in case of intense and more heterogeneous innovation pressures and high innovation rates.

Structuring of activities

The structuring of innovative activities is measured using two separate variables: the level of integration of internal innovative activities and the level of support of bridging institutions. We measured integration of internal innovative activities with the extent that internal departments contribute to a firm's innovation process. The external dimension—the level of support by bridging institutions—was measured with the frequency with which chambers of commerce, industry associations, and innovation centres contributed to a firm's innovation process (for the items, see Table 3).

Control variables

The size of the firm (Baldwin and Scott 1987; Cohen and Levin 1989; Vossen and Nooteboom 1996) is a proxy for a firm's ability to invest in innovation (see Table 3). We used a dummy variable for the measurement of technological dynamics. We made a distinction between traditional industries (supplier-dominated and scale-intensive industries) on the one hand and modern industries (specialized suppliers and science-based industries) on the other hand. Empirical research confirmed the differences in participation and R&D spending between Pavitt sectors in the Netherlands. R&D spending in Dutch industries has the following ranking: (4) the supplier-dominated, (3) scale-intensive, (2) specialized suppliers, and (1) science-based industries (Vossen and Nooteboom 1996: 165). Earlier research (Oerlemans *et al.* 1998) suggests that patterns of interaction with distinct external actors yield different innovation outcomes in different Pavitt sectors. The impact of sectoral differences requires a control for its effects. Therefore, we discern high-tech sectors—the so-called science-based industries (e.g. electronics, chemical industry) and the specialized suppliers (instruments)—and low-tech sectors (the so-called supplier-dominated and scale-intensive industries, e.g. building and construction materials, textile and leather), which are dominated by economies of scale.

Analyses

In this paper, we restrict our analyses to exploratory analyses. In testing our propositions, we used stepwise logistic regression. Owing to the skewed distribution of the level of interactive learning, and the ordinal dependent and independent variables, ordinary least square regression was not allowed. Six separate models were estimated: (1) firms that reported collaboration with a university, (2) small- and medium-sized innovator firms with less than 100 employees that collaborate with a university, (3) firms with 100 employees or more collaborating with a university, (4) firms that reported collaboration with institutes part of the Dutch Centre for Applied Research (TNO), (5) firms with less than 100 employees collaborating with TNO institutes, (6) large firms reporting collaboration with TNO institutes.

The interpretation of our research findings differs for the monotonic and non-monotonic propositions. The variables interactive learning, complexity of innovative activities, the strength of the knowledge resources, the cross-product term "complexity * strength of the knowledge resources", and the structuring of innovative activities were coded from low to high scores.

In logistic regression analysis, a significant exp(b) larger than 1.0 signifies that higher scores on the independent variables are associated with a higher probability of interactive learning. A significant exp(b) smaller than 1.0 means that higher levels of complexity are associated with a lower probability of interactive learning.

To control for non-monotonic effects, we included squared terms for the strength of the knowledge resources, the complexity of innovative activities and their cross-product term. For the squared variables, the interpretation is as follows. A statistically significant exp(b) larger than 1.0 means that the relation between that independent variable and the probability of interactive learning is U-shaped. So, low and high scores on the independent variable are associated with a higher probability level of interactive learning, and the moderate scores on that independent variable are associated with a lower probability of interactive learning. A significant exp(b) smaller than 1.0 signifies an inverted U-shaped relation between independent variables and the probability of interactive learning. In this case, moderate scores on the independent variable are associated with the highest probability of interactive learning, and low and high scores of the independent variable are associated with low probabilities of interactive learning.

RESULTS

First, we will review the outcomes of our descriptive analyses. Then, the results as to Propositions 1–9 will be presented.

Table 4 reveals that there are only weak correlations between interactive learning and the independent variables. The structuring of innovative activities turns out to be associated positively with interactive learning between innovator firms and both universities and TNO institutes. The complexity of innovative activities and the strength of the internal knowledge resources are only correlated with the interactive learning of innovator firms with TU/e. As expected, sectoral technological dynamics impacted on the probability of interactive learning.

Table 5 displays the results relevant to our propositions. Propositions 1 and 2 predicted either a positive or a negative effect of the strength of the internal knowledge resources on the probability of interactive learning with external actors. Our findings in Table 5 (model 3: exp(b) = 1.44, $p \leqslant 0.05$; model 6: exp(b) = 1.40,

TABLE 4: DESCRIPTIVE STATISTICS (LISTWISE $N = 266$)

Variables	Mean scores	SD	Correlation (Spearman's rho) of independent variables with dependent variables: Interactive learning with universities	Interactive learning with TNO institutes
Interactive learning with universities	0.285	0.452	—	—
Interactive learning with TNO institutes	0.380	0.486	—	—
Complexity of innovative activities	0.004	1.576	0.15***	0.06
Complexity of innovative activities [squared]	2.480	3.454	−0.02	−0.07
Strength of internal knowledge resources	0.347	2.175	0.09*	0.03
Strength of internal knowledge resources [squared]	4.859	14.202	0.03	0.02
Cross-product term of strength of internal knowledge resources and complexity	0.366	3.501	−0.01	0.01
Cross-product term of strength of internal knowledge resources and complexity [squared]	12.358	52.745	0.01	−0.04
Level of integration of internal innovative activities	0.003	0.999	0.14**	0.10*
Level of support by bridging institutions	0.003	1.001	0.14***	0.19****
Pavitt sector	0.432	0.496	0.09*	−0.13**

*$p \leq 0.10$; **$p \leq 0.05$; ***$p \leq 0.01$; ****$p \leq 0.001$.

$p \leq 0.10$) support Proposition 2 and confirm the absorptive capacity argument. The resource deficit argument rendered in Proposition 1 is rejected by these findings.

Proposition 3 predicted an inverted U-shaped relation between the strength of internal knowledge resources and the probability of interactive learning with external actors. This proposition is supported only for interactive learning of small- and medium-sized innovator firms with the TU/e (model 2: $\exp(b) = 0.85$, $p \leq 0.05$). This finding refines the absorptive capacity argument in several senses. First, because stronger knowledge resources occasion higher probabilities of interactive learning only up to a threshold, beyond which the presumed absorptive capacity effect is inverted. Second, the effect only holds for small- and medium-sized innovator firms' interactive learning with universities.

Proposition 4 predicted that a higher complexity of innovative activities would occasion a higher probability of interactive learning with external actors. As Table 5 reveals (model 1: $\exp(b) = 1.25$, $p \leq 0.10$; model 3: $\exp(b) = 1.58$, $p \leq 0.10$), this proposition is supported for the probability of interactive learning with the universities. A sample split, controlling for size effects, shows that this complexity effect is significant for innovator firms with more than 100 employees. Proposition 4 was not supported for interactive learning with TNO institutes.

Proposition 5 predicted an inverted U-shaped relation between complexity of innovative activities and the probability of interactive learning. This is confirmed in model 1 ($\exp(b) = 0.87$, $p \leq 0.10$), model 2 ($\exp(b) = 0.75$, $p \leq 0.05$), and model 4 ($\exp(b) = 0.90$, $p \leq 0.10$). This means that innovator firms performing innovative

TABLE 5: STEPWISE LOGISTIC REGRESSION ANALYSES

Independent variables	Indicators	IL with universities: Model 1 All firms exp(*b*)	Model 2 Less than 100 exp(*b*)	Model 3 100 or more exp(*b*)	IL with TNO institutes: Model 4 All firms exp(*b*)	Model 5 Less than 100 exp(*b*)	Model 6 100 or more exp(*b*)
Strength of the internal knowledge resources	P1/2 SIKR	1.12	0.94	1.44**	1.10	0.96	1.40*
	P3 $SIKR^2$	0.94	0.85**	1.03	0.97	0.95	1.16
Complexity of innovative activities	P4 COMP	1.25*	1.15	1.58*	0.99	0.92	1.68
	P5 $COMP^2$	0.87*	0.75**	1.17	0.90*	0.89	1.02
Interaction effects	P6 COMP * SIKR	0.97	1.04	1.03	1.01	1.04	1.36
	P7 $[COMP * SIKR]^2$	1.03**	1.09***	0.95	1.03**	1.02**	0.97
Structuring of innovative activities	P8 LIIA	1.13	0.98	1.14	1.07	0.99	0.87
	P9 LSBI	1.27*	1.39**	1.45	1.56***	1.72****	1.79
Pavitt sectors	PAVITT (dummy)	1.46	1.67	1.32	0.57**	0.56*	0.39
Constant	Constant	−1.09****	−0.99****	−0.57**	−0.27	−0.82****	0.36
−2LL		279.79	181.10	75.337	329.247	228.064	81.732
Goodness of fit		266.87	194.651	61.747	267.456	205.758	62.106
Significance		0.5605	0.5094	0.1377	0.2742	0.3047	0.1625
Percentage correct		75.9%	61.9%	62.1%	65.4%	73.4%	61.9%
Model chi square		13.754	20.394	8.394	20.868	20.117	3.674
Significance		0.0081	0.0004	0.0150	0.0003	0.0002	0.0553
Nagelkerke R^2		7.5%	15.2%	17.0%	10.3%	13.4%	7.6%
n		266	203	63	266	203	63

$^*p \leqslant 0.10$; $^{**}p \leqslant 0.05$; $^{***}p \leqslant 0.01$; $^{****}p \leqslant 0.001$.
COMP = complexity of innovative activities; $COMP^2$ = complexity of innovative activities squared; SIKR = strength of the internal knowledge resources; $SIKR^2$ = strength of internal knowledge resources squared; COMP*SIKR = interaction term of complexity of innovative activities and strength of the internal knowledge resources; $[COMP*SIKR]^2$ = interaction term of complexity of innovative activities and strength of the internal knowledge resources squared; LIIA = level of integration of internal innovative activities; LSBI = level of support by bridging institutions; PAVITT = Pavitt sectors.

activities with moderate levels of complexity have the highest probability of interactive learning, and innovator firms performing innovative activities with low and high levels of complexity have relatively lower probabilities of interactive learning. However, these findings turned out to be quite sensitive for firm size. In the case of interactive learning with universities, a sample split revealed that Proposition 5 is only valid for innovator firms with more than 100 employees. For the models estimating Proposition 5 for TNO institutes the predicted effects disappeared when the sample was split in two size classes.

Proposition 6 was not supported at all. Proposition 7 predicted an inverted U-shaped relation between the cross-product term of "complexity of innovative activities and strength of knowledge resources" and the probability of interactive learning. This proposition was rejected by our findings, which showed that there is a U-shaped relation between the interaction effect and the probability of interactive learning. A sample split again showed that this interaction effect occurred especially among small- and medium-sized innovator firms.

The results with respect to effects of the structuring of innovative activities—P8 and P9—again informed us about the rather specific patterns of interactive learning. Proposition 8 was not supported by our findings. The level of support of bridging institutions was found to affect the probability of interactive learning with universities and TNO institutes positively (model 1: $\exp(b) = 1.27$, $p \leqslant 0.10$; model 2: $\exp(b) = 1.39$, $p \leqslant 0.05$; model 4: $\exp(b) = 1.56$, $p \leqslant 0.01$; model 5: $\exp(b) = 1.72$, $p \leqslant 0.001$). Again the control for firm size revealed that the effect of embeddedness in bridging institutions was particularly strong among small- and medium-sized firms. The effect of sectoral technological dynamics was contrary to our expectations in the sense that especially the traditional sectors (supplier-dominated and scale-intensive) turned out to induce higher probabilities of interactive learning. As with many other tested effects, the technological dynamics appeared to be contingent on the type of actor and size, and were valid only for small- and medium-sized innovator firms' interactive learning with TNO institutes.

DISCUSSION AND CONCLUSIONS

This study provides a possible bridge between the analysis of systems of innovation and organization theory, because it sheds new light on the way in which innovation affects the link between firm behaviour and markets. Economic theorists have focused on institutional effects of interactive learning without theorizing on its antecedents, whereas network theorists, learning theorists, and resource-based theorists concentrated either on the governance, structures, outcome effects, or resources shoved around in networks and ignore the specific learning process going on in networks (Oliver and Ebers 1998). Our theoretical model brings interactive learning into the realm of organization theory and unites several perspectives by exploring levels of interactive learning with a theoretical model that combines resource dependence, resource-based and activity-based arguments.

The relations we proposed between the complexity of innovative activities, the strength of the internal knowledge resources, the structuring of innovative activities, and the level of interactive learning turned out to be very sensitive for the contingencies which were specified. The significant effects were found either after a sample split, or disappeared after a sample split, or remained significant after a sample split for one of the size categories. There were also differences between the science-oriented universities, and TNO institutes, which perform applied science. The empirical findings suggest that our theoretical model yields more significant results for interactive learning with universities. For small- and medium-sized innovator firms, a proximity effect might explain this phenomenon. Recently, van der Panne and Kleinknecht (2003) found that small innovator firms were especially located near Dutch knowledge institutes. However, such an explanation does not hold for larger firms.

Our findings as to Propositions 1 and 2 support and refine the absorptive capacity

TABLE 6: AN OVERVIEW OF THE FINDINGS AS TO PROPOSITIONS 1-9

Proposition	Number of confirmations	Number of rejections
P1 The stronger the innovator firms' internal knowledge resource base, the lower the probability of interactive learning with actors in the knowledge infrastructure.	None	None
P2 The stronger the innovator firms' internal knowledge resource base, the higher the probability of interactive learning with actors in the knowledge infrastructure.	Models 3 and 6	None
P3 Innovator firms with knowledge resources of moderate strength have a higher probability of interactive learning with the knowledge infrastructure than innovator firms with weak or strong knowledge resources.	Model 2	None
P4 Innovator firms performing more complex innovative activities have a higher probability of interactive learning with actors in the knowledge infrastructure.	Models 1 and 3	None
P5 Innovator firms performing innovation projects with moderate levels of complexity have a higher probability of interactive learning with actors in the knowledge infrastructure than firms performing innovative activities with low or high levels of complexity.	Models 1, 2, and 4	None
P6 The effect of the strength of the internal knowledge resources on the probability of interactive learning with actors in the knowledge infrastructure is moderated by the complexity of the innovative activities.	None	None
P7 Innovator firms combining moderate levels of complexity of innovative activities with a moderate strength of their internal knowledge resource have a higher probability of interactive learning with actors in the knowledge infrastructure than innovator firms with low or high scores on the interaction term.	None	Models 1, 2, 4, and 5
P8 A higher level of integration of internal innovative activities increases the probability of interactive learning with actors in the knowledge infrastructure.	None	None
P9 Stronger links with bridging institutions induce a higher probability of interactive learning with actors in the knowledge infrastructure.	Models 1, 2, 4, and 5	None

argument (Cohen and Levinthal 1990). First, the monotonic absorptive capacity effect only holds for larger firms. This result is in line with Sakakibara (2002) who found a positive relation between R&D capabilities of firms and rate of participation in R&D consortia, but contrary to the findings of Santoro and Chakarbarti (2002). Their research revealed a negative relation between firm size and level of industry–university interaction. Second, our test of Proposition 3 confirmed that for small- and medium-sized innovator firms, the strength of knowledge resources is positive up to a certain threshold, after which the relation is inverted. On the one hand, these findings suggest that the marginal information value effect holds especially for SMEs. On the other hand, the knowledge base of larger innovator firms enables them to intensify interactive learning, whereas limited knowledge resources hinder smaller innovator firms' interactive learning.

The same pattern is found for Propositions 4 and 5. For innovator firms with more than 100 employees, a higher complexity of innovative activities was positively related to the probability of interactive learning with universities (P4). However, the complexity effect turned out to have an inverted U-shaped relation for the small- and medium-sized innovator firms' interactive learning with universities (P5). After a certain threshold, a higher complexity of innovative activities was associated with lower probabilities of interactive learning with universities. These findings suggest that larger innovator firms are not bothered by negative reputation effects in expanding interactive learning due to the complexity of their innovative activities and intensify coordination. However, small- and medium-sized innovator firms are more inclined to invest in reputation, and are more anxious to harm their reputation, because it is a comparatively less developed strategic resource.

With respect to Proposition 7, our findings point at a sort of indigenous interactive learning among the small- and medium-sized innovator firms. Despite low levels of complexity of innovative activities, and relatively weak knowledge resource, they have high probabilities of interactive learning. Up to a certain threshold (moderate scores on the interaction term) the probability of interactive learning decreases. The upper left end of the curve represents a sort of low risk zone, collaboration is just an opportunity, and bears no risks for the innovator firms or their external partners. The right part of the U-curve after the inflection point where higher complexity and a stronger knowledge base induce a higher probability of interactive learning needs another interpretation. Beyond an average level of complexity of innovation projects, a stronger internal knowledge base turns out to reinforce innovator firms' behaviour to a more external orientation. This again yields an important refinement of the absorptive capacity argument.

Our findings with respect to Proposition 8 showed that even a received wisdom in organization theory did not hold under all conditions. Especially our findings as to the positive effects of the level of support by bridging institutions on the probability of interactive learning with both universities and TNO institutes showed a kind of "repeated ties effect", in the sense that if one had good contact with technology and innovation brokers, this generated further embeddedness in the knowledge infrastructure. Sakakibara (2002) found a comparable repeated ties effect: past experience with network formation increased the rate of R&D consortia participation. The fact that this effect was limited to small- and medium-sized firms is compatible with the idea that smaller firms are often unaware of the possibilities offered by universities for their innovation projects. It is a confirmation of the paradigm shift toward more interactive NSIs described by Galli and Teubal (1997).

Our findings contrast heavily with the generality of the notion of interactive learning in the systems of innovation literature (Lundvall 1992, 1993; Edquist 1997). Our findings suggest that there is not one avenue for initiating interactive learning between the varieties of actors involved in the innovation process. Especially the findings as to P7 revealed that innovator firms define their own risk areas in which they vary their interaction and exchange in accordance with both complexity and knowledge base as main contingencies.

This study provides evidence suggesting that a singular theoretical perspective would yield only a partial explanation of interactive learning between innovator firms and the knowledge infrastructure. Neither a singular resource-based explanation (Cohen and Levinthal 1990), nor a singular activity-based explanation (Lundvall 1992) would explain the probability of interactive learning sufficiently. The significance of the interaction effect between the complexity of innovative activities and strength of the knowledge base of innovator firms supports an approach of combining theoretical perspectives. Our model of interactive learning suggests that interactive learning of innovator firms with actors in the knowledge infrastructure can and should be studied by considering the internal knowledge base, the complexity of innovative activities, and the external embedddedness of innovator firms in bridging institutions.

Our approach of testing monotonic effects, in tandem with non-monotonic effects, interaction effects, and a control for size and type of actor turned out to be theoretically very fruitful. It allowed us to specify the main arguments advanced. The significance of non-monotonic effects allowed for a refinement of the absorptive capacity argument (Cohen and Levinthal 1990) and the resource deficits arguments of Aiken and Hage (1968) and Evan (1993). The significance of the non-monotonic effects of complexity of innovative activities enhances a refinement of the complexity argument (Pfeffer and Salançik 1978; Lundvall 1988), and illustrates that the absorptive capacity effect is conditional on the complexity of innovative activities.

Despite the contributions of this study, some caution is needed in interpreting our findings. First of all, there is scarce research available that empirically tested explanations of interactive learning, so the empirical value of our estimations is hard to determine. Second, we used cross-sectional data, and surveyed the innovative behaviour, its organizational corollaries, and its outcomes at the aggregate level of all innovation projects over a 5-year period.

Both in terms of the research design and the measurement models, new challenges turn up from our findings. A first opportunity for new research is the elaboration of the measurement model of interactive learning at the inter-organizational project level. Compared to the broad categories generalizing over sets of innovation projects, respondents are confronted with more specific cognitive anchors, which will allow for more robust measurement models of the interaction and learning processes. In the case of project level analysis, the complexity measure would become less difficult to interpret, and systematic comparison of complexity levels would also allow for more direct managerial support. A second interesting option is to survey both actors involved in a collaboration dyad, to sort out the learning process in terms of both information exchange, the type of results achieved with the interaction, especially whether there is outcome symmetry and how that affects firms' dispositions toward further collaboration. In relation to the highly contingent character of the modelled "causes" of interactive learning, a third issue that future research should address is that of cross-sectional data gathering. For future research, this either implies that scholars of interactive learning should include and specify a broad variety of external actors, and industrial sectors in their analyses. Yet, this type of data contains sectoral heterogeneity one can control for, however, that remains superficial. Another way to handle this problem is to homogenize the population. To prevent this heterogeneity it might be better to concentrate on specific technologies within sectors, and concentrate on large sets of projects that are analysed on a longitudinal basis. Again that would yield more specific information about project histories, and give deeper insight in the complexity-learning link and the complexity-interaction link, without having to control artificially for technological dynamics.

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