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Knowledge integration in the shadow of tacit spillovers: Empirical evidence from U.S. R&D labs[☆]

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ABSTRACT

Integrating knowledge across a firm's value chain (e.g. between R&D, marketing and manufacturing functions), which we denote "Knowledge Integration" (KI), has been consistently found to be a strong predictor of product innovation performance in the management literature. Such cross-functional integration does not occur by chance, but by design, as a result of managerial practices and organizational arrangements. The significant heterogeneity characterizing the diffusion of cross-functional integration across firms is suggestive of the well-known tension between internal and external diffusion of knowledge. In this paper, we argue that the hidden cost of KI is to expose firms to a higher risk of knowledge leakages and provide the first systematic empirical evidence of this apparent tension between internal and external knowledge flows. Based on data from the CMU Survey (one of the rare datasets offering observables on both sides of the tension for a representative set of R&D active firms in the US), we investigate the impact of knowledge spillovers to competitors on internal cross-functional knowledge integration involving the R&D function among manufacturing firms. We find that the intensity of (tacit) R&D knowledge spillovers at the industry-level has a negative and significant impact on the likelihood that firms adopt or achieve KI. Our results therefore suggest that firms may trade their optimal innovative performance against superior appropriability of their rents.

1. Introduction

Innovative firms tend to base their competitive advantage on their R&D knowledge. Management scholars have argued that knowledge in general, and tacit knowledge in particular, forms one of the most crucial resources a firm can own (Grant, 1996). Performance differentials across firms critically depend on differential abilities in sharing and transferring knowledge of individuals and groups within the organization (Kogut and Zander, 1992). Yet, innovative firms face a difficult trade-off between the need to integrate and diffuse knowledge internally and the objective to prevent imitation by competitors (Teece, 2000). The need to absorb knowledge from external sources has encouraged firms to open up their innovation processes, which resulted in as similar trade-off, known as the *paradox of openness* (Arora et al., 2016). This trade-off essentially entails that while opening up to external sources may increase innovation, it would also make it harder for the firm to capture the returns on its innovation activity (for instance because knowledge spillovers would make patents less effective).

Our core contribution is to show that these contradicting objectives (absorbing knowledge from the outside world and diffusing and integrating knowledge internally, while keeping valuable knowledge secure inside the organization) result in a tension between inter-firm knowledge spillovers and within-firm cross-functional integration. Our conceptual model and empirical analysis suggest that competitive environments characterized by high levels of inter-firm knowledge spillovers should be associated with a lower propensity to achieve cross-functional integration, especially when spillovers involve tacit knowledge or informal channels.

Scholars in the economics of innovation literature have long believed that links across R&D and other vertical functions such as

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manufacturing and marketing are a key firm-level driver of innovative performance (Cohen, 2010). Dosi et al. (2008) suggest that, as the competitive pace quickens, coordination between R&D and other functions facilitates the identification and linking of new technologies with market opportunities, as well the identification of resources required to effectively utilize product and process innovations.[1] Across these different streams of research, cross-functional integration between marketing, R&D, manufacturing and other functions has been consistently found to be a strong predictor of product innovation performance (see Souder et al., 1994 or Luca and Atuahene-Gima, 2007 for reviews). However, other works also suggest that, in order to efficiently exploit and transfer tacit R&D knowledge within the firm, companies need to employ a variety of organizational practices (Alavi and Leidner, 1999). This is an unavoidable step in the product development process (Clark and Wheelwright, 1993).[2]

Luca and Atuahene-Gima (2007) have shown that cross-functional collaboration between R&D, marketing, and other functions require knowledge integration (KI) mechanisms to contribute to new product performance.[3] More generally, proactive practices aimed at fostering and facilitating cross-functional knowledge transfers are needed to overcome the well-known stickiness of knowledge (Szulanski, 1996; Szulanski et al., 2016).

Despite the benefits associated with implementing KI, the diffusion of these practices is characterized by a significant heterogeneity, suggesting the existence of a trade-off, or at least of significant costs related to the adoption of these practices (Kremp and Mairesse, 2004). This apparent paradox speaks to the well-known tension between internal and external diffusion of knowledge. According to (Teece, 2000), *"in order to contribute to firm performance, knowledge assets need to be usable and transferable within the firm, but difficult for outsiders to access or recreate"*. Our core hypothesis in this paper is that KI practices may expose firms to a higher risk of knowledge leakages benefiting competitors. This could materialize through different channels: employee turnover, informal conversation between employees working for competing establishments, or during scientific conferences.

In this paper we provide the first systematic empirical evidence of this apparent tension between internal and external knowledge flows by investigating the impact of knowledge spillovers to competitors on internal cross-functional knowledge integration among manufacturing firms. We analyze data on R&D practices conducted by corporate laboratories that are part of manufacturing firms in the U.S., collected by the Carnegie-Mellon University (CMU) survey in 1994. This sample is representative of the population of all U.S. R&D labs as part of a US manufacturing firm, hence the question of whether these firms efficiently manage their R&D assets is an important one. Most importantly, this is one of the very rare sources of data that offers large-scale firm-level (and even R&D-lab-level) observables on both parts of the trade-off: spillovers and cross-functional integration. Indeed, the survey asks lab managers detailed questions about KI practices and outcomes on the one hand, and knowledge flows on the other, both between R&D and the other business functions or business units, and between the firm and its competitors. We use the latter to construct a measure of spillovers at the industry level that is exogenous to each individual firm and lab yet varies across firms within an industry (since each firm faces a different set of competitors). Since our theory posits that the trade-off primarily stems from tacit knowledge, our measures of cross-functional integration focus on specific elements of organizational structure design that involve direct interactions (e.g. face-to-face interactions and cross-functional project teams). Analogously, our measure of spillovers can disentangle between codified (patents, reverse engineering, etc.) and tacit sources (turnover, informal conversations, etc.).

Based on a reduced-form econometric approach, our empirical results suggest that in industries in which the risk of knowledge spillovers is higher, the probability that a R&D lab adopts or achieves KI is significantly reduced. This effect however materializes only when inter-firm spillovers involve tacit (rather than codified) knowledge and is magnified when they involve information about early-stage innovations. These results hold, even after controlling for a large set of lab-, firm- and industry-level characteristics, including the effectiveness of patents and secrecy. Furthermore, with a falsification exercise, we observe that the effect does not apply to spillovers between firms and non-competing institutions such as universities, strengthening our claim that the trade-off is really about the threat of imitation. In a complementary set of robustness checks, we find no evidence that higher tacit spillovers at the industry level lead to a shift away from external knowledge sources but rather to the trade-off we posit, which is a lesser degree of KI internally. We take our results for evidence that the risk of losing the returns of R&D stemming from tacit spillovers, hardly protectable through formal intellectual property rights, represents therefore a significant cost that can hinder the adoption of otherwise beneficial management practices.

Our findings contribute to the strategy, innovation, and economic literatures in different ways. First, we examine the role played by knowledge spillovers in affecting R&D incentives from a new perspective. Outgoing R&D spillovers are known to affect the ability of firms to appropriate the returns of their innovations, with a negative effect on R&D incentives. We show that an important channel through which this effect operates is through the spillover of tacit knowledge which hampers the adoption of organizational practices aimed at integrating knowledge across the value chain. Such practices have been intensively studied in the literature on new product development (see e.g. Moenaert and Souder, 1990), but are still relatively unexplored in empirical works on the economics of innovation and growth.

We also contribute to the strategy and knowledge management literature providing systematic empirical evidence on the role of spillovers of tacit knowledge in affecting the incentives to achieve cross-functional integration. A recent review of the knowledge management literature suggests that "*the main focus in the current literature is on the protection of explicit knowledge whilst the tacit knowledge dimension is by and large neglected*" (Manhart and Thalmann, 2015). In the strategy literature, recent work (cf. Giarratana and Mariani, 2014, among others) suggests that the threat of spillovers may be countered by further internalizing R&D and increasing internal knowledge flows. We contribute to this literature suggesting that when the threat of imitation is due to tacit spillovers, the net benefits of adopting KI practices to foster internal knowledge flows between R&D and other functions are significantly reduced.

More broadly, our results speak to the burgeoning literature on the economics of management. In recent years, a major body of research has identified and measured a set of managerial practices, relevant to many areas of firms' operations (e.g. lean manufacturing techniques, performance incentives for employees, among others), that are key drivers of firm productivity (Bloom and Van Reenen, 2007; Bloom et al., 2014). Among these, managerial practices that apply to a pivotal

[1] This view is consistent with Moenaert and Souder (1990)'s work on cross-functional integration in product innovation, which provides a taxonomy of related managerial practices and, in turn, is consistent with extensive work in the technology transfer and public policy literature, which has focused on evaluating the effectiveness of technology transfer programs (Bozeman, 2000).

[2] Absent knowledge transfer across divisions, the firm risks incurring in inefficiencies in the creation of the product, or even malfunctioning and technical problems that can compromise the value of the innovation. See Clark and Wheelwright (1993) for informative case studies related to the development of new MRI prototype for a company in the medical equipment sector.

[3] Similarly, the work of Holbrook et al. (2000) suggests that managerial practices and abilities related to the integration of activities and information flows across R&D, manufacturing, and sales are critical and enduring success factors for firms. Foss et al. (2011) more recently suggest that organizational practices aimed at fostering communication internal to the firm critically conditions the positive effect of interaction with customers on innovative performance.

area of the firm, Research and Development (R&D), remain relatively unexplored. We contribute to this literature by providing empirical evidence consistent with the view that the competitive environment (and in particular the risk of external knowledge flows) may influence the adoption of important managerial practices within the firm, with a negative impact on productivity. In other words, firms may trade their optimal innovative performance against superior appropriability of their rents. Should such an impact materialize, this would add to the extensive list of organizational failures put forward by Garicano and Rayo (2016), by including the market as an obstacle to effective intra-firm communication. While spillovers and market competition have been extensively studied (e.g. Jaffe, 1986; Cockburn and Griliches, 1988; Cohen and Levinthal, 1989; Bloom et al., 2014), so far little is known about their impact on internal management practices.

The paper is organized as follows. Section 2 presents the literature review. Section 3 describes the data and key measures. Our empirical analysis is presented in Sections 4 and 5. Section 6 concludes.

2. Literature review and theoretical development

2.1. Knowledge and the firm

The knowledge-based view (KBV) of the firm (Grant, 1996) considers knowledge as a critical resource determining firm performance. The KBV rests on two pillars: Prahalad and Hamel (1990)'s view of sustainable competitive advantage depending upon building and exploiting core competencies on the one hand, and the more general Resource-Based-View argument that sustainability requires idiosyncratic resources that are difficult to transfer or replicate (Barney, 1986) on the other. The KBV theory provides ex-post support to the works stressing the role of organizations in acquiring, processing, storing, and applying knowledge (Argyris and Schon, 1978; Levitt and March, 1988; Starbuck, 1992). Along these lines, Liebeskind (1996) argued that the structure and systems of the firm may be seen as isolating mechanisms for the protection of knowledge-based rents.

Yet, creating and protecting knowledge is unlikely to generate rents in and of themselves. Knowledge acquisition and protection are different from knowledge application (Spender, 1992). Grant (1996) views firms as organizations that integrate and apply rather than create knowledge. More generally, Grant (1996) posits that the primary role of the firm (and the main justification for its existence) is the integration of knowledge. As he noted, "*if the strategically most important resource of the firm is knowledge, and if knowledge resides in specialized form among individual organizational members, then the essence of organizational capability is the integration of individuals' specialized knowledge.*" (Grant, 1996)

Grant (1996) further emphasized the hierarchy of knowledge integration as an organizational capability. The first level deals with specialized tasks, which require limited knowledge integration. At the next level, "*task-specific capabilities are integrated into broader functional capabilities, [such as] marketing, manufacturing, R&D, and financial.*" (Grant, 1996). Cross-functional integration is required for yet wider capabilities such as new product development (Clark and Fujimoto, 1991). Our focus in this work is on the latter (highest) level in the hierarchy, the one that involves cross-functional knowledge integration. Building on Alavi and Leidner (2001), we define cross-functional knowledge integration (KI) as the synthesis of functional knowledge into situation specific systemic-knowledge.[4]

2.2. Cross-functional integration and R&D

Lundvall (2016) and many others have emphasized the importance of extensive interaction and communication between prospective user and producer in the context of product innovation in order to achieve superior economic performance. Kline and Rosenberg (1986)'s chain-linked model of innovation suggests that these interactions are necessary to reduce uncertainty across innovation processes. In the chain-linked model discussed by Kline and Rosenberg (1986), innovation processes involve multiple exchanges and feedback loops across the firm's departments. As these authors argue, "successful innovation requires the coupling of the technical and economic [forces] in ways that can be accommodated by the organization while also meeting market needs, and this implies close coupling and cooperation among many activities in the marketing, R&D and production functions." This is because successful innovation implies the encounter of technological possibilities with market needs. With other words, innovation performance and new product success require integration across market-facing and technology-facing departments. This is also the view embraced by Amesse and Cohendet (2001) who propose that the linear view of innovation as technology moving from one organizational unit (e.g. R&D) to another one (e.g. marketing) needs to be replaced with a more systemic view of innovation as knowledge management processes aimed at integrating user needs as inputs in the innovation process. In this model too, cross-functional integration becomes critical.

Consequently, the marketing-R&D coupling has specifically received ample attention in the product development literature. In their meta-analysis, Troy et al. (2008) have reviewed 146 papers highlighting a correlation between cross-functional integration and new product success. More broadly, several works in the innovation literature have established a similar correlation between cross-functional collaboration and innovation performance (Griffin and Hauser, 1996; Luo et al., 2006; Song and Parry, 1997; Luca and Atuahene-Gima, 2007). In particular, market knowledge is a critical determinant of product innovation performance (Atuahene-Gima, 1995; Atuahene-Gima et al., 2005; Li and Calantone, 1998; Moorman and Miner, 1997), and the closer proximity of R&D to the market and to production may result in shorter product development times (Clark and Wheelwright, 1993) and distinctive organizational capabilities (see e.g. Clark and Fujimoto, 1991; Malerba and Orsenigo, 2000; Cohendet and Meyer-Krahmer, 2001).[5,6]

Multiple theories support such a positive correlation, but most point at uncertainty reduction, as in Kline and Rosenberg (1986)'s chain-linked model. This is the core argument in the major stream of works by Moenaert and Souder (e.g. Moenaert and Souder, 1990), who identify 4 sources of uncertainty in innovation processes: market (i.e. customer needs), technology, competition, and resources. Cross-functional integration leads to a reduction in these uncertainties, which fosters innovative performance. For instance, employees at the marketing department may learn about the current state of research and development, about the confidence scientists or engineers have about a certain direction of technological developments, or about potentially abandoned options, etc. Conversely, R&D employees acquire knowledge about the current state of the market, recent developments on the demand side, early responses of potential customers to the technology under development, etc. Knowledge about a technology under development becomes more valuable once combined with the confirmatory information that customers have shown interest in it. "Both marketing and R&D need information from each other to accomplish their specific

[4] Lawrence and Lorsch (1967) define integration itself as "*the process of achieving unity of effort among the various subsystems in the accomplishment of the organization's task.*"

[5] The economic literature has also extensively studied intra-firm communication and its impact on productivity (Garicano, 2000; Garicano and Wu, 2012).

[6] In Appendix A.1 we report a quick test of the effect of KI on innovative performance in our data, which is also consistent with the literature.

tasks. That is, the two functions are interdependent on the information exchanged between them" (Moenaert and Souder, 1990).

2.3. KI practices

Cross-functional integration is primarily achieved through knowledge integration across specialized individuals (Moenaert and Souder, 1990). Fostering cross-functional integration is therefore primarily a matter of facilitating KI across functions. Quoting Olson et al. (1995) and Zahra et al. (2000), Luca and Atuahene-Gima (2007) define KI practices as the set of *"formal processes and structures that ensure the capture, analysis, interpretation, and integration of market and other types of knowledge among different functional units within the firm"*.

A large body of literature has looked at such practices from at least two different points of view. On the one hand, the knowledge management literature focuses on the *"systemic and organizationally specified process for acquiring, organizing and communicating both tacit and explicit knowledge of employees so that other employees may make use of it to be more effective and productive in their work"* (Alavi and Leidner, 1999). Most works in this field point at direct face-to-face interactions or the mobility of knowledge-carrying individuals across the organization (Gupta and Govindarajan, 2000; Hansen, 2002; Kogut and Zander, 1992) as the primary channels for such cross-functional knowledge exchanges. This emphasis on direct social interactions stems from the tacit nature of the most valuable knowledge in the firm (making it hard, by definition, to transfer it in formal ways), and from the difficulty for individuals with different specializations and backgrounds to absorb and apply the knowledge of individuals with different codes and knowledge bases. Nonaka (1991) highlights 4 different types of knowledge transfer processes: socialization (from tacit to tacit), combination (from explicit to explicit), articulation or externalization (from tacit to explicit) and internalization (from explicit to tacit). The latter two convey the most creative part of these processes and rest primarily on direct interpersonal interactions (cross-functional teams, job rotation, etc.) (Nonaka and Takeuchi, 1995).

On the other hand, the product innovation literature has studied the Marketing-R&D-Manufacturing interfaces more carefully and provides a comprehensive view of the practices used by firms to achieve integration across these functions. Moenaert and Souder (1990) propose a taxonomy of these practices that is organized in 3 main groups depending on whether they involve task specification, organization structure design or organizational climate methods. The first, task specification, goes essentially about planned coordination of tasks. The last, organizational climate methods, involves primarily the promotion of a culture of openness, trust and collaboration throughout the organization. The authors argue that it might be the most efficient method, but it is also the most difficult to capture given how intangible culture is. To the empirical researcher, this is also the hardest one to observe given that concrete practices to provoke a cultural change are hard to identify. Our focus is therefore on the second category of practices, organization structure design, which Moenaert and Souder (1990) view as the most widely acknowledged. Typical practices in this category include cross-functional teams, business boards, the assignment of interdepartmental representatives, job rotation and integrator persons (Moenaert and Souder, 1990). The typical objective of these practices is the timely introduction of innovations obtained by lowering barriers between groups within the firm and by creating a common code between business functions and departments to stimulate the interactive flow of information and knowledge.

Both currents in the literature therefore converge on the primary role of direct interpersonal interactions among KI practices. This is the subset of practices that we will focus on in our analysis, bearing in mind that our interest is ultimately in the degree of cross-functional integration that is achieved within the firm, regardless of the actual practices involved.

2.4. KI practices and knowledge codification

KI practices aim at reducing the barriers that prevent knowledge from circulating across functions or departments. Although codified knowledge can easily be transferred in paper form or through computer networks, it is of little use without complementary tacit knowledge (Nonaka and Takeuchi, 1995). But tacit knowledge is embodied within individuals and cannot easily be transferred without the creation of shared models and languages (Cohendet and Meyer-Krahmer, 2001). Kogut and Zander (1992) emphasized that knowledge transfers require *"a set of higher-order organizing principles acting as mechanisms by which to codify technologies into a language accessible to a wider circle of individuals"*, so the transfer of tacit knowledge requires a certain degree of codification. According to Cohendet and Meyer-Krahmer (2001), this codification process alters the knowledge itself and creates new knowledge (namely models, languages and messages). According to Nonaka (1991), the conversion of tacit knowledge into codified knowledge and back into tacit knowledge are the most value-enhancing (knowledge-creating) knowledge processes.

These works uncover the processes involved in KI practices in a cross-functional setting like ours. Let us consider two of the main KI practices we reviewed in the category of organization structure design initiatives: cross-functional teams and job rotation. As argued by Nonaka (1991), job rotation *"helps employees understand the business from a multiplicity of perspectives, making organizational knowledge more 'fluid' and easier to put into practice"*. Both practices lead to the creation of a *"common cognitive ground"* among employees which facilitates the transfer of tacit knowledge (Nonaka, 1991). These transfers involve in fact the conversion of knowledge from tacit to explicit, which is a *"process of articulating one's vision of the world"* (Nonaka, 1991). The recipients of this knowledge use it to update their own tacit knowledge, broadening their perspective, extending or reframing their own knowledge basis (Nonaka, 1991). Equipped with an expanded vision and a broader set of norms and languages, employees can more easily absorb and share information across departments.

The story of the development of the famous Solvay process for soda-ash synthesis offers a historical perspective on these processes. Although the principle of the main reactions involved had been written down on paper (and in an initial patent) by Ernest Solvay, the young company (founded in Belgium in 1963) was struggling with the actual implementation of the process on the manufacturing floor.[7] After years of trials and errors, it is a cross-functional team of researchers (the Solvay brothers, regularly corresponding with prominent scientists in Belgium and elsewhere), production technicians (e.g. Louis-Philippe Acheroy and a dozen of low-qualified workers), and a few business angels and lawyers (without technical background but with knowledge of the relevant patents in the field) that developed an effective solution, consisting in a series of small bubblers first arranged horizontally and later vertically (the famous "Solvay column") (Bertrams et al., 2013). Throughout the years, the company was obsessed with the cost differential between their process and the dominant process in the industry (the Leblanc process). The Solvay brothers knew the market well enough to sense the magnitude of the cost advantage their process should yield in order for their ammonia-based soda ash to be attractive, and their R&D efforts were entirely aimed at making their process far cheaper than existing ones. Since he got involved in the development efforts, the firm's lawyer, Eudore Pirmez, could also clearly devise the best way to draft a new patent *"to protect the succession of equipment and operations rather than the principle itself."* (Bertrams et al., 2013).[8] This

[7] In fact, the theoretical process had already been discovered and patented decades earlier, but no one ever succeeded in making it operational.

[8] "That was the advice that Pirmez gave to Solvay, who diligently began describing in scrupulous detail his system by comparing it with those of his predecessors. The elements of the gas being absorbed by a liquid, pressure,

example not only illustrates the benefits of cross-functional integration, but also the fact that this is best achieved by collaborative and cross-functional work arrangements. Cracking such a challenging technical problem required working together, enabling the different area experts to confront their views, intuitions and ideas and develop a shared understanding that expanded their views enough to envision breakthrough changes to the equipment. This process involved both knowledge articulation and internalization (in Nonaka (1991)'s terms), which means it led to the codification and transfer of tacit knowledge between the different parties involved, as well as the creation of new knowledge (both tacit and explicit).

Another interesting example is documented in Wheelwright and Clark (1992)'s chapter on cross-functional integration. The example they set out is about the development, manufacturing and commercialization of the medical device MEI 2010 (premature infant heart monitor) by the company MEI. The discussion of this example is key to the type of knowledge integration we examine in our study. For instance, when discussing the integration between the engineering and menufacturing process, Wheelwright and Clark (1992) comment that "*[…] engineers in the MEI 2010 project had very little interactions or contact with manufacturing engineers on joint issues. […] This requires establishing a forum and context in which joint communication is effective: engineers must comprehend issues on manufacturability, foster skills in developing designs that are robust and exploit manufacturing capability, and be prepared to share designs. Likewise, manufacturing engineers must become oriented to customer satisfaction […].*". Similar problems are also discussed in relation to the interaction between engineering and marketing, for which the traditional approach based on specialization did not deliver the best outcome. "*Engineering did the design of the hardware and software, and marketing talked with customers and conducted clinics. The actual design that emerged from this process, however, did not fit well into the customer's system and did not deliver on all of the important features. While the basic concept was sound and the organization delivered many features that customers found attractive, the problems with the wheels, cart, and difficult-to-read display caused delay and rework and some damage to the perception of the product in the market.*". Note that the most important aspect in the description of integration by Clark and Wheelwright is that, for an integrated approach to be achieved, functions must leverage each others' "skills" and "capabilities", pointing at a crucial role played by tacit knowledge.

2.5. The downside risk of KI

"*In order to contribute to firm performance, knowledge assets need to be usable and transferable within the firm, but difficult for outsiders to access or recreate*" (Teece, 2000). What if the cost of cross-functional integration was a higher risk of knowledge spillovers to the competition? Despite ample evidence on the positive impact of cross-functional integration on innovative performance, our core thesis is that such integration may come with detrimental side effects, resulting in a managerial trade-off. To the best of our knowledge, the literature lacks empirical evidence of this potential collateral damage, but several theoretical works support this view of a tension between strategic initiatives to foster the diffusion of knowledge internally and others to prevent critical knowledge from spilling out of the organization (see e.g. Helms et al., 2000).

Kogut and Zander (1992) argue that "*the codification and simplification of knowledge […] induces the likelihood of imitation. Technology transfer is a desired strategy in the replication and growth of the firm (whether in size or profits); imitation is a principal constraint.*" They add that "*the speed of replication of knowledge determines the rate of growth; control over its diffusion deters competitive erosion of the market position. For a firm to grow, it must develop organizing principles and a widely-held and shared code by which to orchestrate large numbers of people and, potentially, varied functions. Whereas the advantages of reducing the costs of intra- or inter-firm technology transfer encourage codification of knowledge, such codification runs the risk of encouraging imitation. It is in this paradox that the firm faces a fundamental dilemma.*" In a more colorful language, Winter (1987) argued that "*technology transfer and imitation are blades of the same scissor*".

However, few works illuminate the specific mechanisms involved in such potential leakages resulting from superior cross-functional integration (which necessarily involves internal knowledge transfers). In a specific context, Gupta and Govindarajan (2000) observed that knowledge outflows from a subsidiary are positively associated with the value of the subsidiary's knowledge stock and the richness of transmission channels. Yet, Singh (2005) has shown that interpersonal networks are by far the most important vector of knowledge flows. These observations may shed some light on the underlying leakage process: cross-functional integration makes valuable knowledge accessible to a larger audience with its own social network both inside and outside the firm. These new recipients of the knowledge "*may have an incentive to expropriate [it] to their own use or to leak it to competitors*" (Liebeskind, 1996). For instance, a R&D engineer who has spent time in a different job outside R&D, say in sales and marketing, will have developed a better understanding of the market and demand-side dynamics. More than an engineer who has never worked outside of R&D, he will be able to make sense of market insights and data and share them more effectively with other people.

These arguments are core to our thesis. For instance, a marketing employee leaving the company to work at a competing firm may carry sensitive R&D information she got exposed to as a result of cross-functional integration and share it – willingly or unwillingly – at her new job. Similarly, R&D employees attending a trade association's event may encounter employees at competing firms and unwillingly disclose potentially damaging market information they obtained from their marketing colleagues. Because the value of cross-functional integration primarily lies in uncertainty reduction, the disclosed knowledge does not necessarily need to be highly technical and detailed to be valuable enough to a competitor. By the chain-linked model, there are indeed many feedback loops that may help reduce uncertainty and usefully inform innovation processes. We therefore posit that cross-functional integration increases the exposure of a firm's innovation to potential knowledge outflows.

Our thesis here is in fact consistent with prescriptive theories on the appropriation of knowledge assets by firms. The literature on knowledge appropriation has indeed strongly emphasized the importance for firms to prevent knowledge spillovers, on the grounds that rents can be extracted from knowledge only to the extent that it can be protected from theft or imitation. The challenge comes from the fact that "*there is a large body of knowledge that may be valuable to a given owner, but that cannot be protected from expropriation and/or imitation under the law*" (Liebeskind (1996)). Several scholars have argued that protection of such assets can be achieved by putting in place firewalls and other procedures aimed at preventing unwanted knowledge circulation within the organization (Liebeskind, 1996; Helms et al., 2000). This prescription implies that cross-functional integration may indeed expose the firm to a higher risk of imitation, as suggested by Kogut and Zander (1992). In a similar vein, another protective strategy consists in compartmentalizing knowledge by disaggregating tasks, a widespread practice within organizations with highly valuable knowledge, such as in defense systems and pharmaceuticals (Liebeskind, 1996).[9]

(*footnote continued*)
conveying distance, gas division, inverse operation of the gas and liquid, absence of a vacuum in the equipment, and cooling all made the second Solvay patent untouchable" (Bertrams et al., 2013).

[9] This trade-off between internal and external knowledge flows reflects in part the complex and non-linear relation between competition and innovation, especially in regimes in which returns cannot be fully appropriated (Aghion

The most recent literature on spillovers and open innovation has focused on a different type of trade-off, that between the threat of imitation due to knowledge spillovers and the level of openness to external knowledge flows, with the latter reducing the extent to which companies can appropriate innovation rents (Laursen and Salter, 2014). This literature highlights contextual variables moderating such trade-off. Among other factors, the trade-off is found to be stronger when: (a) competitors are the main source of external knowledge flows (Laursen and Salter, 2014); (b) costly R&D investments are conducted in regions populated by organizations with high-absorptive capacity (Giarratana and Mariani, 2014); (c) companies are technological leaders in their industry, heavily investing in R&D, and relying especially on product innovation, i.e. when they are more vulnerable to spillovers (Arora et al., 2016). In terms of managerial implications, key findings from the literature are that firms can manage the open innovation paradox by adjusting their appropriation strategy. For example firms could design policies to deal with employee mobility (Agarwal et al., 2009); implement organizational changes that enhance the ability to effectively use trade-secrecy (Wadhwa et al., 2017); leading firms could both open to external flows and patent more aggressively (Arora et al., 2016). A stream of this literature suggests that the threat of spillovers may be managed by further internalizing R&D to bar imitation in the context of multinational corporations (Alcácer and Zhao, 2012) or relying on internal knowledge flows (Giarratana and Mariani, 2014).

In sum, while the recent literature highlights an important trade-off, it neglects the trade-off between internal and external knowledge flows. Our work complements the literature suggesting that the imitation threat due to knowledge spillovers may be particularly severe when spillovers occur through channels that facilitate the transfer of tacit knowledge. As further discussed in the following section, our work suggests that when the threat of tacit spillovers is high, the incentives to adopt organizational practices such as cross-functional project team linking R&D within the vertical value chain are reduced. In other words, our work suggests that addressing the open innovation paradox resorting to internal KI may not be an optimal option in the context of tacit spillovers. However, the literature above highlighting the paradox of open innovation suggests that firms will endogenously respond to the threats of spillovers by adjusting both their propensity to adopt internal KI practices as well as their propensity to source knowledge from the external environment, and in particular through interactions with competitors. In our empirical work, we will explore the robustness of our key findings by jointly examining the relative importance of internal versus external knowledge sourcing strategies.

Based on the literature review so far, our key theoretical prediction is that a higher degree of outgoing spillovers benefiting a firm's competitors should be negatively associated with the propensity of the focal firm to adopt cross-functional integration practices. As will be further discussed below, it is no trivial to set up a direct empirical test of our core thesis. First of all, there is very limited data available about actual outgoing spillovers and about actual cross-functional integration practices adopted by firms. Second, to the extent that firms pre-emptively adjust the trade-off to minimize their risks, such data would reflect some sort of an equilibrium that may hide the true incentives and tensions that forged it. This perhaps explains the lack of empirical evidence on the existence of this trade-off. We therefore seek an indirect test of the trade-off. Specifically, we will empirically test whether a higher degree of spillovers in its competitive environment is negatively associated with the propensity of a focal firm to adopt cross-functional integration practices. If our thesis is correct, then firms facing a higher risk of spillovers at the industry-level should exhibit a lower propensity to adopt KI. This prediction forms the essence of our empirical test.

(*footnote continued*)
et al., 2005; Spulber, 2013).

2.6. Which type of industry spillovers magnify the disincentives to KI adoption?

Next, we will explore the characteristics of spillovers at the industry level that exacerbate the risks associated with KI adoption. We will first distinguish between the channels through which knowledge flows across firms within the industry. Some of these channels involve formal documentation (i.e. explicit knowledge) as is embedded in patents, publications or products (i.e. reverse engineering). These knowledge flows cannot be avoided once patents or documents are published and once products are commercialized, and they are unlikely to be affected by internal knowledge integration. We would therefore expect that KI adoption is not affected by higher explicit or formal spillovers at the industry level. Instead, we would expect cross-functional integration to be particularly sensitive where knowledge tends to flow across firms through informal, interpersonal, (i.e. tacit) channels such as employee turnover, industry conferences, etc. With other words, we would expect the trade-off to be exacerbated for firms operating in industries characterized by a high degree of tacit or informal spillovers.[10] This prediction is reinforced by the knowledge management literature. Starting from Alavi and Leidner (2001)'s identification of valuable knowledge assets as including the mentally stored knowledge in the minds of employees as well as the policies, routines, documents, identity, culture and systems of an organization, it derives that most valuable knowledge in the firm is tacit (e.g. Quinn, 1992; Spender, 1993; Teece, 2000), to the extent that tacit means "not explicitly codified". It has been shown that tacit market knowledge in particular leads to superior innovation performance as it allows for differences in cross-functional logics (Galunic and Rodan, 1998). Firms should therefore be particularly careful to avoid exposing their tacit knowledge, both because it is most valuable and because it is harder to protect.

Second, we will explore the extent to which the trade-off varies along the development cycle of new products. Specifically, we will seek to determine whether the trade-off is higher in industries where knowledge tends to flow across firms more at early stages in product development (i.e. closer to the research or experimentation phase) or at later stages (typically at the development or near-commercialization stages). There are two arguments why KI adoption might be associated with different downside costs at early v. late stages. One of them is that knowledge is less likely to be formalized or explicit (hence it is more likely to be tacit) in early-stages. Per our previous prediction, there is reason to assume that KI adoption is more likely to facilitate or trigger tacit knowledge flows and hence to be more problematic when early-stage knowledge tends to leak out. The second argument is that earlier-stage knowledge leakages may be more detrimental or costly to the firm (e.g. because it reduces any potential first-mover advantage) and therefore their higher intensity at the industry level makes it even more important to shield from them (and hence to refrain from adopting KI). Both arguments support the prediction that KI adoption should be more negatively associated with spillovers when industry spillovers are more frequent at early-stages in product development processes.

Third, one important mediating factor could consist in appropriability conditions on the market. Intuitively, if appropriability is strong, the firm should be less concerned about spillovers (i.e. it has other ways of enforcing the exclusive use of its knowledge even when it leaks out). However, outside of secrecy (which is equivalent to the absence of spillovers) and first-mover advantages, formal legal protection instruments (such as patents and utility models) require codification. Stronger appropriability regimes in general and formal intellectual property protection (such as patents) in particular, can hardly help

[10] Since Polanyi's pioneering work, tacit knowledge is a notion that has been employed extensively both in the managerial and in the economic literature. The article of Cowan et al. (2000) provides a detailed and critical discussion of the evolution of this concept and the relevant literature.

Table 1
Summary of KI measures.

KI measure	Strengths	Weaknesses
KI adoption (Adoption of project team with cross-functional participation)	• Matches KI definition of Moenaert and Souder (1990) • Associated with flows of tacit knowledge according to Lundvall (1988); Nonaka and Takeuchi (1995) • Reflects an endogenous managerial decision	• Potentially not representative of all KI practices • May not lead to effective transfer of tacit knowledge • Captures a variety of cross-functional information transfers (i.e. not necessarily knowledge, or tacit knowledge)
KI outcome (Frequency of face-to-face interaction between R&D personnel and personnel from Marketing, Sales, or Production)	• Face-to-face interaction between employees has be argued to be important to transfer tacit knowledge (Polanyi, 1958; Lundvall, 1988; Nonaka and Takeuchi, 1995) • Provides a more accurate measure of the actual level of KI than *KI adoption*	• Only indirectly captures effect of adoption of KI practices • Captures a variety of cross-functional information transfers (i.e. not necessarily knowledge, or tacit knowledge). • May capture as a confounding factor the cospecialized nature of complementary assets required to commercialize innovation (cf. Arora and Ceccagnoli, 2006). • It is only an intermediate outcome of KI practices. Effectiveness of technology transfer depends on a complex and hard to measure set of factors (Bozeman, 2000)
KI outcome (robustness) (Importance of information flows from own manufacturing or customers in suggesting new R&D projects or contributing to completion of existing projects)	• Provides a more accurate measure of the actual level of KI than *KI adoption*	• Only indirectly captures effect of adoption of KI practices • Captures a variety of cross-functional information transfers (i.e. not necessarily knowledge, or tacit knowledge) • Mostly captures uni-directional information transfer from downstream activities, i.e. lacks notion of personal interaction among employees associated with exchange of tacit knowledge

protecting tacit (i.e. not codified) knowledge. We therefore expect that the above effects should hold even when controlling for appropriability conditions at the industry level.

3. Data

The data from this study comes from the Carnegie-Mellon survey of U.S. R&D labs. The survey was administered in 1994 to the managers of each laboratory. The sample is representative of the population of R&D labs or units located in the U.S. that are part of a U.S. manufacturing firm. It has been drawn from labs listed in the Directory of American Research and Technology or belonging to firms listed in Compustat, and it is stratified by 3-digit SIC industry.[11] The final sample used, once we exclude variables with missing values, is composed of 1238 labs. The respondents were asked to answer questions with reference to the 'focus industry' of their R&D unit, where the focus industry was defined as the principal industry for which the unit was conducting its R&D (Cohen et al., 2000). Each focus industry is then assigned a SIC code.

The use of the CMU survey to measure knowledge flows presents some advantages and disadvantages.[12] The disadvantages of using survey-based measures (which are not specific to this survey) include the use of rating scales instead of continuous measures (as, for instance, patent citation counts in the context of spillover measures), which reduces the precision of the metrics constructed based on the survey's answers, and the presence of potential noise due to imprecise information held by the respondent. On the other hand, a specific advantage of the CMU survey is that it collects information directly from the R&D lab manager, which presumably has direct and extensive understanding of the type of knowledge that is employed in the R&D lab, along with its various sources and uses. Given the confidentiality with which the information of the survey was collected and processed, we have reason to believe that the measures presented below may suffer from any particular reporting bias.

In this section we provide information about variable construction, measures, and descriptive statistics. Table 1 presents descriptive statistics and correlations for the dependent and independent variables used in the analysis, excluding the controls. The full set of descriptive statistics and correlations are presented in Table A.5.

3.1. Dependent variables: knowledge integration

Measuring KI can be achieved in two ways, either as an input measure (i.e. through the adoption of managerial practices aiming at fostering KI), which we denote *KI adoption*, or as an outcome measure (i.e. the actual level of cross-functional integration achieved), which we denote *KI outcome*.

In terms of practices, as discussed in the theory section, our focus is on the category that Moenaert and Souder (1990) call *organization structure design*. It includes cross-functional teams, business boards, the assignment of interdepartmental representatives, job rotation and integrator persons. In our data, we are able to directly observe the adoption of one typical practice in this category, which is *project teams with cross-functional participation*. In particular, each respondent to the CMU survey was asked whether the firm has used this practice to facilitate interaction between R&D and other functions during the previous three years. We used this dummy variable as our measure of *KI adoption*. The distribution of this variable, presented in Fig. 1, shows widespread adoption across 2-digit sectors. On average, 84% of labs used cross-functional teams to facilitate interaction between R&D and other functions within the value chain. This measure is consistent with prior literature suggesting that interactions between employees is an

[11] For more detailed information about the survey, please refer to Cohen et al. (2000).

[12] Previous papers have also discussed the pros and cons of using the data of the CMU survey, see e.g. Roach and Cohen, 2013.

Fig. 1. *KI outcome* score by SIC-2 sector. *Notes*: Reported score of knowledge integration outcome based on answers from the CMU survey (integer number from 0 to 8). Individual responses have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

important channel to transfer tacit knowledge. In particular, the pioneering work of Polanyi (1962) suggests that tacit knowledge is transferred via inter-personal communication. Lundvall's concept of "learning by interacting" also suggests that interaction between producers and users in the context of innovation commercialization enhances the competence of both (Lundvall, 1988). Finally, Nonaka and Takeuchi (1995) show how Japanese firms organize product innovation by leveraging and transferring tacit knowledge across employees. Tacit knowledge is transferred and shared by observing behavior, communicating or coordinating among employees. Cross-functional or interdepartmental interactions facilitate a spiral movement from tacit to explicit knowledge, then back to tacit knowledge across members of horizontal and cross-functional project teams whose role is to create new products and new knowledge (Nonaka and Takeuchi, 1995).

Although cross-functional teams are one of the most popular practices used by firms to achieve cross-functional integration, this is of course a very incomplete reflection of the firms' potential initiatives in this area, which may lead us to under-estimate the real extent of KI achieved by an organization. Conversely, the mere adoption of cross-functional teams may over-state the actual level of KI when the implementation of such practice was not carried out correctly.[13] To overcome these measurement obstacles, we complement the *KI adoption* variable with a different type of measure for KI, which is not based on practices (i.e. inputs) but on outcomes (i.e. outputs), albeit intermediate, which we denote *KI outcome*. Specifically, we use one question of the CMU survey which asks respondents to indicate *how frequently the R&D personnel talks face-to-face with personnel from marketing/sales and production*. This question captures both the exchange of knowledge with personnel with different business units and the idea of exchange of tacit knowledge.[14] We define *KI outcome* as the total score resulting from summing the reported frequency of interaction (from 0, corresponding to "never or rarely" to 4, "daily") with personnel from sales and production. This measure has the advantage of abstracting from the actual practices adopted by firms to foster knowledge integration, and instead reflects the level of cross-functional integration between R&D and adjacent functions (production and marketing/sales) directly. The distribution of the variable, presented in Fig. 2, shows that the average degree of interaction is quite high across 2-digit sectors, with most of the R&D labs reporting at least monthly interaction. In general, less than half of the labs in our sample reports daily interaction with other business units, which gives us enough variation to employ this variable in the empirical analysis.

Alternatively, as a robustness check, we have also built one extra measure of KI outcome (denoted *KI outcome (robustness)*), based on actual knowledge flows between R&D and adjacent functions (Fig. 3). The CMU survey provides information about the importance of within-firm cross-functional knowledge flows to the productivity of the focal R&D lab.[15] In particular, respondents provide responses on whether the R&D lab obtained information from its own manufacturing operations or its customers (arguably through the marketing function) that either suggested new projects or contributed to completion of existing R&D projects. Based on these data, we construct an alternative measure of *KI outcome* based on the respondent's score (from zero, neither business unit suggested nor contributed, to 4, both suggested and contributed to the completion of projects).[16]

These measures have of course various limitations. Both outcome measures are agnostic in terms of the actual practices used to achieve cross-functional integration. Based on the literature on cross-functional integration, our assumption here is that cross-functional integration does not occur by chance, but primarily by organizational design. We

[13] For instance, this may occur when some individuals or groups do not share culture of openness and collaboration which is required to make cross-functional team to work in practice.

[14] Previous literature has used this variable as a proxy of the degree of co-specialization between R&D, manufacturing and sales required to successfully commercialize new technologies (Arora and Ceccagnoli, 2006; Ceccagnoli, 2009). The possession of co-specialized complementary assets has been linked to greater appropriability of rents from innovation. In this paper we control for the effectiveness of a full set of appropriability mechanisms, including patents, trade secrecy, marketing and manufacturing assets, using related questions from the survey, to focus on the extent to which returns to R&D from the

(*footnote continued*)
possession and internal transfer of tacit knowledge are undermined by tacit spillovers benefiting rivals.

[15] The same question from the CMU survey is used to derive a measure of sourcing of external knowledge and internal knowledge, described in this section, which is then used for the analysis in Section 5.3.

[16] Notice that this variable only captures unilateral flows of knowledge from manufacturing operations and customers toward the R&D unit of the firm. This allows to test whether our theory still holds when abstracting from problems related to low absorptive capacity in the manufacturing and sales departments of the firm, a factor that we are not able to fully control due to limitations of the CMU survey.

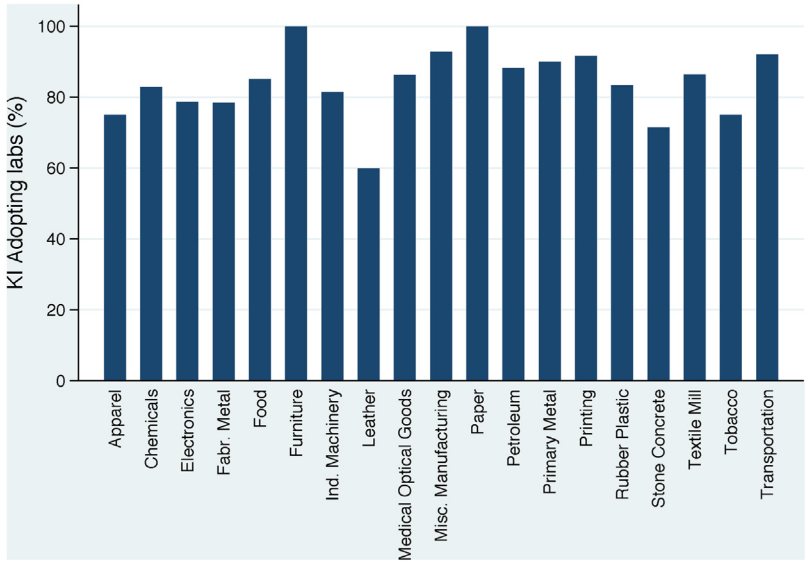

Fig. 2. *KI adoption* score by SIC-2 sector. *Notes*: Reported score of knowledge integration adoption based on answers from the CMU survey (binary response). The bar indicates the average percentage number of adopting labs in a given sector.

Fig. 3. *KI outcome (robustness)* score by SIC-2 sector. *Notes*: Reported score of an alternative measure of knowledge integration outcome based on answers from the CMU survey (score from 0 to 4). Individual responses have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

therefore feel confident about using these outcome measures as proxies for the intensity of managerial efforts in supporting KI. Another limitation of our KI measure is that we cannot observe in the CMU survey any detailed information about the sequential chain of interactions between the different departments; all the knowledge flows that are captured in our outcome measures, with the exception of those measured in *KI outcome (robustness)*, are bilateral, and our measures can only capture the overall intensity of those flows. While these are aspect of great interest, due to the limitations of the data at our disposal, we can only leave the investigation of these aspects to future research.

Table 1 summarizes the different measures that we propose, and the associated advantages and disadvantages. Importantly, our results are qualitatively robust to any of these 3 measures of KI.

External v. Internal Knowledge Sourcing We construct measures of knowledge sourcing that allow us to examine the impact of spillovers on the sourcing of internal and external knowledge. To do so, we exploit the same question employed to generate the variable *KI outcome (robustness)*, explained above. In that question, the respondent identifies one or more sources of knowledge that either suggested new projects or provided knowledge that contributed to completion of existing R&D projects. Crucially, the list encompasses sources that are internal and sources that are external to the firm. We construct two score measures, one for internal knowledge sourcing (*Internal Knowledge Sourcing*) (Fig. 4) and another for external knowledge sourcing (*External Knowledge Sourcing*) (Fig. 5).[17] We classify as internal knowledge sources: affiliated suppliers (linked to the R&D lab through ownership), the firm's manufacturing operations, customers and the other R&D units of the firm.[18] We classify as external sources: independent suppliers (not linked through ownership), cooperative or joint ventures, universities or government research institutes and labs, competitors and consulting or contract R&D firms.

[17] To calculate the score, we assign one point if a source either suggested new projects or provided knowledge that contributed to completion of existing R&D projects, and two points if both suggested and contributed with knowledge. The overall score for internal and external is the sum of the score across sources.

[18] We classify customers as an internal source, consistently with the definition of the variable *KI outcome (robustness)*. Results are qualitatively unchanged if we classify customers as a source of external knowledge.

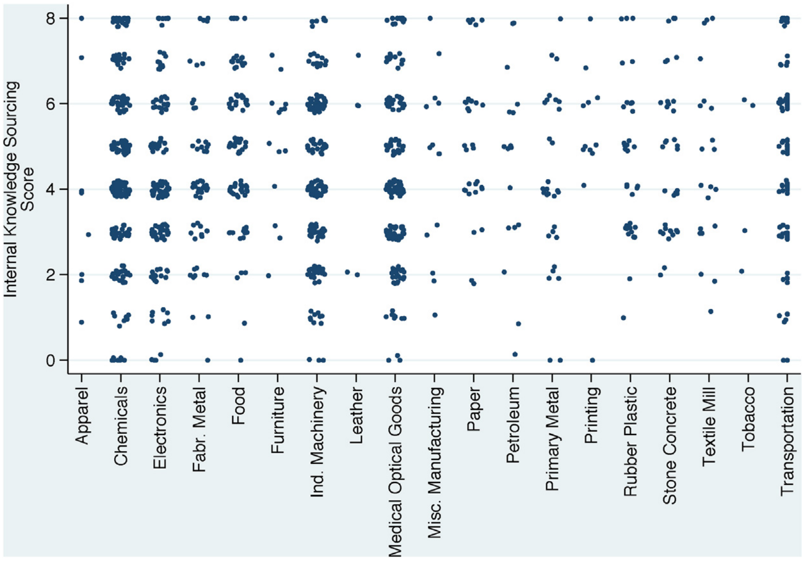

Fig. 4. *Internal Knowledge Sourcing* score by SIC-2 sector. *Notes*: Reported score of an alternative measure of knowledge integration outcome based on answers from the CMU survey (score from 0 to 6). Individual responses have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

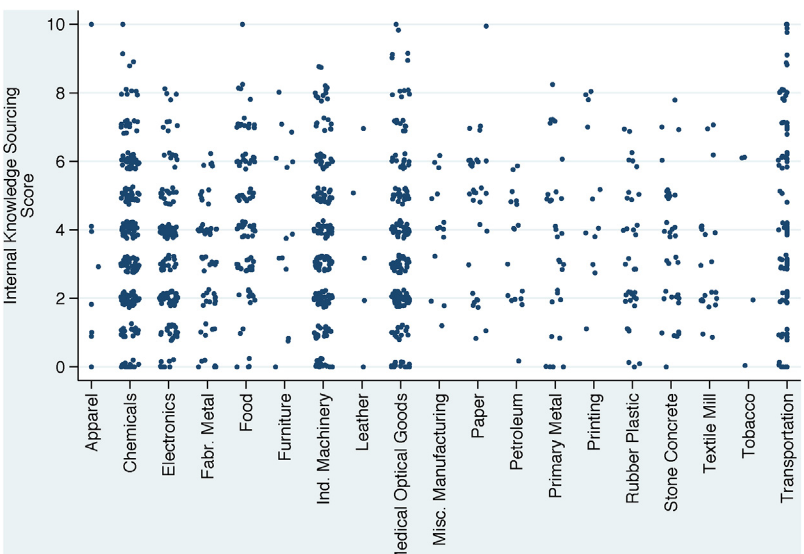

Fig. 5. *External Knowledge Sourcing* score by SIC-2 sector. *Notes*: Reported score of an alternative measure of knowledge integration outcome based on answers from the CMU survey (score from 0 to 6). Individual responses have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

3.2. Independent variables: knowledge spillovers

The CMU survey features detailed questions about the importance of information about R&D activities or innovation of competitors and the channel through which they are obtained, as well as the frequency and the timing of such spillovers (for an in-depth analysis of intra-industry R&D information flows using the CMU and an analogous survey conducted in Japan, see Cohen et al., 2002). As we explain below, some of the measures we propose have already been used in previous papers for the purpose of measuring knowledge flows from different channels, and in particular by operating a distinction between codified and non-codified knowledge (Roach and Cohen, 2013).

Importantly, since respondents are asked about the information they receive from competitors, these are not direct measures of outgoing spillovers. To capture the potential for outgoing knowledge spillovers we compute the mean of each answer at the industry level (measured at the 3-digit SIC code of the lab), excluding the focal lab. Since the range of the possible answers for each question is different, we standardize each measure using the standard deviation of the variable's distribution. This facilitates comparison of the estimated coefficients related to the outgoing spillover variables across specifications. The next paragraphs provide a more detailed description of the different spillovers variables that we employ in our analysis.

Generic spillovers We construct a variable which captures the extent of the exchange of information that has contributed to complete or suggest a new existing R&D project coming from competitors. This spillover measure does not differentiate whether the type of knowledge exchange is codified or tacit.[19] Respondents are asked to report whether, during the last three years, the R&D department has obtained information from competitors that have either suggested or contributed to complete and existing R&D project (binary reponse). We take the sum of each of the two answers, and then we take the average of standardized scores of all labs operating in the same industry excluding the focal lab. to construct the lab-level score of spillovers (Fig. 6).

Codified v. tacit spillovers Our key variables of interest are two spillover measures that allow us to differentiate between codified and tacit spillovers. We use a question of the CMU survey in which the

[19] Moreover, a potential limitation of our benchmark measure of generic spillovers is that respondents (despite assurance of confidentiality of the survey) may not truthfully reveal if they actually used information from competitors that either suggested new R&D projects or suggested new projects. We thank one of the reviewers for raising this concern.

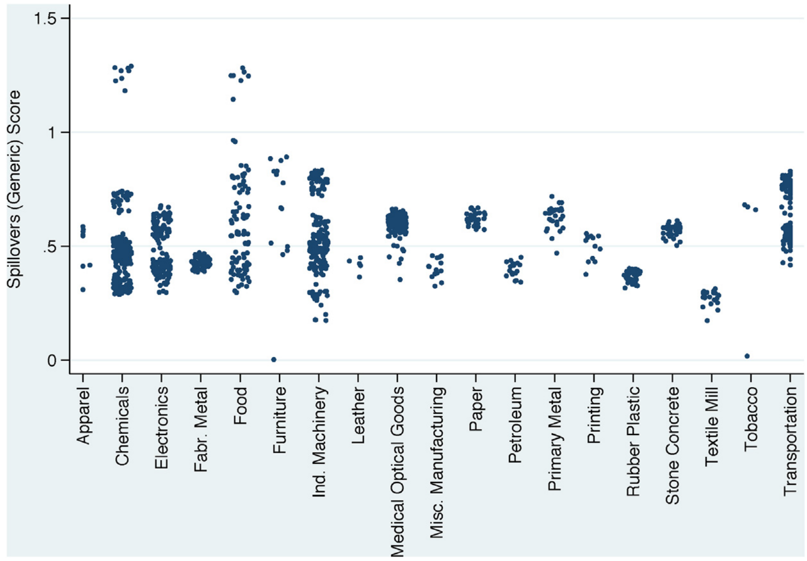

Fig. 6. Generic spillovers by SIC-2 sector. *Notes*: Standardized spillovers score based on answers from the CMU survey. Scores computed at the SIC-3 level. Individual scores have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

respondent is asked to indicate the sources of information on the R&D activities of innovation of other firms in its focus industry and their importance (from 1, "not important" to 4, "very important").[20] To construct the codified spillovers variable, we focus on the importance of patents, publications and reports, licensed technology and reverse engineering of competing products. For tacit spillovers, we focus instead on public conferences and meetings,[21] informal information exchange, recently hired technical personnel, joint or cooperative R&D projects[22] and trade associations.[23] For both the tacit and codified spillovers measures, we take the unweighted sum across channels, and then we take the average of standardized scores of all labs operating in the same industry excluding the focal lab (Figs. 7 and 8).

Frequency and timing We complement the two previous measures with data on the frequency and the timing of information received about the activities of competitors. These measures do not directly differentiate between tacit and codified spillovers, but they can be correlated with our dimension of interest; therefore, we consider them to evaluate the sensitivity of our results to different ways to measure spillovers. The first of these measures reflects the frequency of spillovers obtained from R&D competitors located in North-America. This provides an intensity measure for the generic spillovers dimension and we therefore expect it to have the same effect as our main generic spillovers measure.

The second measure is based on a question asking at what stage of the innovation process has the respondent become aware of the competitor's project (from "project initiation" to "product/process introduction"). We refer to this measure as the "timing" of the spillovers. Spillovers are considered more harmful earlier in the process. Indeed, it has been argued that spillovers in the earlier phases of an R&D project are relatively more likely to involve tacit knowledge. Cowan et al. (2000) suggest that "…early in the life of a discipline or technology, standardization of the discipline (and of the models) will be an important part of the collective activity of codification. When this 'dictionary' aspect of the codebook becomes large enough to stabilize the 'language', the 'document' aspect can grow rapidly." Consistent with this argument, in the economic literature on clustering, the propensity of economic activity to cluster has been linked to industries where new knowledge plays a more important role (Audretsch and Feldman, 1996), and in particular the early phases of the industry lifecycle, where tacit knowledge is thought to play a relatively more important role (Audretsch and Feldman, 1996). In the management literature cross-functional knowledge integration has been found to be effective for idea-generation in earlier phases of idea generation (Troy et al., 2001). Moreover, the relationship between cross-functional integration and new product success has been found to be stronger when integration occurs at earlier stages of the product development process (Troy et al., 2008), consistent with the idea that KI practices facilitate the transfer of tacit knowledge, which is critical in the earlier phases of an R&D project.

As per the prior measures of outgoing spillovers, these two alternative spillover measures are computed at the industry level to capture the potential for outgoing spillovers benefiting rivals (Figs. 9 and 10).

3.3. Control variables

In the empirical analysis we include various control variables that capture firm and industry level characteristics. In the following we list each set of controls, starting from the sector to the lab level of measurement. Additional details for each variable are reported in Appendix A.6.

[20] In a previous paper, Roach and Cohen (2013) have correlated the different channels of knowledge as reported in the CMU survey with data on patent citations to distinguish between open science and private relationship and, to a lesser extent, to argue about different levels of codifications of each source.

[21] Following the suggestion of a reviewer, there may be various reasons why conferences and meetings, as well as joint R&D, could be excluded: one is that conferences and meetings could involve the exchange of both tacit and codified knowledge; second, meetings and presentations could be considered as planned or intentional ways to share knowledge with partners or the scientific community. For both these reasons, conferences and meeting may not be an appropriate channel to be included in our definition of spillovers. Our results are robust to alternative ways to define tacit spillovers, for instance when excluding conferences and meetings and joint R&D. See Appendix A.2 for more details.

[22] Previous research has argued that joint and cooperative research is an effective way of transferring more complex and less codified knowledge and know-how. See for instance Cockburn and Henderson (1998), Cohen et al. (1998), Zucker et al. (1998), Thursby et al. (2009). Because we focus on spillovers, we include in our measure "joint or cooperative R&D projects" but we exclude "contract research with other firms", in which the level of confidentiality is supposed to be much higher. Note that our results remain qualitatively unchanged when the score of "joint or cooperative R&D projects" is excluded from the construction of tacit spillovers.

[23] Hired personnel can be considered a good proxy for spillovers when KI targets the manufacturing department, while trade association can represent a source of information when KI involves personnel working in sales or marketing. Our results are qualitatively unchanged when we consider public conferences and meetings as a source of codified knowledge.

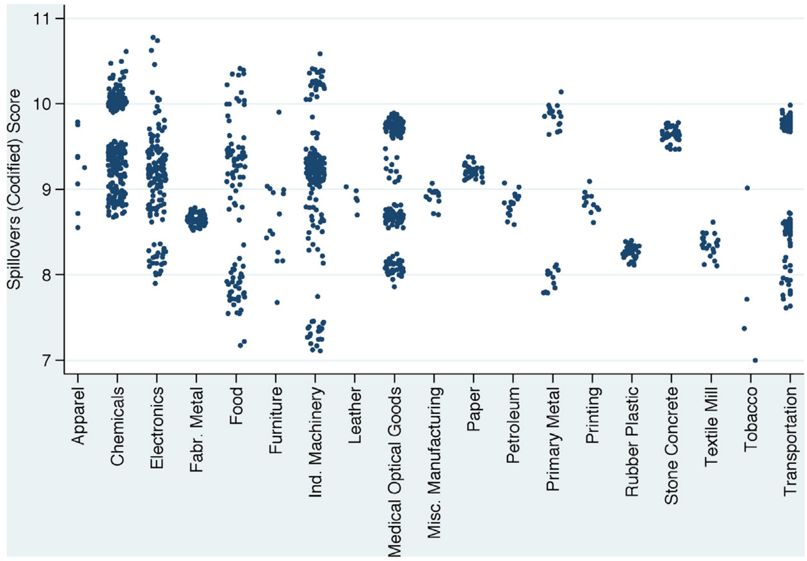

Fig. 7. Codified spillovers score by SIC-2 sector. *Notes*: Spillovers score based on answers from the CMU survey. Scores computed at the SIC-3 level. Individual scores have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

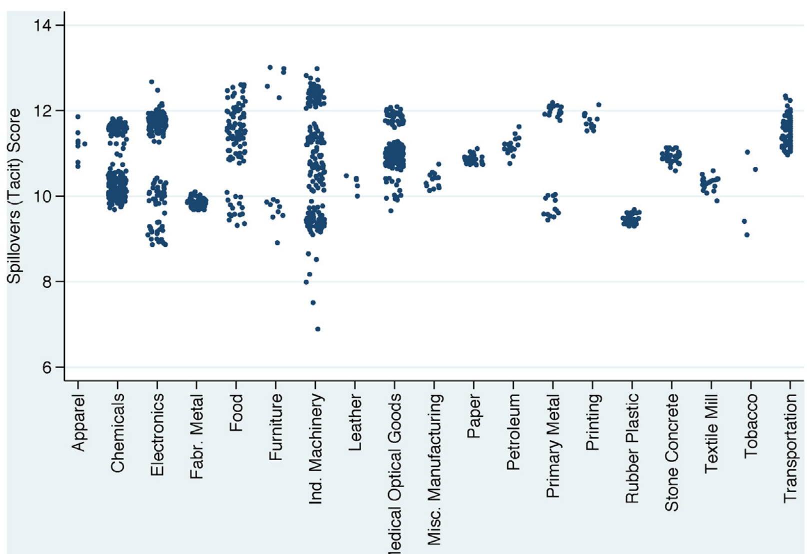

Fig. 8. Tacit spillovers score by SIC-2 sector. *Notes*: Spillovers score based on answers from the CMU survey. Scores computed at the SIC-3 level. Individual scores have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

3.3.1. Focus-industry controls

We include a set of industry-level controls that refer to the focus-industry of the lab. These controls target factors that have the potential of limiting or offsetting the negative effect of spillovers, induce adoption of KI and affect its outcome. Similarly to the spillover variables, these controls are all generated by taking the average across labs operating at the same 3-digit SIC industry excluding the focal lab. This allows us to produce an industry-level average whenever the CMU questionnaire only provides information related to the individual R&D laboratory, while limiting the possibility that our measures are endogenous to our dependent variable, which is taken at the R&D lab level.

Appropriability conditions The risk of spillovers can vary according to the probability that such knowledge can effectively be used by competitors for imitation. These controls will play a key role to identify the effect of spillovers. For instance, a company may establish its competitive advantage in a given market by developing a strategy based on the ownership of complementary assets, rather than the protection of key knowledge (e.g. the strategy followed by Tesla in the electric cars market).[24] Not taking into account the effectiveness of complementary assets across industry would bias the estimated impact of spillovers.[25] We control for the effectiveness of appropriability mechanisms aimed at preserving the firm's competitive advantage: secrecy, patenting, lead times, and ownership of complementary sales and manufacturing capabilities. These controls are generated by taking the average across labs operating at the same 3-digit SIC industry excluding the focal lab. By doing so, we accomplish two objectives. First, we control for differences in appropriability conditions across industries, which are mostly independent of firms' decision or cannot be easily changed in the short run (while reducing the risk of endogeneity). Second, we can focus on explaining the effect of outgoing knowledge

[24] We thank a referee for suggesting this example.

[25] If we assume that a company with high level of KI operates in a market with a high degree of tacit knowledge spillovers because of the presence of complementary assets, the bias on the estimated impact of spillovers would be negative.

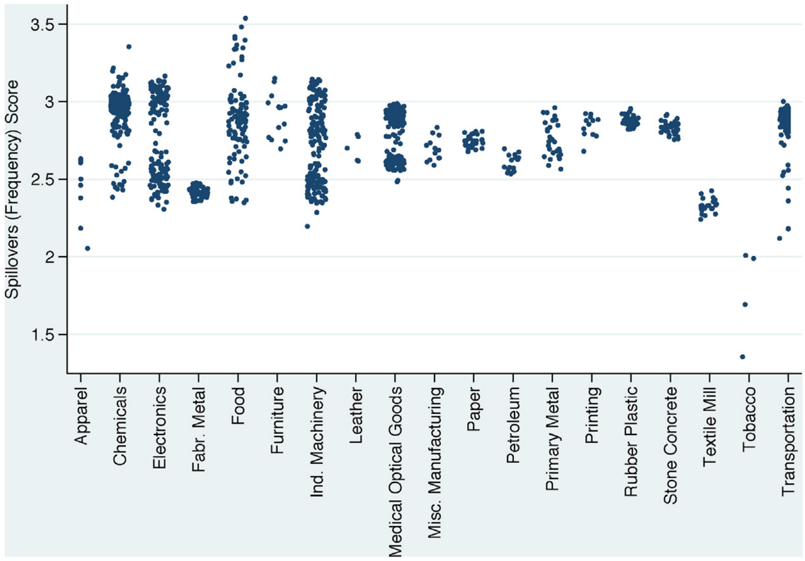

Fig. 9. Frequency spillovers score by SIC-2 sector. *Notes*: Spillovers score based on answers from the CMU survey. Scores computed at the SIC-3 level. Individual scores have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

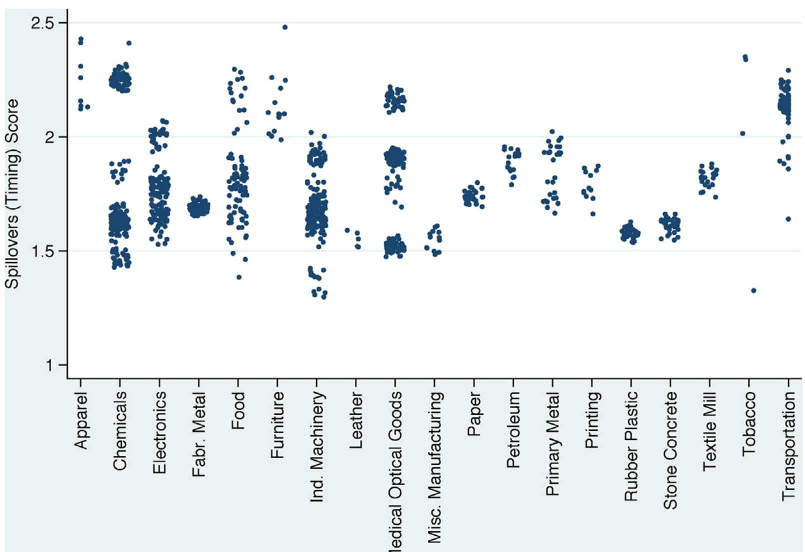

Fig. 10. Timing spillovers score by SIC-2 sector. *Notes*: Spillovers score based on answers from the CMU survey. Scores computed at the SIC-3 level. Individual scores have been represented in a cloud format to highlight the variation in density of each score levels across the SIC-2 sectors.

flows that cannot be effectively protected by appropriability mechanisms commonly used to protect the competitive advantage from product and process innovations.

Technological rivals The risk of effective imitation will also depend on the capability of rivals. We therefore control for the number of technology rivals faced by the firm in the focus industry.

Industry innovation rate We also control for the innovation rate of the industry. A high rate of innovation is an incentive to improve the effectiveness of R&D and increase knowledge integration.

3.3.2. *Industry fixed-effects*

Finally, we include a full-set of 2-digit SIC-based dummies based on the focus industry of the lab to control for other unobserved more aggregate factors.

3.3.3. *Firm and lab-level controls*

The CMU questionnaire asks several other questions related to the lab or its firm with reference to the focus industry of the responding R&D lab. We control for the market share, the total number of employees, employees working in R&D, public ownership, and the degree of vertical integration. These are important controls, for instance because larger organizations have greater needs for knowledge integration. The same holds for vertically integrated companies, in which a higher share of the operating revenue comes from sales of manufactured products. We control for the share of R&D personnel devoted to gather information on new scientific developments to control for a firm's ability to absorb incoming knowledge flows (i.e. absorptive capacity).[26] The percentage of basic research (scientific research with no specific commercial objectives) is included to control for the type of R&D activity that may increase the risk of spillovers. Finally, the physical distance of the lab from other facilities (a dummy = 1 for labs physically located in

[26] Following the suggestion of a reviewer, we run additional sensitivity analysis to provide corroborating evidence that our main variable of interest are not correlated with lack of absorptive capacity, either at the R&D lab or in other departments of the firm. These analyses are outlined in the Appendix.

Table 2
Summary statistics for the dependent and independent variables.

	1	2	3	4	5	6	7	8
1. KI outcome								
2. KI adoption	0.054							
3. KI outcome (robustness)	0.167	0.152						
4. Spillovers (generic)	−0.016	0.023	−0.027					
5. Spillovers (codified)	−0.007	−0.011	−0.038	0.137				
6. Spillovers (tacit)	−0.098	0.007	−0.090	0.286	0.273			
7. Spillovers (frequency)	−0.023	0.011	−0.034	0.279	0.156	0.329		
8. Spillovers (timing)	−0.133	0.056	−0.101	0.273	0.173	0.574	0.284	
Mean	6.412	0.84	2.975	0.530	9.072	10.828	2.784	1.803
Standard deviation	1.613	0.367	1.086	0.156	0.695	0.898	0.236	0.23
Min	0	0	0	0	7	7	1.333	1.306
Max	8	1	4	1.295	10.857	13	3.538	2.5

Notes: All variables based on the CMU survey. Spillover scores non-standardized. The full set of variables used in the analysis is summarized and described in Tables A.3 and A.4.

Table 3
Full sample, generic spillover measure.

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Spillovers (Contribution/Suggestion)	0.043	0.036	0.013	−0.024	−0.105	−0.167
	(0.045)	(0.057)	(0.056)	(0.088)	(0.107)	(0.127)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
Focus industry controls (3-digit SIC)	No	Yes	Yes	No	Yes	Yes
Firm and lab-level controls	No	No	Yes	No	No	Yes
R^2	0.029	0.042	0.090			
Pseudo R^2				0.021	0.027	0.134
Observations	1238	1238	1238	1238	1238	1238

Notes: Dependent variables are *KI outcome* (OLS) and *KI adoption* (Logit) based on the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.

a stand-alone facility) may affect the adoption and outcome of KI. Table 2 presents descriptive statistics with correlation coefficients.

4. Empirical results

In this section we present our empirical strategy to estimate the effect of tacit knowledge spillovers on the adoption and outcome of knowledge integration practices.

The central hypothesis from our conceptual development is that outgoing spillovers have a larger impact on knowledge integration practices when they are generated through tacit knowledge exchange. To test this prediction we regress our two main measures of KI on several different measures of outgoing spillovers. First, we begin by regressing our knowledge integration outcome and adoption measures using a generic measure of spillovers. Next we focus on whether the importance of knowledge spillovers for KI depends on the level of codification of the knowledge flows. Since in our sample some R&D labs belong to the same firm, we correct for correlation of the residuals by clustering standard errors at the firm level in all regression models.

Our approach can be considered a reduced-form approach with respect to the relationship between the dependent variables and the main independent variables in the following sense: in our underlying structural model, outgoing spillovers (generic or tacit) benefiting competitors have a direct effect on KI adoption, which in turn has a direct effect on KI outcome. For the lack of plausibly valid instruments, we do not estimate the structural equation whereby KI outcome is a function of KI adoption. We instead estimate KI outcome as a function of outgoing spillovers, whose effect in these regressions ought to be considered indirect and exogenous.

4.1. Generic spillover measure

In Table 3 we present the results of our estimated model using a generic measure of spillovers. This variable captures acquisition of information from competitors that has contributed to completion of an existing project or suggested a new R&D project, without differentiating whether the type of knowledge exchange is codified or tacit. We report only a summary of the estimation results, focusing on our variable of interest (the table with all the estimated coefficients is available in Table A.4). We find that the estimated impact of spillover on knowledge integration adoption and outcome is close to zero and not statistically significant across models. The estimated coefficient varies slightly when including different sets of controls, while the standard errors remain stable. The largest variation in the coefficient occurs when introducing the controls at the lab and firm level, which represents the largest source of variability.

This set of results is not surprising. As pointed out by Kogut and Zander (1992), knowledge integration mainly involves codification and transfer of tacit knowledge. Crucially, industries in which the risk of spillovers of codified knowledge is high, may not necessarily suffer the same problem with respect to tacit knowledge. In the remainder of the paper, we focus on a different measure of spillover intensity that allows us to distinguish between the degree of codification of the knowledge flows.

4.2. Codified v. tacit spillovers

In this section we focus on the source of spillovers, and in particular whether the knowledge spillovers are codified or tacit. We do so by estimating our main regression using two different spillover variables:

Table 4
Full sample, codified vs. tacit spillover measure.

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Spillovers (Codified)	0.078	0.096	0.059	0.038	−0.049	0.063
	(0.057)	(0.068)	(0.066)	(0.092)	(0.119)	(0.137)
Spillovers (Tacit)	−0.140**	−0.212***	−0.164**	−0.082	−0.215	−0.282**
	(0.060)	(0.070)	(0.069)	(0.092)	(0.133)	(0.142)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
Focus industry controls (3-digit SIC)	No	Yes	Yes	No	Yes	Yes
Firm and lab-level controls	No	No	Yes	No	No	Yes
R^2	0.034	0.050	0.094			
Pseudo R^2				0.022	0.029	0.137
Observations	1238	1238	1238	1238	1238	1238

Notes: Dependent variables are *KI outcome* (OLS) and *KI adoption* (Logit) based on the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.
** Significance level: 5%.
*** Significance level: 1%.

Spillovers (Codified), representing the extent of spillovers mediated by channels of communications for more codified knowledge. As detailed in the data description section, such variable measures spillovers generated by patents, publications and reports, licensed technology and reverse engineering of competing products; *Spillovers (Tacit)*, a variable that captures the average amount of spillovers generated from tacit knowledge sources, such as public conferences and meetings, informal information exchange, recently hired technical personnel, joint or cooperative R&D projects, and trade associations.

The estimated results, presented in Table 4, show that *Spillovers (Codified)* do not have any significant impact on KI; on the contrary, *Spillovers (Tacit)* have a negative and significant impact on the outcome and adoption of KI. Most importantly, the impact remains strong after controlling for firm and lab-level characteristics. In terms of magnitude, we can interpret our results as follows: when taking specification (3) as the most complete and preferred specification (since it includes the full set of controls), an increase of *Spillovers (Tacit)* by one standard deviation reduces the *KI outcome* score by 0.164 (p-value < .05).[27] For specification (6) estimated with Logit, the computed marginal effect of tacit spillovers (not show in the table) indicates that a one standard deviation increase in Tacit Spillovers reduces the probability of adoption of cross-functional knowledge integration practices by 0.033 (p-value < .05). Given the nature of the data, however, we suggest our results to be interpreted in terms of the sign and the statistical significance of our estimated coefficients, rather than its magnitude.[28]

5. Robustness

In this section we discuss the extent to which our results hold when using alternative measures of knowledge integration and spillovers.

5.1. Alternative measure of knowledge integration

We now turn to the results of our robustness test using the alternative measure of KI outcome (*KI outcome (robustness)*), which is based on whether the R&D lab obtained and exploited information from its own manufacturing operations or its customers (arguably through the marketing function). Results are outlined in Table 5. These results are qualitatively and quantitatively in line with those derived with our main measure of knowledge integration. While the size of the effects cannot be compared to our previous results due to the different scale of measurement of the alternative KI measures, the statistical significance of the effect of *Spillovers (Tacit)* on this alternative *KI outcome* measure is actually stronger (p-value < .01). Despite the very strong statistical effect that we find,[29] we believe that the findings using *KI outcome (robustness)* should be interpreted with caution: as explained in the data section, *KI outcome (robustness)* does not capture knowledge integration that necessarily involve exchange of tacit knowledge at the firm level (our main measure captures frequency of "face-to-face" interaction). Moreover, information from customers may be not necessarily channeled through the marketing function and therefore not represent within-firm knowledge flows.

Table 5
All firms, tacit spillovers, alternative KI measure.

	(1)	(2)	(3)
Spillovers (Codified)	0.022	0.098**	0.097**
	(0.036)	(0.044)	(0.045)
Spillovers (Tacit)	−0.144***	−0.135***	−0.128***
	(0.039)	(0.046)	(0.048)
Industry FE (2-digit SIC)	Yes	Yes	Yes
Appropriability and Tech. Rivalry	No	Yes	Yes
Firm and lab-level controls	No	No	Yes
R^2	0.027	0.051	0.059
Observations	1238	1238	1238

Notes: Dependent variables is *KI outcome (robustness)* based on the self-reported contribution and suggestion of manufacturing and customers to an R&D project (*source*: CMU survey). Estimation method: OLS. Robust standard errors clustered at the firm level included in parenthesis.
** Significance level: 5%.
*** Significance level: 1%.

[27] Because of the difference in metrics, it is hard to compare the impact of tacit spillovers to that of other factors. It should be noted that, while being significant, tacit spillovers are not the only factor affecting the adoption of knowledge integration practices. For instance, we find that when the laboratory is physically isolated from the rest of the company, knowledge integration score is reduced by 0.469; please see the Appendix for the complete list of all the estimated coefficients in our regressions.

[28] Note that one potential criticism to our identification strategy is that our spillover measures may be correlated to a lack of absorptive capacity on the side of employees in other functions. Appendix A.3 offers some empirical elements in response to that concern.

[29] This effect may be partly driven by the higher variability across industry that we observe for *KI outcome (robustness)* with respect to our other KI measures.

Table 6
All firms, alternative spillovers measures.

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Spillovers (Frequency)	0.045	−0.042	−0.050	−0.019	−0.013	−0.032
	(0.060)	(0.070)	(0.070)	(0.106)	(0.132)	(0.141)
Spillovers (Timing)	−0.206***	−0.214***	−0.194***	0.035	−0.061	−0.126
	(0.061)	(0.071)	(0.069)	(0.108)	(0.125)	(0.128)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
Focus industry controls (3-digit SIC)	No	Yes	Yes	No	Yes	Yes
Firm and lab-level controls	No	No	Yes	No	No	Yes
R^2	0.039	0.051	0.098			
Pseudo R^2				0.021	0.026	0.134
Observations	1238	1238	1238	1238	1238	1238

Notes: Dependent variables *KI outcome* (OLS) and *KI adoption* (Logit) based on the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.
*** Significance level: 1%.

5.2. Alternative measures of spillovers

We now verify the robustness of our results to alternative measures for outgoing spillovers. In particular, while the question of the CMU survey on channels of external information flows used in our benchmark results is based on a reasonably clear distinction between tacit and codified spillover channels, there are other questions in the survey that explore the importance of spillovers among competitors capturing different dimensions of the mechanisms at play. In particular, we have introduced in the previous section two measures based respectively on the frequency and timing of outgoing spillovers.

The results, presented in Table 6, are qualitatively in line with those derived with our main measures of generic and tacit spillovers. While the size of the effects cannot be compared due to the different scale of measurement, the statistical significance of the effect of this alternative measure of generic spillovers based on frequency of interaction with competitors is not significantly different than zero in any of the estimated specifications and is therefore consistent with the main generic spillovers effect.

The alternative measure of tacit spillovers based on the timing of the spillovers tend to have a negative effect, which is also highly significant (p-value < .01) when using the outcome measure of KI (cf. column 3, Table 6). Its effect on *KI adoption* is directionally consistent but not significant at conventional levels. These results are compatible with our core finding on tacit spillovers.

5.3. The paradox of openness

We have shown that the risk of knowledge spillovers can have important implications on the organization of knowledge flows and adoption of practices within the firm. Importantly, the impact of spillovers may extend beyond the organization of internal knowledge, by affecting the decision of the firm to source knowledge from external sources. This question is relevant in this context because the effect of spillovers on external knowledge sources can contribute to mitigate or exacerbate the impact on the firm's innovation performance.

Various pieces of research have examined the implications of the “fear of imitation” on the firm's R&D choices, for instance in terms of joint R&D projects, restriction of personnel mobility, choice of firm location and ability to source external R&D knowledge in general.[30]

In the spirit of this research, this section investigates whether the risk of tacit and codified spillovers has indeed an impact on the mechanisms that govern the sources of external knowledge. For instance, the threat of tacit spillovers may induce a company to dissuade the participation of its R&D employees in international conferences, which could represent an important obstacle to the sourcing of knowledge and induce additional loss of R&D opportunities. On the other hand, if the type of R&D knowledge that is exchanged in public conferences has already been codified (and it can therefore be protected through patent or other mechanisms), then we should hardly observe any relation between the risk of tacit spillovers and the sourcing of external knowledge.

To do so, we estimate a version of the previous regression equation in which the dependent variable is a measure of external knowledge sourcing, defined using information contained in the CMU survey. Results are illustrated in Table 7.

The table shows that, once controlling for industry and lab characteristics, there is no statistically significant impact of either tacit or codified spillovers on the sourcing of external knowledge. While not statistically significant, we note that the sign of the estimated coefficients associated to our spillover measures are reversed with respect to the case in which the dependent variable is a measure of knowledge integration: the coefficient of tacit spillovers has a positive coefficient (which becomes smaller as additional controls are introduced in the equation), while the coefficient associated to codified spillovers has a negative coefficient. While no clear inference can be made based on these results, it seems to suggest that knowledge sourced from external sources is more likely to be codified, and that the presence of different type of spillovers may induce the firm to substitute between internal and external knowledge sources.

In order to better investigate the presence of this substitution pattern, following Giarratana and Mariani (2014) we derive a new variable that captures the relative importance of external knowledge with respect to internal knowledge sourcing. This variable is defined as follows:

$$\frac{(\text{External Knowledge} + 1) - (\text{Internal Knowledge} + 1)}{(\text{External Knowledge} + 1) + (\text{Internal Knowledge} + 1)} \qquad (1)$$

Table 8 presents the results of the estimation when the measure (1) is the depend variable of our regression equation.

These results are consistent with our previous finding and show stronger evidence that, after controlling for industry and lab characteristics, the threat of codified spillovers reduces the use of external knowledge sources with respect to internal knowledge sources. This occurs substantially because the threat of codified spillovers reduces the use of external knowledge sources. At the same time, we do not find any

[30] See for instance Liebeskind (1996), Cassiman and Veugelers (2002, 2006), Oxley and Sampson (2004), Agarwal et al. (2009) and Giarratana and Mariani (2014).

Table 7
Full sample, codified vs. tacit spillover measure.

	(1)	(2)	(3)
Spillovers (Codified)	−0.010	−0.123	−0.104
	(0.075)	(0.094)	(0.094)
Spillovers (Tacit)	0.148**	0.115	0.087
	(0.071)	(0.100)	(0.095)
Industry FE (2-digit SIC)	Yes	Yes	Yes
Appropriability and Tech. Rivalry	No	Yes	Yes
Firm and lab-level controls	No	No	Yes
R^2	0.037	0.041	0.111
Observations	1238	1238	1238

Notes: Dependent variables is the score of *External Knowledge Sourcing* (OLS), based on the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.
** Significance level: 5%.

Table 8
Full sample, codified vs. tacit spillover measure.

	(1)	(2)	(3)
Spillovers (Codified)	0.004	−0.022**	−0.024**
	(0.008)	(0.010)	(0.010)
Spillovers (Tacit)	0.022***	0.017*	0.017
	(0.008)	(0.011)	(0.011)
Industry FE (2-digit SIC)	Yes	Yes	Yes
Appropriability and Tech. Rivalry	No	Yes	Yes
Firm and lab-level controls	No	No	Yes
R^2	0.016	0.035	0.056
Observations	1238	1238	1238

Notes: Dependent variables is the relative importance of external knowledge sources to internal knowledge sources (OLS) as defined in (1), which is based on scores calculated using the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.
* Significance level: 10%.
** Significance level: 5%.
*** Significance level: 1%.

strong evidence that the threat of spillovers may induce a substitution of external sources with internal knowledge sources, as the estimated coefficient of tacit spillovers, while positive, is never statistically significant in our most complete specification (which includes the R&D lab characteristics controls).

6. Discussion and conclusions

How do firms manage their most valuable R&D knowledge? The central hypothesis of this paper is that cross-functional knowledge integration may come with detrimental side effects, resulting in a managerial trade-off. Specifically, we have developed a theory supporting the view that cross-functional integration increases the exposure of a firm's innovation to potential knowledge outflows. Using survey data on a representative sample of U.S. R&D labs that are part of a U.S. manufacturing firm located in the U.S., our empirical research is consistent with the existence of such a trade-off, as it indicates that the propensity of firms to adopt KI practices or achieve effective cross-functional integration is lower for firms operating in a spillover-prone competitive environment. This relationship is magnified when industry spillover channels are more tacit and when they tend to involve knowledge about earlier-stage innovations. The results are robust to controls for appropriability conditions. Because KI involves tacit knowledge, it is only in part related to appropriability conditions such as secrecy or patents due to the limited effectiveness of these mechanisms in protecting tacit knowledge.

Several works have highlighted that R&D is more productive when knowledge is more integrated across departments along the firm's internal value chain. *Knowledge Integration (KI)* denotes this synthesis of functional knowledge into situation-specific systemic knowledge. Since KI leads to superior R&D performance, adopting practices aimed at fostering such integration should be a dominant choice for every innovative firm. If firms do not seek to achieve cross-functional integration, as it appears in our survey data, it suggests that KI does not always constitute a dominant strategy. Multiple theoretical frameworks point at a trade-off between internal knowledge transfers and external knowledge leakages. As tacit knowledge is transferred across functional areas, it may be exposed to a higher risk of spilling out to the competition. This trade-off has been emphasized by several prominent scholars, yet rarely put to the empirical test, if at all.

Based on the chain-linked model of innovation (Kline and Rosenberg, 1986) and the prolific literature on product innovation (Moenaert and Souder, 1990), our theory posits that cross-functional integration rests on cross-functional knowledge flows. These flows lead to uncertainty reduction, which are critical in innovative processes. R&D information becomes more valuable once complemented with market information such as customer feedback and, likewise, knowledge about the market becomes more valuable once combined with knowledge about technical solutions that have been successfully tested or failed. Cross-functional integration therefore involves the dissemination of knowledge that can be extremely useful in reducing critical uncertainties. Our theory posits that this dissemination exposes valuable knowledge (or its combination) to larger social circles not only inside but also outside the firm, as more employees – each with their own social network or mobility beyond the firm – carry it. Our empirical research suggests further that this is primarily a matter of tacit information flows and informal (interpersonal) channels, such as employee mobility.

To our knowledge, our results provide some of the first empirical evidence of the trade-off between knowledge management (inside the firm) and knowledge spillovers (outside the firm). Fostering knowledge flows within the firm seems – at least in the expectations of managers – associated with a higher risk of knowledge leakages to the competition. Our results have therefore important implications for the fields of knowledge and innovation management, given that such a trade-off needs to be carefully acknowledged and managed.

Our results also speak to the product innovation literature, which has deeply analyzed the virtues of cross-functional integration and ways or practices to achieve it effectively. Our research provides a disclaimer to that literature, emphasizing the potential downside cost of cross-functional integration. This might inspire further research about the sensitivity of different integration practices to the risk of external spillovers.

It should be acknowledged, however, that the preemptive avoidance of knowledge integration might not be the only option for firms facing the risk of spillovers. This points among others at the burgeoning literature on open innovation and its paradox. A number of works have recently shown that firms also face a trade-off as they open up their innovation processes, since they benefit from external knowledge sources, but also expose their own innovation to imitation. Companies facing this *paradox of openness* may simultaneously adjust other policies, such as their mix of appropriation mechanisms, the extension of their openness, or other adjustments in terms of investments in absorptive capacity. Conversely, firms might choose to close their innovation and foster internal integration to escape the trade-off. But this approach would cut the firm from prime sources of knowledge and innovation, which goes against the general trend toward openness. Our results suggest that in presence of high tacit knowledge flows in their industry, firms tend to prefer preserving their access to external sources of knowledge (hence remain open or branched out to their environment), but instead refrain their internal integration (KI) as a defensive strategy.

This result implies that market conditions or externalities may commend internal organizational practices. As a result, firms may trade their optimal innovative performance against superior appropriability of their rents. These observations therefore speak not only to the literature on innovation and knowledge management, but more generally illustrate the interdependence of internal and external factors in managerial practices, thereby also speaking to the growing literature on the economics of management.

6.1. Limitations

Our research is subject to a number of limitations, which open avenues for future empirical research on this topic.

First of all, our empirical analysis is focused on R&D labs and their integration with other departments and restricted to US manufacturing firms. Generalizing our findings to other types of knowledge (beyond R&D) or firms (e.g. service firms) is therefore subject to caution.

The main limitations stem from our own data constraints, which prevent us from inferring causal relationships. Further research would be needed to analyze the causal mechanisms that connect the simultaneous choices involved in our theory, preferably within a longitudinal setting with time and firm fixed effects. The time dimension would help scholars shedding light on the intricate interplay between KI and appropriability mechanism, which our work isolates from. These adjustment mechanisms are key to more precisely quantify the extent to which spillovers and variations in the competitive conditions affect innovative performance of firms, a topic of high policy relevance (e.g. to evaluate the dynamic efficiencies of mergers and acquisitions).

One would also benefit from more detailed measures of KI practices to potentially highlight different sensitivities to spillovers, before generalizing our findings to any type of knowledge integration.[31] This type of integration, which differs from that examined in this paper, may require a new type of survey to be systematically investigated across industry. One could also wish for more direct measures of spillovers, preferably at the firm (rather than industry) level, and a way to control for different disclosure strategies. Such data are unfortunately very hard to obtain, and we believe that the CMU survey data we use is still one of the very few datasets offering a view into these phenomena. More recent data could potentially also include measures relating to digital knowledge management and collaboration tools (such as wikis, blogs and instant messaging) that may yield different levels of the trade-off.

Finally, data covering non manufacturing sectors would also be important since an increasing fraction of R&D is conducted in non-manufacturing industries. This leaves many avenues for more research in this area, which we hope the present paper will help inspire.

Appendix A

A.1 KI and innovation performance

An important assumption of our analysis is that KI practices can bring an increase in the innovative performance of the firm. While these results have been confirmed in several studies, we examine the relation between different alternative measures of KI practices and outcomes and the innovative performance of the firm in our sample. This is to reassure the reader that the managerial practices considered in this study appear to be associated, on average, to higher innovative performance, as suggested by the managerial literature. We estimate the probability that the firm reports an above-than-average innovating performance (as reported in the CMU survey). The dependent variable is a dummy that takes value 1 when the R&D lab reports an innovation rate above the average of its firm's focus industry. The information is available for both product and process innovations. Results, obtained using a Logit model, are presented in Tables A.1 and A.2.

Table A.1
Performance, product innovation.

	(1)	(2)	(3)	(4)	(5)	(6)
KI outcome	0.116***	0.113***	0.150***			
	(0.037)	(0.037)	(0.039)			
KI adoption				0.600***	0.614***	0.596***
				(0.157)	(0.158)	(0.165)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
Focus industry controls (3-digit SIC)	No	Yes	Yes	No	Yes	Yes
Firm and lab-level controls	No	No	Yes	No	No	Yes
Pseudo R^2	0.019	0.023	0.041	0.021	0.026	0.040
Observations	1238	1238	1238	1238	1238	1238

Notes: Robust standard errors clustered at the firm level included in parenthesis.
*** Significance level: 1%.

Results show that our benchmark KI variables have a strong and positive relationship with product innovation performance; results on process innovation are more mixed (stronger for the adoption of cross-functional KI practices). These results present interesting correlations; however, we refrain from interpreting these results due to the endogeneity of both KI variables.

A.2 Alternative definition of the spillover variables

As pointed out by the reviewers, “public conferences and meetings”, “joint or cooperative R&D projects” and “trade associations” may either not necessarily capture tacit spillovers or be considered as planned and intentional ways to share knowledge with partners or the scientific community (thus not relevant for our spillover measure).

[31] Depending on the industrial sector, knowledge exchanges may occur between various departments of the firm (without necessarily involving an R&D department). This type of knowledge exchange has very important implications for the functioning of the firm, yet it remains largely understudied from an empirical perspective.

To verify the robustness of our results we have replicated the main results using alternative definitions of the tacit spillover variable. The table below shows the results when only “informal information exchange” and “recently hired technical personnel” are included in the definition of tacit spillovers. While the results on the *KI adoption* variable become weaker, our findings using the *KI outcome* variable remain significant and all results are directionally consistent. We note that we are also controlling in the same regression for codified sources of spillovers that may also flow though public conferences and meetings, for example through conference proceedings and, arguably, formal presentations. In other words, by controlling for codified spillovers that may be channeled through some of the tacit spillovers channels as well, we are more likely to capture the variance associated with tacit knowledge.

Table A.2
Performance, process innovation.

	(1)	(2)	(3)	(4)	(5)	(6)
KI outcome	−0.021	−0.018	0.008			
	(0.036)	(0.036)	(0.037)			
KI adoption				0.347**	0.356**	0.402**
				(0.159)	(0.161)	(0.170)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
Focus industry controls (3-digit SIC)	No	Yes	Yes	No	Yes	Yes
Firm and lab-level controls	No	No	Yes	No	No	Yes
Pseudo R^2	0.013	0.015	0.028	0.016	0.018	0.032
Observations	1238	1238	1238	1238	1238	1238

Notes: Robust standard errors clustered at the firm level included in parenthesis.
** Significance level: 5%.

A.3 Absorptive capacity as a confounding factor: a falsification exercise

One potential criticism to our identification strategy is that our spillover measure may be correlated to a lack of absorptive capacity on the side of employees in other functions.

In our regression model we include two variables aimed at controlling for the degree of incoming spillovers to the R&D lab: *“Absorptive capacity”* is defined as the percentage of R&D personnel devoted to gathering information on new scientific and technical developments. These controls only serves as an indirect and potentially incomplete proxy for the absorptive capacity in the non-R&D departments of the firm. We acknowledge that no information to directly control is available in the CMU survey.

We have performed additional robustness tests using as an additional control of spillovers coming from the university or government research institutes and labs.[32] If it is true that the effect of these spillovers may capture an effect of the AC of the recipients within the focal firm, and not the asserted trade-off, then this variable should have a similarly negative effect on KI. The table below shows that indeed when introducing university spillovers (distinguished between tacit and codified), only tacit spillovers to competitors induce a reduction in the adoption of KI (although results are weaker than in the baseline regression for *“KI outcome”*).

	KI outcome		KI adoption	
	(1) Low	(2) High	(3) Low	(4) High
Spillovers (Codified)	0.082	−0.060	0.209	0.298
	(0.104)	(0.109)	(0.216)	(0.210)
Spillovers (Tacit)	−0.182	−0.184	−0.508**	−0.722*
	(0.130)	(0.161)	(0.252)	(0.433)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes
Appropriability and Tech. Rivalry	Yes	Yes	Yes	Yes
Firm and lab-level controls	Yes	Yes	Yes	Yes
R^2	0.128	0.095		
Pseudo R^2			0.204	0.110
Observations	619	619	619	619

[32] See for instance Roach and Cohen (2013) for another piece of research using this variable to capture knowledge flows, who validate the measure using backward patent citations.

Table A.3
Full sample, alternatively defined tacit and codified spillover measure.

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Spillovers (Codified, robustness)	0.064	0.074	0.058	−0.023	−0.216	−0.164
	(0.067)	(0.080)	(0.079)	(0.114)	(0.154)	(0.180)
Spillovers (Tacit, robustness)	−0.165**	−0.228***	−0.192***	−0.027	−0.021	−0.056
	(0.068)	(0.071)	(0.071)	(0.117)	(0.131)	(0.143)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
Appropriability and Tech. Rivalry	No	Yes	Yes	No	Yes	Yes
Firm and lab-level controls	No	No	Yes	No	No	Yes
R^2	0.034	0.049	0.095			
Pseudo R^2				0.021	0.029	0.135
Observations	1238	1238	1238	1238	1238	1238

Notes: Dependent variables *KI outcome* (OLS) and *KI adoption* (Logit) based on the CMU survey. *Spillovers (robustness, tacit)* only including "informal information exchange" and "recently hired technical personnel". Robust standard errors clustered at the firm level included in parenthesis.
** Significance level: 5%.
*** Significance level: 1%.

A.4 Full estimation result table

The following table reports the full set of estimated results of our model.

Table A.4
Full sample, general spillover measure.

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Spillovers (Contribution/Suggestion)	0.043	0.036	0.013	−0.024	−0.105	−0.167
	(0.045)	(0.057)	(0.056)	(0.088)	(0.107)	(0.127)
Innovation Rate		−0.054	0.055		0.257	0.129
		(0.195)	(0.193)		(0.308)	(0.339)
Secrecy		−1.541*	−1.391*		−1.477	−2.161
		(0.822)	(0.811)		(1.346)	(1.539)
Patent		0.068	0.371		1.007	0.444
		(0.691)	(0.680)		(1.243)	(1.416)
First to Market		1.710*	1.082		−1.203	−0.382
		(0.909)	(0.887)		(1.513)	(1.644)
Complementary Sales		2.383**	1.790*		−0.995	−0.303
		(0.978)	(0.941)		(1.684)	(1.838)
Complementary Manufacturing		−1.542	−1.045		1.935	1.469
		(0.997)	(1.003)		(1.974)	(2.042)
Technology Rivals		−0.033	−0.004		0.140	0.109
		(0.061)	(0.060)		(0.111)	(0.114)
BU Market Share			−0.642**			−1.510***
			(0.283)			(0.365)
BU R&D Employees			−0.030**			0.049
			(0.014)			(0.370)
BU Employees			−0.001			0.038*
			(0.001)			(0.022)
Public Firm			−0.246***			0.754***
			(0.095)			(0.184)
BU Integration			0.667**			0.604
			(0.289)			(0.529)
R&D unit budget			0.001			0.039**
			(0.001)			(0.015)
Isolated Lab			−0.484***			0.616**
			(0.116)			(0.251)
Absorptive Capacity			−0.460			−1.750***
			(0.432)			(0.615)
Basic Research Effort			−1.327*			4.154**
			(0.707)			(1.662)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.029	0.042	0.090			
Pseudo R^2				0.021	0.027	0.134

(*continued on next page*)

Table A.4 (*continued*)

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Observations	1238	1238	1238	1238	1238	1238

Notes: Dependent variables *KI outcome* (OLS) and *KI adoption* (Logit) based on the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.
* Significance level: 10%.
** Significance level: 5%.
*** Significance level: 1%.

A.5 Complete correlation table

Table A.5
Full sample, codified vs. tacit spillover measure.

	KI outcome			KI adoption		
	(1)	(2)	(3)	(4)	(5)	(6)
Spillovers (Codified)	0.078	0.096	0.059	0.038	−0.049	0.063
	(0.057)	(0.068)	(0.066)	(0.092)	(0.119)	(0.137)
Spillovers (Tacit)	−0.140**	−0.212***	−0.164**	−0.082	−0.215	−0.282**
	(0.060)	(0.070)	(0.069)	(0.092)	(0.133)	(0.142)
Innovation Rate		0.334	0.345*		0.558	0.456
		(0.212)	(0.208)		(0.387)	(0.422)
Secrecy		−1.936***	−1.651**		−1.314	−2.084
		(0.742)	(0.739)		(1.331)	(1.597)
Patent		−0.399	0.091		1.515	0.353
		(0.801)	(0.786)		(1.476)	(1.729)
First to Market		1.481	0.899		−1.555	−0.175
		(0.911)	(0.895)		(1.508)	(1.583)
Complementary Sales		2.012**	1.585*		−1.023	−0.518
		(0.989)	(0.951)		(1.660)	(1.824)
Complementary Manufacturing		−1.214	−0.795		2.705	1.842
		(0.979)	(0.995)		(1.944)	(1.984)
Technology Rivals		−0.030	−0.003		0.142	0.113
		(0.060)	(0.060)		(0.110)	(0.113)
BU Market Share			−0.613**			−1.469***
			(0.289)			(0.361)
BU R&D Employees			−0.026*			0.067
			(0.014)			(0.360)
BU Employees			−0.002			0.039*
			(0.001)			(0.023)
Public Firm			−0.235**			0.753***
			(0.095)			(0.185)
BU Integration			0.615**			0.514
			(0.289)			(0.527)
R&D unit budget			0.001			0.041***
			(0.001)			(0.016)
Isolated Lab			−0.481***			0.614**
			(0.115)			(0.250)
Absorptive Capacity			−0.449			−1.719***
			(0.430)			(0.614)
Basic Research Effort			−1.257*			4.085**
			(0.696)			(1.648)
Industry FE (2-digit SIC)	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.034	0.050	0.094			
Pseudo R^2				0.022	0.029	0.137
Observations	1238	1238	1238	1238	1238	1238

Notes: Dependent variables *KI outcome* (OLS) and *KI adoption* (Logit) based on the CMU survey. Robust standard errors clustered at the firm level included in parenthesis.
* Significance level: 10%.
** Significance level: 5%.
*** Significance level: 1%.

A.6 Complete list of variables and their description

Variable	Definition	Construction
KI outcome	Frequency of face-to-face communication between the personnel of an R&D lab operating in SIC3 industry and personnel from other business units of the same firm.	Sum of the score of all questions. There are two questions, one referring to meetings with manufacturing, the other with sales. Each question has score from 0 to 4 (0 = non applicable). Total KI outcome score is from 0 to 8.
KI outcome (robustness)	Cross-functional information that suggested or helped completing new R&D projects.	The question asks whether the R&D unit of a given lab, during the last three years, has received information that either contributed to the completion or suggested new project from a given source. We focus on own manufacturing operations or customers as sources. We compute the total score for the two sources (each source has a score from 0 to 2).
External Knowledge Sourcing	Extent to which the R&D lab sources knowledge from external sources.	The question asks whether the R&D unit of a given lab, during the last three years, has received information that either contributed to the completion or suggested new project from a given source. We focus on independent suppliers (not linked through ownership), cooperative or joint ventures, universities or government research institutes and labs, competitors and consulting or contract R&D firms (each source has a score from 0 to 2).
Internal Knowledge Sourcing	Extent to which the R&D lab sources knowledge from internal sources.	The question asks whether the R&D unit of a given lab, during the last three years, has received information that either contributed to the completion or suggested new project from a given source. We focus on affiliated suppliers (linked to the R&D lab through ownership), the firm's manufacturing operations, customers and the other R&D units of the firm (each source has a score from 0 to 2).
KI adoption	Adoption of cross-functional knowledge integration managerial practices at the R&D lab level	The survey asks whether the R&D lab has, over the last 3 years, used project teams with cross-functional participation in order to facilitate interaction between the R&D and other functions.
Spillovers (Generic)	Importance of generic knowledge spillovers in a SIC3 industry	The question asks whether the R&D unit of a given lab, during the last three years, has received information that either contributed to the completion or suggested new project from a given source. We focus on competitors as source. We compute a score from 0 to 2 based on the answer for each lab, and then we take the average of standardized scores of all labs operating in the same industry excluding the focal lab.
Spillovers (Codified)	Importance of generic knowledge spillovers in a SIC3 industry	The survey asks, for each source of information, to indicate the score in terms of importance that such source had in providing information on R&D activity and innovations of other firms in the industry. Sources considered for codified spillovers are: patents, publications and reports, licensed technology and products (e.g. reverse engineering). Each source is associated a score from 1 to 4. We compute the score across sources for each lab in a given SIC3 industry, and then we take the average of standardized scores of all labs operating in the same industry excluding the focal lab.
Spillovers (Tacit)	Importance of tacit knowledge spillovers in a SIC3 industry	The survey asks, for each source of information, to indicate the score in terms of importance that such source had in providing information on R&D activity and innovations of other firms in the industry. Sources considered for tacit spillovers are: public conferences and meetings, informal information exchange, recently hired technical personnel, joint or cooperative R&D projects and trade associations. Each source is associated a score from 1 to 4. We compute the score across sources for each lab in a given SIC3 industry, and then we take the average of standardized scores of all labs operating in the same industry excluding the focal lab.
Spillovers (Frequency)	Importance of the frequency of knowledge spillovers in a SIC3 industry	The survey asks to indicate the frequency (from "rarely or never" to "daily") with which the R&D unit receives useful technical information about the activity of competitors in different geographic regions. We focus on the frequency of spillovers received in North America. To compute the score for frequency of spillovers, we take the average of standardized scores of all labs operating in the same industry excluding the focal lab.
Spillovers (Timing)	Importance of the timing knowledge spillovers in a SIC3 industry	The survey asks to indicate, for a recent major innovation by one of the competitors, at what stage in the innovation process did the respondent first become aware of the project. The stages from which it was possible to choose include "at project initiation", "during the research stage", "during the development stage", and "at product/process introduction". To compute the score for timing of spillovers, we codify the score for this

		answer from 4 (“at project initiation”) to 1 (“at product/process introduction”), and then we take the average of standardized scores of all labs operating in the same industry excluding the focal lab.
Industry innovation rate	Process and product innovation rate in industry.	The survey asks the respondent to indicate the rate at which product and process innovation were introduced in the lab's focus industry over the last three years. We take the weighted average of the score for product and process innovations (1 to 4 for each) using the percentage of effort devoted to product (and process) innovation, and then we take the average of the scores of all labs operating in the same industry excluding the focal lab.
Secrecy	Effectiveness of secrecy in protecting firms’ innovations in a SIC3 industry.	The percentage of product and process innovations for which secrecy was effective in protecting the firm's competitive advantage. We take the weighted average of the percentage for product and process innovations using the percentage of effort devoted to product (and process) innovation, and then we take the average of the scores of all labs operating in the same industry excluding the focal lab.
Complementary sales	Effectiveness of complementary sales in protecting firms’ innovations in a SIC3 industry.	The percentage of product and process innovations for which complementary sales were effective in protecting the firm's competitive advantage. We take the weighted average of the percentage for product and process innovations using the percentage of effort devoted to product (and process) innovation, and then we take the average of the scores of all labs operating in the same industry excluding the focal lab.
First to market	Effectiveness of a first to market strategy in protecting firms’ innovations in a SIC3 industry.	The percentage of product and process innovations for which a first to market strategy was effective in protecting the firm's competitive advantage. We take the weighted average of the percentage for product and process innovations using the percentage of effort devoted to product (and process) innovation, and then we take the average of the scores of all labs operating in the same industry excluding the focal lab.
Complementary manufacturing	Effectiveness of complementary manufacturing in protecting firms’ innovations in a SIC3 industry.	The percentage of product and process innovations for which complementary manufacturing was effective in protecting the firm's competitive advantage. We take the weighted average of the percentage for product and process innovations using the percentage of effort devoted to product (and process) innovation, and then we take the average of the scores of all labs operating in the same industry excluding the focal lab.
Patent	Effectiveness of patents in protecting firms’ innovations in a SIC3 industry.	The percentage of product and process innovations for which patents were effective in protecting the firm's competitive advantage. We take the weighted average of the percentage for product and process innovations using the percentage of effort devoted to product (and process) innovation, and then we take the average of the scores of all labs operating in the same industry excluding the focal lab.
Tech. Rivals	Number of competitors with innovating capabilities.	Number of firms that were able to introduce competing innovation in time to effectively diminish the firm's profit from innovation. The respondent can choose different ranges from 0 to more than 20. We assign a score to each range and then we take log of the score for each lab.
BU Market share	Market share of a firm	The ratio between the firm's sales in the focus industry (or BU = business unit) based on the CMU survey and the market size computed using total shipment from 1992 Census of manufacturing matching the product of the focal industry of the firm.
BU R&D Employees	Number of employees in R&D in a firm	The firm's total number of professional and technical R&D employees working in the focus industry (including all facilities). Expressed in thousands.
BU Employees	Total number of employees in a firm	The approximate number of employees working for the focus industry in the U.S. as indicated in the CMU survey. Expressed in thousands.
Public	Dummy identifying public firms	The dummy is equal to 1 if a firm is publicly listed (using Compustat).
R&D lab's budget	The budget of the R&D lab	The approximate R&D unit total budget during the last fiscal year as indicated in the CMU survey. Expressed in million USD.
Isolated lab	Dummy identifying labs physically isolated from the rest of the firm.	The respondent is asked to indicate whether the R&D lab is physically located in a stand-alone R&D facility.
Absorptive capacity	Percentage of R&D personnel devoted to gathering information on new scientific and technical developments.	The respondent is asked to indicate what percentage of R&D personnel's time is devoted to monitoring and gathering information on new scientific and technical developments.
Basic Research	Percentage of R&D devoted to research with no specific commercial objectives	The respondent is asked to indicate what percentage of the R&D effort is devoted to research with no specific commercial objective.
Integration	Percentage of revenue from sales of manufactured products.	Approximate percentage of total operating revenue of the firm originating in the sale of products manufactured by the firm.

Table A.6
Complete table of correlation and descriptive statistics.

	1	2	3	4	5	6	7	8	9	10	11
1. KI outcome	1.000										
2. KI adoption	0.054	1.000									
3. Spillovers (generic)	−0.016	0.023	1.000								
4. Spillovers (codified)	−0.007	−0.011	0.137	1.000							
5. Spillovers (tacit)	−0.098	0.007	0.286	0.273	1.000						
6. Spillovers (frequency)	−0.023	0.011	0.279	0.156	0.329	1.000					
7. Spillovers (timing)	−0.133	0.056	0.273	0.173	0.574	0.284	1.000				
8. Innovation Rate	0.020	−0.014	0.235	0.154	0.492	0.421	0.175	1.000			
9. Secrecy	−0.000	0.005	−0.211	0.064	0.037	0.193	0.152	0.088	1.000		
10. Patent	−0.047	0.027	0.065	0.482	0.032	0.123	0.273	0.055	−0.027	1.000	
11. First to Market	0.038	0.025	0.108	−0.022	0.265	0.099	0.206	0.365	0.053	0.216	1.000
12. Complementary S	0.068	−0.016	−0.072	0.216	0.075	0.071	−0.126	0.095	0.098	−0.014	0.350
13. Complementary M	0.056	0.027	0.028	0.242	0.169	0.137	0.125	0.116	0.209	0.030	0.361
14. BU Market Share	−0.113	−0.103	−0.040	−0.018	0.016	0.011	−0.027	−0.032	0.033	−0.025	−0.083
15. BU R&D Employees	−0.098	0.048	−0.020	0.004	0.098	0.004	0.057	0.023	−0.008	0.062	0.015
16. BU Employees	−0.081	0.071	0.110	0.034	0.071	0.034	0.089	0.000	0.031	−0.038	0.041
17. Public Firm	−0.104	0.215	0.039	−0.003	0.046	0.035	0.096	0.009	−0.013	0.100	−0.004
18. Technology Rivals	0.000	0.041	0.062	0.051	0.054	0.140	0.029	0.044	0.056	−0.076	−0.067
19. BU Integration	0.094	0.016	0.072	0.009	−0.074	−0.044	−0.096	−0.026	−0.051	−0.052	−0.001
20. R&D unit budget	−0.057	0.080	0.010	−0.000	0.070	0.077	0.102	−0.012	0.041	0.049	0.011
21. Isolated Lab	−0.161	0.115	0.008	0.001	0.034	−0.006	0.033	−0.065	0.098	−0.020	−0.136
22. Absorptive Capacity	−0.025	−0.100	−0.048	0.062	0.036	0.064	0.061	0.059	0.053	0.022	−0.011
23. Basic Research Effort	−0.070	0.058	−0.003	0.081	0.022	0.056	0.109	0.003	0.099	0.064	−0.060
Mean	6.412	0.840	0.530	9.072	10.828	2.784	1.803	2.945	0.530	0.330	0.496
Standard deviation	1.613	0.367	0.156	0.695	0.898	0.236	0.230	0.378	0.087	0.097	0.092
Min	0.000	0.000	0.000	7.000	7.000	1.333	1.306	1.796	0.265	0.050	0.242
Max	8.000	1.000	1.295	10.857	13.000	3.538	2.500	4.200	0.820	0.679	0.733

	12	13	14	15	16	17	18	19	20	21	22	23
1. KI outcome												
2. KI adoption												
3. Spillovers (generic)												
4. Spillovers (codified)												
5. Spillovers (tacit)												
6. Spillovers (frequency)												
7. Spillovers (timing)												
8. Innovation Rate												
9. Secrecy												
10. Patent												
11. First to Market												
12. Complementary S	1.000											
13. Complementary M	0.616	1.000										
14. BU Market Share	−0.062	−0.065	1.000									
15. BU R&D Employees	−0.022	−0.014	0.111	1.000								
16. BU Employees	−0.019	0.021	0.230	0.245	1.000							
17. Public Firm	−0.031	0.004	−0.072	0.086	0.110	1.000						
18. Technology Rivals	−0.060	0.021	0.023	0.043	0.054	0.017	1.000					
19. BU Integration	0.077	0.011	−0.033	−0.061	−0.016	−0.071	−0.034	1.000				
20. R&D unit budget	−0.037	−0.021	0.108	0.267	0.173	0.127	0.053	0.001	1.000			
21. Isolated Lab	−0.124	−0.055	0.120	0.132	0.091	0.155	0.074	−0.032	0.198	1.000		
22. Absorptive Capacity	0.039	0.007	0.003	−0.023	−0.034	−0.095	0.054	−0.005	−0.031	−0.046	1.000	
23. Basic Research Effort	−0.019	0.058	0.083	0.031	0.025	0.024	−0.001	−0.040	0.128	0.088	0.147	1.000

(*continued on next page*)

Table A.6 (*continued*)

	12	13	14	15	16	17	18	19	20	21	22	23
Mean	0.393	0.449	0.076	0.367	6.418	0.658	1.951	0.583	14.093	0.233	0.130	0.033
Standard deviation	0.079	0.077	0.211	2.648	30.561	0.474	0.779	0.162	59.349	0.423	0.115	0.064
Min	0.114	0.114	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Max	0.598	0.665	1.000	75.000	710.800	1.000	5.994	0.693	1200.000	1.000	0.850	0.600

Notes: All variables based on the CMU survey.

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