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Knowledge searching strategies, testing for complementarities on the innovation behavior of the firm

Alejandro Bello-Pintado[a], Felipe Berrutti[b], Carlos Bianchi[c*], Pablo Blanchard[d]

Abstract

According to two basic building blocks of neo-Schumpeterian economics, firms' innovation process shows idiosyncratic features related to their specific characteristics of the firm and of the environment where it acts. Moreover, firms' innovation is recognized as an interactive process. Hence, due to systemic functioning, it is expected that the effect of two simultaneous external linkages will be different from the sum of their isolated effects. However, the external search for knowledge and information sources (KISs) may present constraints related to the searching costs and the cognitive distance between the firm and the KISs. This paper aims to contribute empirical evidence to revisit these theoretical building blocks by analyzing the search strategies conducted by firms. We identify three types of external KISs and analyze the effects of eight search strategies (KIS combinations) on firms' innovation behavior. In addition, we test the complementarity or substitution effects of the simultaneous use of different KISs on the innovation behavior – effort and performance – of Uruguayan firms. We identify the specific effect of different KIS combinations but find no evidence of a linear relation between search scope and innovation behavior. Moreover, we find evidence of complementary effects between relatively closer and more distant KISs and substitution effects between relatively near KISs.

Keywords: information sources, search strategy, complementarity, supermodularity

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Resumen

De acuerdo a dos pilares básicos de la economía neo-Shumpeteriana, el proceso de innovación de las firmas tiene componentes idiosincráticos relacionados a las características específicas de cada firma y al entorno en que opera; además, se trata de un proceso interactivo donde la firma amplía sus límites en intercambios con otros agentes. Por lo tanto, debido a su funcionamiento sistémico, se espera que el efecto de dos vínculos simultáneos con agentes externos a la firma muestre resultados distintos a la suma aislada de sus efectos. Sin embargo, la búsqueda externa de fuentes de conocimiento e información (KIS) puede presentar restricciones asociadas a los costos de búsqueda y la distancia cognitiva entre la firma y las diferentes KIS. Este trabajo busca contribuir con evidencia empírica para revisitar los pilares teóricos mencionados, analizando la estrategia de búsqueda realizada por la firma. Se identifican tres tipos de KIS externas y se analizan los efectos de ocho estrategias de búsqueda (combinaciones de KIS) sobre el desempeño innovador de las firmas. Por su parte, se testen los efectos de complementariedad o sustitución del uso simultáneo de diferentes KIS sobre el comportamiento innovador –esfuerzo y desempeño- de las firmas uruguayas. Los resultados permiten identificar efectos específicos de diferentes combinaciones de KIS pero no se encuentra evidencia de una relación lineal entre amplitud de búsqueda y comportamiento innovador. Además, se encuentra evidencia de efectos de complementariedad entre KIS relativamente cercanas respecto a las más distantes, y efectos de sustitución entre KIS relativamente cercanas entre sí.

Palabras clave: fuentes de información, estrategias de búsqueda, complementariedad, supermodularidad

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1. Introduction

Firms' innovation process can be described as a learning path along which they integrate knowledge and information from different sources. Rather than a linear and smooth process, firms follow an uneven innovation path, which is marked by successive problem-solving events. During that process, they articulate internal and external knowledge, operating under limited rationality and building a specific trajectory (Dosi, 1988; Laursen and Foss, 2003; Nelson, 1991; Nelson and Winter, 1982). Hence, studying the innovation paths requires the identification of the search strategies followed by firms and their effects on their innovation behavior (Becker and Dietz, 2004; Criscuolo et al., 2018; Katila and Ahuja, 2002; Lundvall, 1988).

A large body of literature has stressed the relevance of firms' internal capabilities in searching for, identifying and using external knowledge (Arora and Gambardella, 1990; Cohen and Levinthal, 1989; Rothaermel and Alexandre, 2009; Teece, 1986). In particular, previous research has analyzed the effects of integrative strategies that combine internal and external knowledge and information sources (KISs) on the innovative performance of firms (Criscuolo et al., 2018; Grimpe and Kaiser, 2010). While there seems to be theoretical agreement on the relevance and potential complementarity between the use of internal and the use of external KISs (Arora and Gambardella, 1990; Denicolai et al., 2016; Mowery, 1983), the empirical evidence about their effects on innovation behavior is not conclusive (Barge-Gil, 2013; Cassiman and Veugelers, 2006; Grimpe and Kaiser, 2010; Hagedoorn and Wang, 2012; Love et al., 2014). Moreover, most prior research has focused only on the complementarity between internal and external KISs; the complementary effects between different types of external KISs have received little attention (Belderbos et al., 2006; Love and Roper, 2009; Vega-Jurado et al., 2009). On the other side, a number of empirical studies have analyzed the effects of specific search strategies, including combinations of external KISs, on the innovation performance of firms (Belderbos et al., 2004; Criscuolo et al., 2018; Grimpe and Sofka, 2016; Laursen and Salter, 2006; Leiponen and Helfat, 2010), but, as far as we know, no previous works have studied the complementary (substitution) effects between external KISs on firms' innovation behavior.

Firms use different search strategies – KIS combinations – that differ over time according to their productive and innovative objectives (Criscuolo et al., 2018; Laursen, 2012; Leiponen, 2012). However, firms are not able to follow any innovation strategy by changing their KIS combination at any time. Accessing external KISs, and developing internal ones, is expensive and requires time and expertise. Therefore, firms are only able to follow a reduced number of search strategies, which imply sunk costs and learning through an interactive process, in turn becoming path dependency constraints (Hecker and Ganter, 2014; Mowery and Rosenberg, 1989).

Moreover, several studies have highlighted that the relationship between innovation behavior and openness to external KISs is not linear (Gkypali et al., 2017; Homburg and Kuehnl, 2014; Katila and Ahuja 2002; Laursen, 2012). External KISs represent access to valuable knowledge that may become a strategic asset to differentiate the firm from its competitors (Barney, 1991; Laursen and Salter, 2006; Leiponen and Helfat, 2010). However, the search for, access to and interaction with external KISs may imply several exchanges, in which the agents build a common language and articulate more or less close interests and goals (Grimpe and Sofka, 2016; Nooteboom et al., 2007). According to this view, the effects of open searching strategies on firms' behavior will present an inverted U-shaped relationship in which, after a certain threshold, the costs of searching are higher than the benefits (Katila and Ahuja, 2002; Laursen and Salter, 2014).

This paper aims to contribute to the ongoing research efforts on the effects of search strategies on the innovation behavior of firms. Using an unbalanced panel data set from three waves of the Uruguayan Innovation Survey (UIS) that cover the period 2004–2012, we follow a two-step approach. First, aiming to identify specific search strategies (Criscuolo et al., 2018), we classify three types of external KISs: science and technology organizations (*S&T*); firms belonging to the firm's value chain used as external KISs (*Business*); and external KISs in the form of published knowledge, such as fairs, conferences and so on (*Codified*). Using this KIS classification, we compute eight potential search strategies that result from combining them. We estimate the extent to which each of these combinations determines innovation behavior. Second, adapting previous approaches based on supermodular equations (Ballot et al., 2015; Mohnen and Röller, 2005), we estimate the complementary or substitution effects of the different combinations of KISs on the innovation behavior of Uruguayan firms. We define innovation behavior considering both the effort that a firm makes to innovate (expenditure devoted to innovation activities) and the innovation performance (the innovative share of the firm's business results) (Becker and Dietz, 2004).

Our results show robust evidence of complementarity effects between the simultaneous use of *S&T* and *Codified* KISs on innovative effort, while the combination of *Business* and *Codified* KISs shows substitution effects on the innovation performance of the firm. Considering that almost all previous research has stressed the high contingency of the empirical findings (Antonioli et al., 2017; Guisado-González et al., 2017; Hagedoorn and Wang, 2012; Serrano-Bedia et al., 2018), these results are valuable. Moreover, regarding the growing concern for an innovation policy mix, the study of complementarities is a useful tool to inform a systemic policy rationale based on complementary instruments (Borrás and Edquist, 2013).

2. Theoretical framework and empirical background

Search strategies are defined as the way in which firms organize the search process for knowledge and information to solve problems and to produce new ideas and combinations (Laursen and Salter, 2004). The search for external KISs expands the borders of a firm, allowing it to access new and non-redundant resources that are critical assets for firm differentiation and growth (Penrose, 1959; Wernerfelt, 1984). These theoretical contributions from the resource-based view of the firm have been widely adopted by the economics of innovation research, which has defined innovation as an interactive process whereby firms interact in a systemic manner with other agents (Lundvall, 1988; Mowery, 1983). This definition embraces two basic building blocks of neo-Schumpeterian economics. First, it postulates that each firm follows a specific growth path, building a unique set of resources in an interactive way. Second, these authors pose that the systemic (emergent) outcome originating from interactions will be more than the sum of the isolated action of each part (Dosi, 1988; Nelson and Winter, 1982).

Hence, it is theoretically expected that firms follow a specific search strategy to access information and knowledge from external KISs. In addition, complementary effects from search strategies that integrate different and non-redundant KISs are theoretically expected.

2.1 Benefits of openness, transaction costs and cognitive distance

From both the economics and the management literature, a growing body of research has shown that the degree of openness (breadth and depth) determines the innovation behavior of a firm (Laursen and Salter, 2006; Leiponen, 2012; Leiponen and Helfat, 2010). These authors have shown that a broad open innovation strategy, usually measured as the number of different and non-redundant KISs consulted by the firm, determines the firm's innovation propensity and performance positively. Moreover, innovation behavior is determined by the intensity of interactions, understood as their frequency and relevance (Laursen and Salter, 2006; Lazzarotti et al., 2015).

However, the relation between openness and innovation performance is not linear. The effects of open innovation processes depend critically on the internal capabilities of the firm (Foss et al., 2011). According to the concept of absorptive capacities, internally developed innovation activities – mainly R&D – increase the knowledge production capacities and, simultaneously, the capabilities to recognize, understand and use external KISs (Cohen and Levinthal, 1989; Kaiser, 2002; Veugelers, 1997; Zahra and George, 2002). Moreover, building on these basic principles, a rich stream of research on the complementarity of internal and external KISs has been developed (see Antonioli et al., 2017; Cassiman and Veugelers, 2006; Grimpe and Kaiser, 2010; Hagedoorn and Wang, 2012; among others). Even though the results are not conclusive, it is broadly accepted that the simultaneous use of internal and external KISs has complementary effects on firms' innovation behavior.

The complementary effects between external KISs on innovation behavior have received less attention (Belderbos et al., 2006; Love and Roper, 2009; Vega-Jurado et al., 2009). However, since different external KISs can offer access to different knowledge and information that the firm requires to innovate, a potential complementary effect between external KISs is also expected (Grimpe and Sofka, 2016; Van Beers and Zand, 2014).

Nevertheless, the relationship between the openness degree of the firm's innovation strategy (the number of external KISs regularly used) and its innovation performance can be described as quadratic rather than linear, showing an inverted U shape (Gkypali et al., 2017; Homburg and Kuehnl, 2014; Katila and Ahuja, 2002; Laursen and Salter, 2014).

The so-called "openness paradox" (Arora et al., 2016; Laursen, 2012; Laursen and Salter, 2014) has been explained through different and complementary arguments. Early institutionalist works tackled the use of different external resources by analyzing the alternative strategies adopted by firms according to the transaction cost associated with each external linkage (Williamson, 1981). Later institutionalist works included the study of potentially complementary sources (Pisano, 1990). Even though this approach has been criticized for its inability to capture firms' learning process (Foss and Klein, 2010; Love et al., 2014), it offers a simple but coherent theoretical argument related to the cost of external searching as a critical factor that constrains the search strategy options of firms.

In addition, empirical works have shown that external searches using varied KISs require cognitive and social capabilities (Bertrand and Mol, 2013; Laursen, 2012). Hence, a study of firms' search strategies needs to complement the transaction cost analysis with a theoretical argument related to the cognitive and interactive requirements that the different strategies imply. The use of one or many external KISs and their potential complementary effects on innovation behavior will depend on the costs associated with each strategy as well as the cognitive distance between the firm and each external KIS (Criscuolo et al., 2018; Nooteboom et al., 2007).

The cognitive distance between organizations has been defined according to the shared norms, the institutional goals and the regular practices of each organization (Colombelli and Quatraro, 2014; Nooteboom et al., 2007). Accessing cognitively distant KISs involves a high level of uncertainty. However, these authors have highlighted the non-linear relation between cognitive distance and innovative effects. Actually, a sort of optimal cognitive distance is considered to be long enough to offer new knowledge resources to the firm but not so long that access to the KIS requires a bigger effort than the information and knowledge resource obtained (Nooteboom et al., 2007).

2.2 Idiosyncratic features and complementarities of firms' innovation behavior

To deal with contingent and idiosyncratic features, Criscuolo et al. (2018) identified specific KIS combinations used by firms. The finding of these authors showed some winning KIS combinations that positively affect innovation performance. Moreover, in line with previous research (Leiponen, 2012), their results indicated that a broad combination usually exerts greater effects on innovative performance than more restrictive search strategies.

This paper aims to identify specific KIS combinations used by Uruguayan firms and estimate their effect on their innovative effort and performance. In addition, it aims to study the effects of external search strategies in depth by determining whether KIS combinations have complementary or substitution effects on firms' innovation behavior.

Milgrom and Roberts (1990) developed an analytical model based on supermodular equations that has been adopted as the methodological benchmark in innovation studies about complementarity between different events, such as types of innovation (Ballot et al., 2015; Guisado-González et al., 2017), internal and external innovation activities (Cassiman and Veugelers, 2006; Hagedoorn and Wang, 2012) and innovation policies (Mohnen and Röller, 2005), among others.

Regarding complementarity between KISs, there is also a large background (Antonioli et al., 2017; Belderbos et al., 2006; Grimpe and Sofka, 2016; Serrano-Bedia et al., 2018; Vega-Jurado et al., 2009). However, previous research on complementary effects between external and internal KISs has obtained contingent results. A number of works have provided evidence of substitution effects on innovation performance (Vega-Jurado et al., 2009), while others have shown evidence of both complementary and substitution effects on innovation performance according to specific firm characteristics (Belderbos et al., 2006) or conditional on the presence of other sources (Serrano-Bedia et al., 2018).

Conversely, some works have found robust evidence showing that the size of the firm determines its capabilities to access and use external KISs (Belderbos et al., 2006). In this regard, Cassiman and Veugelers (2006) pointed out that small and medium firms select one strategy while big firms with a larger scale of production and financial resources may combine different strategies.

Finally, following early works on the relationship between firms' external cooperation and their innovation behavior (Becker and Dietz, 2004; Kaiser, 2002; Veugelers, 1997), we use a definition of innovation behavior that captures two phases of firm behavior. In this sense, we consider the intensity of a firm's innovation expenditure as a proxy for its innovative effort and the share of innovative outcomes in the total turnover of the firm as a proxy for its innovation performance (Grimpe and Sofka, 2016; Laursen and Foss, 2003). Moreover, in accordance with previous works (Becker and Dietz, 2004; Kaiser, 2002), we distinguish analytically the search strategy from the innovation behavior of the firm. We expect that the use of external KISs will affect the innovation behavior by demanding higher innovation investment from the firm and fostering higher innovation results.

This theoretical definition of innovation behavior allows us to analyze the differentiated impacts of the search strategy on the innovation effort and performance of firms. In addition, it captures a critical feature of Latin America and other developing regions, the intensity of private innovation expenditure (Grazzi and Pietrobielli, 2016). In this sense, the methodological guidelines summarized in the Bogotá Manual (Jaramillo et al., 2001) stress the relevance of studying in depth the innovative initiative of firms and their willingness to invest in innovation beside analyzing their innovative performance. It is particularly relevant to have a comprehensive approach to firm innovation in developing countries, which are characterized by a small critical mass of innovative firms and considerable systemic weakness, to obtain successful innovation results (Dutrénit et al., 2018; Yoguel and Robert, 2010).

3. Methodology

Our methodological design is based on two main questions: What search strategies did Uruguayan firms follow between 2006 and 2012? Is there evidence of complementary effects between the KISs that compose each search strategy?

Aiming to answer these questions, we follow a two-step approach. First, we identify three types of KISs that are empirically relevant and theoretically consistent. Hence, we estimate the effects of each KIS combination (search strategy) on the innovation behavior of firms. Second, adapting previous approaches based on innovation function equations (Ballot et al., 2015; Mohnen and Röller, 2005), we test the complementarity effects between different KISs.

3.1 Innovation behavior of firms

As explained above, we analyze the effects of search strategies on two observable attributes of firms' innovation behavior, measured through two dependent variables, one related to innovative performance and one related to innovative effort.

Our measure of innovative performance is similar to those used in other works based on innovation survey data (Cassiman and Veugelers, 2006; Criscuolo et al., 2018; Laursen and Salter, 2006). We use the share of sales of innovative products, measured as the total turnover attributable to new or improved products, considering sales to the internal market and exports in the last year. To measure innovation effort, following previous works (Becker and Dietz, 2004; Kaiser, 2002), we consider the ratio between the whole firm's innovative expenditure and the total turnover of the firm in the last year.

3.2 Search strategies as KIS combinations

Following previous research (Criscuolo et al., 2018; Grimpe and Kaiser, 2010), we identify three specific KISs that cover the main types of KISs usually considered in the literature (Belderbos et al., 2006; Grimpe and Sofka, 2016; Laursen and Salter, 2006). Moreover, the selected KISs cover the KISs most reported by Uruguayan firms.

Therefore, our explanatory variables are search strategies defined as combinations of external KISs used by firms to innovate: *Business sources*, including suppliers and customers, *S&T sources*, including universities, and *Codified sources*, including magazines, fairs, conferences, exhibitions and databases.

For each KIS, the responses to the survey are converted from a four-point Likert scale into binary variables that take the value of one if the use of the source is high or medium and zero if it is low or irrelevant. *Business* and *Codified* are constructed using more than one survey question, and the variables take the value one if the use of at least one of the sources is medium or high and zero otherwise. Table 1 displays the frequency of each binary variable.

Business KISs exclude competitors and include the agents that are integrated into the value chain of the firm. Hence, this type of KIS represents useful and non-redundant knowledge that contributes to reducing uncertainty in the development process (suppliers) and in the innovation design (customers) (Menguc et al., 2014). Since the supplier and the customer usually share a basic common goal with the firm's innovative agent, *Business* KISs are considered as closer than *S&T* KISs.

Due to the information collected through the Uruguayan Innovation Survey, we only consider universities as KISs related to science and technology (*S&T*). According to previous research in the field, firms' access to university KISs implies access to general knowledge that is potentially applicable to solve specific problems. In addition, through university contacts, a firm can envision the body of available knowledge and obtain resources to manage other codified knowledge. We consider *S&T* as the most distant type of KIS, regarding the institutional differences between firms and research institutions (Nooteboom et al., 2007).

The literature has stressed that *Business* and *S&T* sources may provide firms with unique knowledge that is difficult to imitate. However, these KISs are intensive in relational effort, resources and managerial capacities (Laursen and Salter, 2006). On the contrary, *Codified* sources are related to generic solutions, which are available on equal terms for all the agents and provide knowledge that is easily imitable.

Codified sources have received less attention in the empirical literature, but they play a critical role in firms' search strategy (Arora et al., 2016; Brusoni et al., 2005). As Brusoni et al. (2005) pointed out, this type of KIS indicates the availability of technological or economic information in the form of generic algorithms, which is relatively easily and cheaply accessed by firms, which, in turn, aim to use it in specific situations other than those for which it was created.

Codified KISs play a critical role in knowledge distribution and, in particular, in the access to useful knowledge from non-high-tech firms (David and Foray, 1996). Moreover, general, abstract and codified KISs have grown due to the availability of computational and storage systems that make the access to these resources easier (Arora et al., 2016; Cowan and Foray, 1997). It is expected that the wider the available codified knowledge, the wider the KIS search options of firms.

Even though *Codified* KISs are more easily accessed than *Business* or *S&T* KISs, the effective use of codified knowledge requires the ability to understand and manage abstract knowledge and the way in which it is transmitted through different methods, such as conferences, fairs and so on. Moreover, the effective use of *Codified* KISs will require information on the specific process or product innovation that the firm is undertaking. Therefore, it is expected that this type of source shows complementary effects with both *S&T* and *Business* KISs.

The combinations of three KISs produce eight innovation search strategies: from not using any external sources of information to using the three sources. Table 2 displays the frequency of each strategy, showing that the number of observations in each cell is enough to ensure the reliability of the test.

Table 1 – KIS distribution

	Frequency	Percentage
Business	1,442	65.66
S&T	647	29.46
Codified	1,774	80.78

Source: authors

Table 2 – External search strategies

Strategies	Frequency	Percentage
All sources	450	20.49
Codified and S&T	62	2.82
Business and S&T	96	4.37
Codified and Business	799	36.38
S&T	39	1.78
Business	429	19.54
Codified	131	5.97
No sources	190	8.65
Total	2196	100

Source: authors

It is worth noticing that we include internal KISs as a control variable. This variable capture the effects of the cognitively nearest KIS, and, jointly with a number of variables regarding the workforce's qualifications (professional employees) and the main features of the organizations (size and economic group), we use proxies for internal capabilities as a control (Table 3).

Moreover, we include a set of variables that captures firms' innovation strategy, embodied innovation activities based on capital goods acquisition and disembodied activities based on R&D as well as variables that are usually considered as indicators of the innovative paths of the firms, such as the perception of financial constraints and the use of public support to innovate (Table 3).

Table 3. Summary of control variables

Variable	Description
Public support	Dummy variable that indicates whether the firm received any public funding for innovative activities
Coop with research institutions	Dummy variable that indicates whether the firm had links with universities or research centers
Coop with other firms	Dummy variable that indicates whether the firm had links with other firms
Size	Number of employees of the firm (in logs)
Foreign capital	Dummy variable that indicates whether the firm declares a positive percentage of foreign capital
Economic group	Dummy variable that indicates whether the firm belongs to an economic group
Age	Difference between the date when the firm initiated its activities and the year of the survey
High or medium tech int sector	Dummy variable that indicates whether the firm belongs to a high-technology sector according to the OECD (2011) classification
Internal sources	Dummy variable that indicates whether the firm uses internal KISs
Export	Dummy variable that indicates whether the firm reports exports
Services	Dummy variable that indicates whether the firm belongs to the service sector
Industry	Dummy variable that indicates whether the firm belongs to the industry sector
Professional employees	Dummy variable that indicates whether the firm has professional employees
Financial obstacles	Dummy variable that indicates whether the firm has experienced financial obstacles to innovation
Embodied innovation	Dummy variable that indicates whether the firm has invested in embodied innovation (capital goods or information technologies)
Disembodied innovation	Dummy variable that indicates whether the firm has invested in disembodied innovation (R&D, internal and external and reception of technology transfer)

This first research step is mostly inductive, aiming to identify the main search strategies in Uruguayan firms. However, in accordance with the literature, we expect a positive and significant relationship between combined strategies (more than one KIS) and firms' innovation behavior.

H1. Firms conducting combined search strategies present greater innovation effort and performance than firms that conduct search strategies based on only one external KIS or that do not use external KISs.

3.3 Testing for complementarity

Considering the literature review and the specific KISs analyzed in this work, we expect a complementary effect between non-redundant and useful KISs on the innovation behavior of the Uruguayan firms. However, considering the transaction costs and cognitive distance associated with external search strategies, we expect heterogeneous results among different KISs.

H2. There are complementary effects between closer and more distant KISs on the innovation behavior of firms.

H3. There is not a regular pattern of complementary (substitution) effects of external searching strategies and innovation behavior.

A complementarity and substitution test can be undertaken with different methodologies (Mohnen and Röller, 2005). Milgrom and Roberts (1990), building on the work of Topkis (1978), proposed a supermodularity framework using production functions as a way to formalize a complementarity test. More recently, this concept has been operationalized in the context of innovation studies (Cassiman and Veugelers, 2006; Mohnen and Röller, 2005).

Mohnen and Röller (2005) proposed a discrete test that consists of determining whether the production function is supermodular or submodular, which indicates whether the studied actions are complementary or substitutive. These authors assume that the innovative outputs of firm j are determined by the function f: $f(S_j,Z)$, where Z is a set of control variables and S_j is an element from a source set $S(S_j \in S)$, where j = 1, ... , 8 (since there are three relevant sources of information).

The function f is supermodular if and only if:

$$f(s_j^{'}, Z_{ij}) + f(s_j^{''}, Z_{ij}) \leq f(s_j^{'} \vee s_j^{''}, Z_{ij}) + f(s_j^{'} \wedge s_j^{''}, Z_{ij})$$

where $\vee$ indicates the component-wise minimum between $S_j^{'}$ and $S_j^{''}$ and $\wedge$ the component-wise maximum. Illustratively, suppose that we are interested in knowing whether internal R&D complements or substitutes external R&D in a firm's revenue. Our set S will consist of four elements: S = {(1,1), (0,1), (1,0), (0,0)}. The function is supermodular if $f(1,0) + f(0,1) \leq f(1,1) + f(0,0)$. Rearranging yields a more intuitive expression:

$$f(1,0) - f(0,0) \leq f(1,1) - f(0,1)$$

which implies that, if the function f is supermodular, the return of adopting a new strategy (internal R&D, for instance) is larger when the firm is already conducting the other activity (external R&D) than when the firm is not conducting it.

When more than two sources are present, it suffices to check pairwise complementarities. This is a result of the fact that a function is supermodular over a subset of its arguments if and only if all the pairwise components in the subset satisfy the above inequality (Topkis, 1978). Formally, to test the complementarity of sources 1 and 2:

$$\text{Ho:} \begin{cases} f(100, Z_{ij}) + f(010, Z_{ij}) \leq f(000, Z_{ij}) + f(110, Z_{ij}) \\ f(101, Z_{ij}) + f(011, Z_{ij}) \leq f(001, Z_{ij}) + f(111, Z_{ij}) \end{cases}$$

This implies that, to test each complementarity, we need to test two inequalities simultaneously. Kodde and Palm (1986) derived a statistical test for checking the previous inequalities based on regression coefficients. We follow this approach, estimating a model for a number of dependent variables related to firms' performance and effort. In the independent variables, we include dummy variables for each combination of information sources, called s_j. Let γ_j be the coefficient of each of the s_j. The supermodularity test can be carried out through a comparison of these coefficients, substituting $f(S_j^{'}, Z_{ij})$ for $\gamma_j^{'}$. In other words, the complementarity between source 1 and source 2 can be tested through the following inequalities:

$$\gamma_j^{10X} + \gamma_j^{01X} \leq \gamma_j^{00X} + \gamma_j^{11X}, \quad X = \{0,1\}$$

The hypothesis test can be expressed as $H_0 = S\gamma \leq 0$ against $H_1 = S\gamma > 0$. The test statistic has the following expression:

$$W = [S(\gamma^* - \bar{\gamma})]' \left(S\Omega S'\right)^{-1} S(\gamma^* - \bar{\gamma})$$

where γ^* is an 8×1 vector of consistent estimates of γ and Ω is the estimated covariance matrix. $\bar{\gamma}$ is a vector of estimators that minimize W subject to the null hypothesis.[1]

To conclude that complementarity or substitution is present, it is necessary to carry out tests of supermodularity and substitution separately and then interpret the results together (Table 4).

We define complementarity as the presence of supermodularity with at least one of the inequalities holding strictly positive.[2] Therefore, when we accept the hypothesis of supermodularity and submodularity simultaneously (which can only happen if $f(100, Z_{ij}) + f(010, Z_{ij}) = f(000, Z_{ij}) + f(110, Z_{ij})$ and $f(101, Z_{ij}) + f(011, Z_{ij}) = f(001, Z_{ij}) + f(111, Z_{ij})$), there is no evidence of complementarity or substitution.

[1] Kodde and Palm (1986) showed that the previous statistic follows a mixture of chi-square distributions and provided relevant critical values at the usual significance levels for a test with many inequalities. The main difficulty in constructing W is the estimation of $\bar{\gamma}$. We use numerical methods in *R Software* to minimize W.

[2] Mohnen and Röller (2005) defined complementarity as the presence of strict supermodularity (see Topkis, 1978), that is, with both inequalities holding strictly positive.

Table 4 – Supermodularity test: interpretation criteria

	Test of supermodularity	Test of submodularity	Interpretation
Case 1	H0 accepted	H0 rejected	Complementarity
Case 2	H0 rejected	H0 accepted	Substitution
Case 3	H0 accepted	Doubt	Weak complementarity
Case 4	Doubt	H0 accepted	Weak substitution
Case 5	H0 accepted	H0 accepted	Rejected
Case 6	H0 rejected	H0 rejected	Rejected
Case 7	Doubt	Doubt	Inconclusive

Source: authors adapted from Ballot et al. (2015)

The main disadvantage of the Mohnen and Röller (2005) test is that the Kodde and Palm (1986) critical values have a sizeable inconclusive area. Ballot et al. (2015) proposed an alternative test to overcome this problem, called the *conditional complementarity test* and defined as complementarity between two actions conditional on the presence or absence of the third action.

The test considers the firm objective function *f*: $f(S_j,Z)$, as in the previous test, but focuses on two types of sources at a time while including or excluding the remaining source. Testing the complementarity between two information sources, for example 1 and 2, implies testing separately conditional on the absence and presence of the third source. Formally, we test separately the following restrictions:

$$f(100, Z_{ij}) + f(010, Z_{ij}) < f(000, Z_{ij}) + f(110, Z_{ij})$$

$$f(101, Z_{ij}) + f(011, Z_{ij}) < f(001, Z_{ij}) + f(111, Z_{ij})$$

The conditional complementarity test allows us to overcome the inconclusive area of the Mohnen and Röller (2005) approach and provides extra information about which of the inequalities is holding strictly.

3.2 Data

The data for the analysis are drawn from three triennial waves of the Uruguayan Innovation Survey (UIS), which cover the period 2004–2012. The surveys are based on the methodological guidelines proposed by the Bogotá Manual (Jaramillo et al., 2001), which in turns adapts the Oslo Manual (OECD, 2005) for Latin American countries. Since it is an official survey, participation is compulsory for all the sampled firms, which ensures high response rates.

We work with an unbalanced panel data set with 3 waves of the UIS. Since the questions about sources of knowledge are only posed to firms that declare that they perform innovative activities, in our main specification, we work only with innovative firms. After removing outliers and firms with no innovative activities, the dataset contains 2,196 observations belonging to 1,464 firms (Table 5).

Table 5 – Structure of the panel

Frequency	Percentage	Pattern		
		2006	2009	2012
380	25.96	X		
326	22.27		X	
218	14.89			X
192	13.11	X	X	X
186	12.70		X	X
113	7.72	X	X	
49	3.35	X		X
1464	100			

Source: UIS database

Table 6 contains the descriptive statistics of the dependent and control variables for the sample of innovative and non-innovative firms.

Table 6 – Descriptive statistics

Variable	Innovative firms (2196)		Non-innovative firms (3286)	
	Mean	SD	Mean	SD
Intensity of the innovative effort	0.09	0.51	-	-
Share of sales from innovative products (%)	0.26	0.37	-	-
Inn cooperation with firms (D)	0.87	0.33	-	-
Inn cooperation with research inst (D)	0.36	0.48	-	-
Exporter firm (D)	0.36	0.48	0.18	0.39
Firm size (log employees)	4.20	1.36	3.37	1.25
High or medium tech int sector (D)	0.14	0.35	0.08	0.28
Firm age	27.27	22.21	22.06	18.33
Foreign capital (D)	0.17	0.38	0.09	0.29
Part of a group (D)	0.22	0.41	0.11	0.31
Financial obstacles (D)	0.37	0.48	0.41	0.49
Government support (D)	0.12	0.33	-	-
Professional employees (D)	0.83	0.38	0.53	0.50
Internal sources (D)	0.86	0.35	-	-
Services (D)	0.49	0.50	0.54	0.50
Industry (D)	0.51	0.50	0.46	0.50

Source: authors based on the UIS database

3.4. Econometric strategy

Aiming to identify the combinations of KISs that are associated with better results in innovative performance and effort, we regress innovation performance and innovation effort on the search strategies and a set of control variables.

Due to the dependent variables are only observed for innovative firms, we need to correct for censoring. Therefore, we estimate a probit equation for the probability of innovating and then a random-effect tobit model with the inverse Mill's ratio to correct for censoring.[3] Formally, we have:

$$y_{it} = \alpha + \gamma^{001} s_{it}^{001} + \cdots + \gamma^{111} s_{it}^{111} + \alpha Z_{it} + \mu_l + \delta_t + \beta_i + \varepsilon_{it}$$

where y is the *share of sales from innovative products* or the *intensity of the innovative effort*, μ_l is a set of industry dummies, δ_t are survey-year dummies, Z_{it} is the set of control variables and s is the strategies, omitting the strategy of not using external sources. The error term has a firm-specific component β_i, which is assumed to be normally distributed with mean 0 and variance σ_β^2 and allows us to control for unobserved individual-specific determinants.

For the test of complementarity, we use a main specification with a pooled OLS, without a constant and including the eight strategies. We employ some alternative specifications to check the consistency and robustness of our results (see the Appendix). First, we estimate a tobit random-effect model. Second, we estimate a two-stage Heckman model to correct for the possible selection bias derived from not observing the dependent variables for non-innovative firms. Finally, we estimate a two-stage model with a probit in the first stage and a tobit random effect in the second stage. Our main specification is formally defined as follows:

$$y_{it} = \gamma^{000} s_{it}^{000} + \cdots + \gamma^{111} s_{it}^{111} + \alpha Z_{it} + \mu_l + \delta_t + \varepsilon_{it}$$

where s includes the eight possible strategies and omits the constant term.

4. Results

The estimates of the relationship between search strategies and firms' innovation behavior show, unexpectedly, that only the strategy that combines three KISs has a significant effect on innovative effort (model 1). Moreover, regarding innovative performance (model 2), all the search strategies are significantly and positively associated with innovation performance except *Business and S&T* and *S&T* only. Hence, there is no evidence of a linear association between the openness degree and the effect on innovation behavior; therefore, H1cannot be accepted in general.

Among the three KISs considered in this research, *Codified* sources are a sort of public good, which is not free but is easily consulted without restrictions for other agents, and

[3] As pointed out by Arvanitis et al. (2016), when using innovation survey unbalanced panel data, random-effect models are preferable to fixed-effect models because they allow firms with one observation and time-invariant variables to be retained and they do not suffer from the incidental parameters problem.

they are the KISs that present a shorter distance to the firm. On the contrary, *Business* sources require interaction with similar agents (firms), but the specific information offered by suppliers and customers makes them excludable and rivalry goods. Thus, we consider them as institutionally closer than *S&T*, which is the most distant KIS considered. We find that the use of more distant sources without being integrated with the less distant ones is associated with worse results for innovative performance.

Table 7 – Random-effect tobit model

	Effort (1)		Performance (2)	
	Coef.	Std err.	Coef.	Std err.
1 1 1 (All sources)	0.089**	(0.040)	0.177***	(0.063)
1 0 1 (Codified and S&T)	-0.104	(0.066)	0.253**	(0.100)
1 0 0 (Codified only)	0.003	(0.050)	0.192**	(0.080)
0 1 1 (Business and S&T)	-0.011	(0.055)	0.098	(0.088)
0 0 1 (S&T only)	-0.007	(0.077)	0.046	(0.123)
0 1 0 (Business only)	0.001	(0.039)	0.174***	(0.063)
1 1 0 (Codified and Business)	0.005	(0.037)	0.222***	(0.059)
Disembodied innovation			0.058	(0.045)
Embodied innovation			0.036	(0.033)
Inn cooperation with firms	-0.004	(0.029)	0.314***	(0.115)
Inn cooperation with research inst	0.006	(0.022)	0.110	(0.076)
Exporter firm	0.140	(0.090)	0.113	(0.089)
Firm size (log employees)	0.100	(0.061)	0.001*	(0.001)
High or medium tech int sector	0.031	(0.078)	0.031	(0.047)
Firm age	-0.001	(0.001)	0.123*	(0.072)
Foreign capital	0.002	(0.038)	0.120***	(0.030)
Part of a group	0.100*	(0.054)	0.025	(0.045)
Financial obstacles	0.043**	(0.021)	0.420*	(0.227)
Government support	0.007	(0.029)	0.050	(0.043)
Professional employees	0.384**	(0.175)	1.146**	(0.580)
Internal sources	0.008	(0.028)	0.256***	(0.036)
Inverse Mill's ratio	0.871*	(0.456)	0.541***	(0.019)
sigma_u	0.479***	(0.014)	0.356***	(0.032)
sigma_e	0.292***	(0.009)	0.112***	(0.037)
Constant	-1.605*	(0.859)	-2.688**	(1.091)
Observations	2,196		2,196	
Wald Chi2	98.42***		226.13***	
Number of firms	1,464		1,464	

Standard errors in are parentheses. *** p<0.01, ** p<0.05, * p<0.1. All the specifications include seven industry dummies and year dummies. The omitted category is 000, no sources. IMR is the inverse Mills ratio for innovators obtained from a probit regression using the set of controls as dependent variables, as presented in the Appendix.

Table 8 shows the results of the tests proposed by Mohnen and Röller (2005).[4] For each pair of KISs, we present the results of the Wald test for supermodularity and submodularity. In the intermediate values, between the critical values, there is an inconclusive area, with weak evidence of super- or submodularity (Kodde and Palm, 1986).

We find evidence of a complementarity effect between *Codified* and *S&T* sources on the innovative effort of firms. We also find weak evidence of a substitution effect between *Business* and *Codified* sources on the innovative performance of firms. This result is in line with the idea that the use of different types of sources could increase the managerial cost and complexity and may not necessarily result in improved performance (Belderbos et al., 2006). Moreover, according to previous research on firms' use of codified knowledge, this result can be understood as the complementary effect of the combination of access to public sources (*Codified*) and specific research-based knowledge (*S&T*). On the contrary, the combination of *Codified* and *Business* KISs seems to reflect the substitution effects between closer KISs that do not offer substantially new information and knowledge but increase the transaction costs. Therefore, we accept H2 and H3.

Table 8 – Complementarity test (Mohnen and Röller, 2005)

Dep. variable		Codified and Business	Codified and S&T	Business and S&T
Effort	Supermodularity test	0.29	0.00	0.33
	Submodularity test	0.37	4.40	0.31
	Result	No	Comp	No
Performance	Supermodularity test	3.52	0.00	1.08
	Submodularity test	0.00	0.37	0.00
	Result	Sust weak	No	No

Wald test of inequality restrictions based on OLS estimates. At the 10% significance level: lower bound = 1.624 (null hypothesis accepted for lower values), upper bound = 3.808 (null hypothesis rejected for higher values) (Kodde and Palm, 1986). Sources: authors

In line with the proposed interpretation, the results of the conditional complementarity test (Table 9) provide additional information. We find complementarity between *Codified* and *S&T* sources on the innovative effort, conditional on the presence of *Business* sources. For the estimation of effects on innovation performance, we confirm the substitution effect found with the previous test between *Codified* and *Business* but conditional on the absence of the third source.

[4] The innovation production functions using OLS estimations, used to apply the complementarity test proposed by Mohnen and Röller (2005), are reported in Table A2. It should be taken into account that, in this model, the coefficients and the significance of the KIS combinations by themselves do not allow us to conclude whether the innovation function presents complementarity or substitutability.

Table 9 – Conditional complementarity test (Ballot et al., 2015)

Dep. variable		Codified and Business	Codified and S&T	Business and S&T
With the third source				
Effort	Supermodularity test	0.188	0.007	0.291
	Submodularity test	0.811	0.992	0.708
	Result	No	Comp***	No
Performance	Supermodularity test	0.768	0.278	0.770
	Submodularity test	0.231	0.721	0.229
	Result	No	No	No
Without the third source				
Effort	Supermodularity test	0.729	0.260	0.916
	Submodularity test	0.270	0.739	0.083
	Result	No	No	Sust*
Performance	Supermodularity test	0.960	0.409	0.794
	Submodularity test	0.039	0.590	0.205
	Result	Sust**	No	No

P-values of t-test, source: authors

In Table 10, we summarize the results of both tests. There is no evidence of a general pattern of complementarity or substitution between the three KISs. However, we find substitution effects between *Codified* and *Business* in innovation performance and complementarity effects between *Codified* and *S&T*. These results are corroborated by robustness checks (Tables A3 and A4).

Table 10 – Summary of patterns of complementarity and substitution

Dep. variable	KIS	Mohnen and Röller	Ballot	
			With the third source	Without the third source
Effort	Codified and Business	No	No	No
	Codified and S&T	Comp	Comp***	No
	Business and S&T	No	No	Sust*
Performance	Codified and Business	Sust weak	No	Sust**
	Codified and S&T	No	No	No
	Business and S&T	No	No	No

Source: authors

4 Conclusions

This paper contributes to revisiting two basic building blocks of the economics of innovation by analyzing the relationship between firms' external search strategy and their innovation behavior.

In the first research step, we identify specific search strategies and their effects on innovation behavior. Our findings are in line with the previous research (Antonioli et al., 2017; Gkypali et al., 2017; Serrano-Bedia et al., 2018), as they show an idiosyncratic relationship between the external search strategy and both the innovative effort intensity and the innovative performance. This reinforces the first theoretical postulate related to the specificity of a firm's innovation path. In this regard, contrary to the empirical background of innovation studies in Latin America, we find more significant evidence of the effect of integrative search strategies on the innovation performance than on the intensity of the innovation effort.

However, according to the expected results, the search strategies that do not show significant effects on innovation performance are those related to the use of some of the most distant KISs only or the combination of the most distant KISs (Table 7). Hence, we corroborate our interpretation based on the cognitive distance between the firm and the KIS as a determinant of the effect of the search strategy on innovation behavior. In addition, we are able to conjecture that the simultaneous use of cognitively distant sources, *Business* and *S&T*, implies high transaction costs regarding the internal capabilities of Uruguayan firms. In this regard, it is worth noticing the relevance of the *Codified* sources, a type of KIS that has received less attention in the literature (Arora et al., 2016) but that has experienced a growing process, regarding KISs' volume and availability, and can imply a change in the available set of useful knowledge. In particular, when considering firms operating in traditional activities and following no radical innovation strategies, this type of source seems to be critical to participate in a knowledge-based economy (David and Foray, 1996).

In the second step, to discuss the theoretical postulate related to the systemic functioning of innovation, we assessed the complementarity or substitution effects between search strategies on firms' innovation behavior by estimating complementarity and conditional complementarity. In agreement with the previous literature, our findings show that there is an idiosyncratic relationship rather than a general pattern between the three sources considered, but systemic effects can be observed.

We found a robust substitution effect between *Codified* and *Business* KISs on innovation performance and a complementarity effect between *Codified* and *S&T* sources on innovative effort. Even though the latter result is in line with our theoretical framework and hypotheses, a satisfactory explanation for the negative effect of an integrative search using *Codified* and *Business* KISs requires further research.

In line with previous research (Arora et al., 2016), an interpretation of these results suggests that they reflect a trade-off between the search openness to codified available KISs and the restrictions to articulate it with the tacit knowledge of the business partners (Antonioli et al., 2017; Grimpe and Kaiser, 2010).

When testing for conditional complementarities, the results are in line with the previous ones but allow us to determine that the substitution effect between *Codified* and *Business* KISs is present only when firms do not use *S&T* as a third KIS and that the complementarity effect between *Codified* and *S&T* sources on innovative effort is only present when the firms use the *Business* KIS as a third source. Therefore, the general interpretation that more integrative search strategies have positive effects on firms' innovation behavior is partially accepted. In this regard, we interpret the presence of the third source as bridging the gap between distant KISs and the innovative firm, overcoming the potential increasing openness costs.

Finally, the use of both measures of innovation behavior allows us to observe whether the effects of external KISs differ according to the different dimensions of innovation behavior, which, in turn, are usually critical and differentiated targets for innovation policies (Borrás and Edquist, 2013).

References

Antonioli, D., Marzucchi, A., Savona, M., 2017. Pain shared, pain halved? Cooperation as a coping strategy for innovation barriers. J. Technol. Transf. 42 (4), 841–864.

Arora, A., Athreye, S., Huang, C., 2016. The paradox of openness revisited: collaborative innovation and patenting by UK innovators. Res. Policy 45 (7), 1352–1361.

Arora, A., Gambardella, A., 1990. Complementarity and external linkages: the strategies of the large firms in biotechnology. J. Ind. Econ. 38 (4), 361–379.

Arvanitis, S., Seliger, F., Stucki, T., 2016. The relative importance of human resource management practices for innovation. Econ. Innov. New Technol. 25 (8), 769–800.

Ballot, G., Fakhfakh, F., Galia, F., Salter, A., 2015. The fateful triangle: complementarities in performance between product, process and organizational innovation in France and the UK. Res. Policy 44 (1), 217–232.

Barge-Gil, A., 2013. Open strategies and innovation performance. Ind. Innov. 20 (7), 585–610.

Barney, J., 1991. Firm resources and sustained competitive advantage. J. Manag. 17 (1), 99–120.

Becker, W., Dietz, J., 2004. R&D cooperation and innovation activities of firms—evidence for the German manufacturing industry. Res. Policy 33 (2), 209–223.

Belderbos, R., Carree, M., Diederen, B., Lokshin, B., Veugelers, R., 2004. Heterogeneity in R&D cooperation strategies. Int. J. Ind. Org. 22, 1237–1263.

Belderbos, R., Carree, M., Lokshin, B., 2006. Complementarity in R&D cooperation strategies. Rev. Ind. Org. 28, 401–426.

Bertrand, O., Mol, M., 2013. The antecedents and innovation effects of domestic and offshore R&D outsourcing: the contingent impact of cognitive distance and absorptive capacity. Strat. Manag. J. 34 (6), 751–760.

Borrás, S,. Edquist, C., 2013. The choice of innovation policy instruments. Technol. Forecast. Soc. Chang. 80 (8), 1513–1522.

Brusoni, S., Marsili, O., Salter, A., 2005. The role of codified sources of knowledge in innovation: empirical evidence from Dutch manufacturing. J. Evol. Econ. 15 (2), 211–231.

Cassiman, B., Veugelers, R., 2006. In search of complementarity in innovation strategy: internal R&D and external knowledge acquisition. Manag. Sci. 52 (1), 68–82.

Cohen, W., Levinthal, D., 1989. Innovation and learning: the two faces of R&D. Econ. J. 99, 569–596.

Colombelli, A., Quatraro, F., 2014. The persistence of firms' knowledge base: a quantile approach to Italian data. Econ. Innov. New Technol. 23 (7), 585–610.

Cowan, R., Foray, D., 1997. The economics of codification and the diffusion of knowledge. Ind. and Corp. Chang. 6 (3), 595–622.

Criscuolo, P., Laursen, K., Reichstein, T., Salter, A., 2018. Winning combinations: search strategies and innovativeness in the UK. Ind. Innov. 25 (2), 115–143.

David, P., Foray, D., 1996. Information distribution and the growth of economically valuable knowledge: a rationale for technological infrastructure policies. In: M. Teubal, D. Foray, M. Justman, E. Zuscovitch (Eds), Technological Infrastructure Policy. Economics of Science, Technology and Innovation. Springer, Dordrecht.

Denicolai, S., Ramirez, M., Tidd, J., 2016. Overcoming the false dichotomy between internal R&D and external knowledge acquisition: absorptive capacity dynamics over time. Technol. Forecast. Soc. Chang. 104, 57–65.

Dosi, G., 1988. The nature of innovative processes. In: G. Dosi, C. Freeman, *R*. Nelson, *G*. Silverberg, L. Soete (Eds.), Technical Change and Economic Theory. Pinter Publishers, London and New York.

Dutrénit, G., Natera, J., Puchet, M., Vera-Cruz, A.O., 2018. Development profiles and accumulation of technological capabilities in Latin America. Technol. Forecast. Soc. Chang. In press, DOI: 10.1016/j.techfore.2018.03.026.

Foss, N., Laursen, K., Pedersen, T., 2011. Linking customer interaction and innovation. Org. Sci. 22 (4), 980–999.

Foss, N., Klein, P., 2010. Critiques of transaction cost economics: an overview. In: The Elgar Companion to Transaction Cost Economics, Edward Elgar Publishing, pp. 263–272.

Gkypali, A., Filiou, D., Tsekouras, K., 2017. R&D collaborations: is diversity enhancing innovation performance? Technol. Forecast. Soc. Chang. 118, 143–152.

Grazzi, M., Pietrobelli, C., 2016. Firm Innovation and Productivity in Latin America and the Caribbean. IDB, Palgrave Macmillan, New York.

Grimpe, C., Kaiser, U., 2010. Balancing internal and external knowledge acquisition: the gains and pains from R&D outsourcing. J. Manag. Stud. 47 (8), 1483–1509.

Grimpe, C., Sofka, W., 2016. Complementarities in the search for innovation—managing markets and relationships. Res. Policy 45 (10), 2036–2053.

Guisado-González, M., Wright, L., Guisado-Tato, M., 2017. Product–process matrix and complementarity approach. J. Technol. Transf. 42 (3), 441–459.

Hagedoorn, J., Wang, N., 2012. Is there complementarity or substitutability between internal and external R&D strategies? Res. Policy 41 (6), 1072–1083.

Hecker, A., Ganter, A., 2014. Path and past dependence of firm innovation. Econ. Innov. New Technol. 23 (5–6), 563–583.

Homburg, C., Kuehnl, C., 2014. Is the more always better? A comparative study of internal and external integration practices in new product and new service development. J. Bus. Res. 67 (7), 1360–1367.

Jaramillo, H., Lugones, G., Salazar, M., 2001. Normalización de Indicadores de Innovación Tecnológica en América Latina. Manual de Bogotá. Cuaderno Indicios N° II. RICYT-CYTED. OEA.

Kaiser, U., 2002. An empirical test of models explaining R&D expenditures and R&D cooperation. Int. J. Ind. Org. 20 (6), 747–774.

Katila, R., Ahuja, G., 2002. Something old, something new: a longitudinal study of search behavior and new product introduction. Acad. Manage. J. 45 (6), 1183–1194.

Kodde, D., Palm, F., 1986. Wald criteria for jointly testing equality and inequality restrictions. Econometrica, 1243–1248.

Laursen, K., 2012. Keep searching and you'll find: what do we know about variety creation through firms' search activities for innovation? Ind. Corp. Chang. 21 (5), 1181–1220.

Laursen, K., Foss, N., 2003. New human resource management practices, complementarities and the impact on innovation performance. Camb. J. Econ. 27 (2), 243–263.

Laursen, K., Salter, A., 2004. Searching high and low: what types of firms use universities as a source of innovation? Res. Policy 33 (8), 1201–1215.

Laursen, K., Salter, A., 2006. Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms. Strat. Manag. J. 27 (2), 131–150.

Laursen, K., Salter, A., 2014. The paradox of openness: appropriability, external search and collaborations. Res. Policy 43, 867–878.

Lazzarotti, V., Manzini, R., Pellegrini, L., 2015. Is your open-innovation successful? The mediating role of a firm's organizational and social context. Int. J. Hum. Res. Manag. 26 (19), 2453–2485.

Leiponen, A., 2012. The benefits of R&D and breadth in innovation strategies: a comparison of Finnish service and manufacturing firms. Ind. Corp. Chang. 21 (5), 1255–1281.

Leiponen, A., Helfat, C., 2010. Innovation objectives, knowledge sources, and the benefits of breadth. Strat. Manag. J. 31 (2), 224–236.

Love, J., Roper, S., 2009. Organizing the innovation process: complementarities in innovation networking. Ind. Innov. 16 (3), 273–290.

Love, J., Roper, S., Vahter, P., 2014. Dynamic complementarities in innovation strategies. Res. Policy 43 (10), 1774–1784.

Lundvall, B.A., 1988. Innovation as an interactive process: from user-producer interaction to national systems of innovation. In: G. Dosi, C. Freeman, *R*. Nelson, *G*. Silverberg, L. Soete (Eds.), Technical Change and Economic Theory. Pinter Publishers, London and New York.

Menguc, B., Auh, S., Yannopoulos, P., 2014. Customer and supplier involvement in design: the moderating role of incremental and radical innovation capability. J. Prod. Innov. Manag. 31 (2), 313–328.

Milgrom, P., Roberts, J., 1990. The economics of modern manufacturing: technology, strategy, and organization. Am. Econ. Rev. 80, 511–528.

Mohnen, P., Röller, L., 2005. Complementarities in innovation policy. Eur. Econ. Rev. 49 (6), 1431–1450.

Mowery, D., 1983. The relationship between intrafirm and contractual forms of industrial research in American manufacturing, 1900–1940. Explor. Econ. Hist. 351–374.

Mowery, D., Rosenberg, N., 1989. Technology and the Pursuit of Economic Growth. Cambridge University Press, New York.

Nelson, R., 1991. Why do firms differ, and how does it matter? Strat. Manag. J. 12 (S2), 61–74.

Nelson, R., Winter, S., 1982. An Evolutionary Theory of Economic Change. Belknap Press, Harvard University Press.

Nooteboom, B., Van Haverbeke, W., Duysters, G., Gilsing, V., Van den Oord, A., 2007. Optimal cognitive distance and absorptive capacity. Res. Policy 36 (7), 1016–1034.

OECD 2005. Oslo Manual. Guidelines for collecting, reporting and using data on innovation. OECD, Paris.

Penrose, E., 1995 [1959]. The Theory of the Growth of the Firm. John Wiley, New York.

Pisano, G., 1990. The R&D boundaries of the firm: an empirical analysis. Adm Sci Q, 35(1), 153-176.

Rothaermel, F., Alexandre, M., 2009. Ambidexterity in technology sourcing: the moderating role of absorptive capacity. Org. Sci. 20 (4), 759–780.

Serrano-Bedia, A., López-Fernández, M., García-Piqueres, G., 2018. Complementarity between innovation knowledge sources: does the innovation performance measure matter? BRQ Bus. Res. Q. 21 (1), 53–67.

Teece, D., 1986. Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. Res. Policy 15, 285–305.

Topkis, D., 1978. Supermodularity and Complementarity. Princeton University Press, New Jersey.

Van Beers, C., Zand, F., 2014. R&D cooperation, partner diversity, and innovation performance: an empirical analysis. J. Prod. Innov. Manag. 31 (2), 292–312.

Vega-Jurado, J., Gutiérrez-Gracia, A., Fernández-de-Lucio, I., 2009. Does external knowledge sourcing matter for innovation? Evidence from the Spanish manufacturing industry. Ind. Corp. Chang. 18 (4), 637–670.

Veugelers, R., 1997. Internal R&D expenditures and external technology sourcing. Res. Policy 26, 303–315.

Wernerfelt, B., 1984. A resource-based view of the firm. Strat. Manag. J. 5 (2), 171–180.

Williamson, O., 1981. The economics of organization: the transaction cost approach. Am. J. Sociol. 87 (3), 548–577.

Yoguel, G., Robert, V., 2010. Capacities, processes, and feedbacks: the complex dynamics of development. Seoul J. Econ. 23 (2), 187–237.

Zahra, S., George, G., 2002. Absorptive capacity: a review, reconceptualization, and extension. Acad. Manag. Rev. 27 (2), 185–203.

Appendix

Table A1 – Selection equation, propensity to innovate (first stage of table 7)

	Probit (1)	
	Coef.	Std err.
Exporter firm	0.309***	(0.046)
Firm size (log employees)	0.206***	(0.016)
High or medium tech int sector	0.190**	(0.076)
Firm age	0.001	(0.001)
Foreign capital	-0.027	(0.063)
Part of a group	0.172***	(0.057)
Professional employees	0.522***	(0.045)
Constant	-1.617***	(0.077)
Observations	5,469	
LR test	896.83***	
Pseudo R squared	0.1217	

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. All the specifications include 7 industry dummies and year dummies.

Table A2 – OLS regressions with all strategies

	Effort (1)		Performance (2)	
	Coef.	Std err.	Coef.	Std err.
Disembodied innovation			0.155***	(0.017)
Embodied innovation			0.059***	(0.020)
1 1 1 (all sources)	0.148***	(0.049)	0.110**	(0.054)
1 0 1 (Codified and S&T)	0.102*	(0.059)	0.167**	(0.070)
1 0 0 (Codified only)	0.046	(0.039)	0.138**	(0.054)
0 1 1 (Business and S&T)	0.028	(0.043)	0.070	(0.064)
0 0 1 (S&T only)	0.053	(0.048)	0.052	(0.072)
0 1 0 (Business only)	0.060	(0.054)	0.114**	(0.051)
1 1 0 (Codified and Business)	0.046	(0.040)	0.129**	(0.051)
0 0 0 (no external KIS)	0.025	(0.037)	0.046	(0.052)
Inn cooperation with firms	-0.046	(0.051)	0.010	(0.024)
Inn cooperation with research inst	0.005	(0.029)	0.008	(0.018)
Exporter firm	-0.009	(0.025)	0.036**	(0.018)
Firm size (log employees)	-0.018**	(0.009)	-0.019***	(0.007)
High or medium tech int sector	-0.087	(0.083)	-0.018	(0.029)
Firm age	-0.002***	(0.001)	0.000	(0.000)
Foreign capital	0.026	(0.032)	0.026	(0.024)
Part of a group	0.015	(0.020)	0.012	(0.022)
Financial obstacles	0.051**	(0.022)	0.064***	(0.017)
Government support	0.077	(0.049)	0.005	(0.026)
Professional employees	0.066*	(0.036)	-0.018	(0.024)
Internal sources	0.011	(0.013)	0.012	(0.023)
Observations	2,196		2,196	
R-squared	0.082		0.382	

OLS estimations. Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.1. All the specifications include 7 industry dummies and year dummies. In the combinations of sources, the first 1 or 0 is for coded sources, the second is for firm sources and the third is for universities. The model includes the 8 searching strategies and excludes the constant

Table A3 – Regression robustness check

	Random-effect tobit with selection				Random-effect tobit				Heckit with OLS in second stage			
	Effort (1)		Performance (2)		Effort (3)		Performance (4)		Effort (5)		Performance (6)	
	Coef.	SD	Coef.	SD	Coef.	SD	Coef.	SD	Coef.	SD	Coef.	SD
1 1 1 (all sources)	-0.208	(0.469)	0.174	(0.682)	0.119	(0.074)	-0.366***	(0.100)	-1.189	(0.857)	-1.237	(0.755)
1 0 1 (Codified and S&T)	-0.403	(0.473)	0.256	(0.689)	-0.075	(0.089)	-0.286**	(0.123)	-1.244	(0.861)	-1.183	(0.758)
1 0 0 (Codified only)	-0.294	(0.470)	0.187	(0.683)	0.033	(0.076)	-0.353***	(0.104)	-1.296	(0.856)	-1.208	(0.754)
0 1 1 (Business and S&T)	-0.308	(0.471)	0.096	(0.686)	0.018	(0.083)	-0.444***	(0.118)	-1.305	(0.859)	-1.277*	(0.756)
0 0 1 (S&T only)	-0.305	(0.478)	0.046	(0.694)	0.025	(0.097)	-0.498***	(0.141)	-1.290	(0.860)	-1.295*	(0.758)
0 1 0 (Business only)	-0.297	(0.470)	0.169	(0.683)	0.031	(0.072)	-0.371***	(0.096)	-1.277	(0.856)	-1.231	(0.754)
1 1 0 (Codified and Business)	-0.292	(0.469)	0.217	(0.682)	0.035	(0.071)	-0.323***	(0.094)	-1.295	(0.856)	-1.218	(0.754)
0 0 0 (no external KIS)	-0.297	(0.469)	-0.006	(0.683)	0.030	(0.075)	-0.545***	(0.102)	-1.307	(0.857)	-1.299*	(0.755)
Inn cooperation firms	-0.004	(0.029)	0.059	(0.045)	-0.004	(0.029)	0.058	(0.045)	-0.041	(0.033)	0.011	(0.029)
Inn cooperation research inst	0.007	(0.022)	0.039	(0.033)	0.008	(0.022)	0.038	(0.033)	-0.020	(0.025)	0.005	(0.022)
Exporter firm	0.031	(0.081)	0.009	(0.117)	-0.023	(0.027)	0.098***	(0.035)	0.130	(0.093)	0.172**	(0.082)
Firm size (log employees)	-0.013	(0.012)	-0.040***	(0.014)	-0.014	(0.012)	-0.038***	(0.014)	0.079	(0.060)	0.073	(0.053)
High or medium tech sector	-0.013	(0.101)	-0.117	(0.136)	-0.072	(0.056)	-0.019	(0.059)	-0.001	(0.074)	0.063	(0.067)
Firm age	-0.002**	(0.001)	0.001	(0.001)	-0.002**	(0.001)	0.001	(0.001)	-0.001	(0.001)	0.001	(0.001)
Foreign capital	0.032	(0.044)	0.025	(0.057)	0.016	(0.038)	0.052	(0.046)	0.006	(0.046)	0.008	(0.042)
Part of a group	0.071	(0.086)	-0.090	(0.127)	0.014	(0.028)	0.006	(0.041)	0.089	(0.060)	0.084	(0.054)
Financial obstacles	0.042**	(0.021)	0.119***	(0.031)	0.041*	(0.021)	0.120***	(0.030)	0.033	(0.030)	0.051*	(0.027)
Government support	0.007	(0.029)	0.017	(0.045)	0.005	(0.029)	0.020	(0.045)	0.122***	(0.034)	0.012	(0.031)
Professional employees	0.165	(0.157)	-0.200	(0.230)	0.056*	(0.032)	-0.020	(0.043)	0.342*	(0.183)	0.267*	(0.161)
Internal sources	0.006	(0.028)	0.047	(0.043)	0.005	(0.028)	0.047	(0.043)	0.020	(0.031)	0.015	(0.027)
Disembodied innovation			0.358***	(0.032)			0.358***	(0.032)			0.154***	(0.021)
Embodied innovation			0.117***	(0.037)			0.116***	(0.037)			0.056**	(0.024)
IMR	0.389	(0.551)	-0.647	(0.809)					0.740	(0.454)	0.726*	(0.400)
sigma_u	0.479***	(0.014)	0.253***	(0.037)	0.479***	(0.014)	0.256***	(0.036)				
sigma_e	0.292***	(0.009)	0.543***	(0.019)	0.292***	(0.009)	0.542***	(0.019)				
Observations	2,196		2,196		2,196		2,196		5,469		5,469	
Number of correlation	1,464		1,464		1,464		1,464					

Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.1. All the specifications include 7 industry dummies and year dummies. In the combinations of sources, the first 1 or 0 is for coded sources, the second is for firm sources and the third is for universities. The model includes the 8 searching strategies and excludes the constant. Columns 1 and 2: tobit random effect with selection estimations. IMR is the inverse Mills ratio for innovators obtained from a probit regression using the set of controls as dependent variables. Columns 3 and 4: random-effect model estimations. Columns 5 and 6: two-stage Heckman estimations. IMR is the inverse Mills ratio for innovators obtained from a probit regression using the set of controls as dependent variables.

Table A4 – Test robustness check

Dep. variable	Sources	Random-effect tobit with selection	Random-effect tobit	Heckit with OLS in second stage
Effort	Codified and Business	No	No	No
	Codified and S&T	No	No	Comp
	Business and S&T	No	No	No
Performance	Codified and Business	Sust	Sust	Sust weak
	Codified and S&T	No	No	No
	Business and S&T	No	No	No

Sources: authors