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Internal and external effects of R&D subsidies and fiscal incentives: Empirical evidence using spatial dynamic panel models

Benjamin Montmartin[a,b,*], Marcos Herrera[c]

[a] University of Nice Sophia-Antipolis, Nice F-06000, France
[b] CNRS, GREDEG UMR 7321, Valbonne F-06560, France
[c] CONICET – IELDE, National University of Salta, Av. Bolivia 5150 (A4408FVY), Salta, Argentina

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ABSTRACT

Most studies evaluating the macroeconomic effects of financial support policies on business-funded R&D use econometric methods that do not consider the existence of spatial effects, and generate biased estimates. In this paper, we discus and address this problem using spatial dynamic panel data methods. This allow us to provide new insights on the internal (in-country) and external (out-of-country) effects of both Research and Development (R&D) subsidies and fiscal incentives. We use a database of 25 OECD countries for the period 1990–2009. In relation to internal effects, for both instruments, we find a non-linear relationship between their effect on private R&D and their level (suggesting the possibility of leveraging and crowding-out effects). We also find a substitution effect between the R&D subsidies and fiscal incentives implemented within a country. Concerning the spatial component, we find evidence of positive spatial spillovers among private R&D investments. However, our results suggest the existence of competition/substitution effects between national R&D policies.

1. Introduction

The European Commission has set an R&D investment objective for the “2020 European Strategy” at 3% of GDP, two-thirds of which should be financed by the private sector. In 2012, the EU’s R&D investment is estimated at 2.06% of GDP, financed 55% by the private sector (source: Eurostat). Thus, the public sector investment objective (0.93% vs. 1%) has almost been achieved but, the private sector contribution is lagging (1.13% vs. 2%). The rationale for these objectives and public support for private R&D, is the common belief that R&D specificities generate numerous market failures[1] leading to a sub-optimal equilibrium and private under-investment in R&D.

A growing literature[2] discusses and evaluates the capacity of financial support policies to increase private investment in R&D through two main instruments: tax incentives (indirect support) and direct subsidies (direct support). This topic is especially important in a context of public budget pressure that requires all public expenditure to be justified and effective. In the context of financial support for R&D, although most macroeconometric studies provide evidence on the effectiveness of such measures to increase private investment in R&D, some basic questions remain unaddressed. These are related to crowding-out effects and distortions between firms and sectors that can be generated by direct and indirect support. In an empirical context, while the cost of financial support for R&D has increased significantly in European countries, the evolution of privately financed R&D has been relatively flat.[3] Also, in EU countries with the highest level of private investment in R&D (Denmark, Germany, Finland, Sweden) support for R&D – either, direct (subsidies) or indirect (fiscal incentives) – is less than the EU and OECD averages.

The economic literature distinguishes tax incentives and direct subsidies according to their design, timing, cost and potential welfare impact. Obviously, the main difference between direct and

* Corresponding author at: CNRS, GREDEG UMR 7321, 250 rue Albert Einstein, Batiment 2, Valbonne F-06560, France. Tel.: +33 0493954356.
E-mail addresses: benjamin.montmartin@unice.fr (B. Montmartin), mherreragomez@gmail.com (M. Herrera).

[1] Such as knowledge spillovers, duplications, see Montmartin and Massard (2014) for a review.

[2] See reviews by David et al. (2000), Hall and Van Reenen (2000), Lentile and Mairesse (2009) and Lokshin and Mohnen (2009).

[3] Privately financed R&D increased from 1.03% of GDP in 1999 to 1.13% in 2012.

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Table 1
Advantages and disadvantages of support.

Advantages	Disadvantages
Direct support	
• Adapted to target upon activities and projects where there is a significant gap between private and social returns to R&D.	• High administrative costs for both firms and public authorities.
• Theoretically, competition between firms ensures that public funds are used for the best R&D projects.	• Impossible to put into practice for a large number of projects.
• May be used to reduce the effects of economic cycles on firms' R&D investments.	• Causes distortions on the markets for the allocation of resources between different R&D fields and firms.
• May encourage cooperation and the transferal of technology thereby reinforcing knowledge externalities	• Project selection tends to reward lobbies. The pressure related to the result objectives of the established policies entails the risk of projects being selected due to their high success potential, i.e., projects with high private productivity carried out without any public funding.
• Allows the verification of costs entailed by measures.	
• May enhance the reputation of firms who have received financing thereby reducing their capital cost (SMEs).	• Numerous potential eviction sources, due to the fact that direct measures are targeted and affect returns to R&D.
Indirect support	
• Measures are more neutral as they encourage investment in R&D for all firms, particularly SMEs (although specific sectors may also be targeted).	• It is difficult to control the cost of financial measures.
• The firms themselves decide which projects they wish to invest in.	• The effects are limited for firms who do make sufficient profit or which invest heavily in R&D (large companies) because they do not reap the maximum benefit from the financial measures.
• Reduces the risk of public markets being rigged.	• Non-neglectable risk of eviction as these measures can reduce the cost of projects which would have been carried through anyway (particularly in the case of a large tax credit).
• Does not require a specific budget line as the cost is only expressed in terms of a loss of financial income.	• Financial incentives favor R&D projects with the highest short-term returns. Hence, projects with high social returns to R&D will not be favored by this type of measure.
• Implementation and management costs are relatively low.	
• Financial measures reduce the cost of R&D directly which theoretically reduces the potential eviction sources.	• Few knowledge externalities are generated as the firms choose the projects and cooperation is rarely a factor for eligibility.

Notes: Adapted of Carvalho (2011).

indirect support is that the former typically allows firms to choose projects, while the latter usually is related to a public authority project choice. Concerning timing, R&D subsidies do not always require an initial R&D investment from the firm, and thus can be used to finance a current R&D project. However, to benefit from fiscal incentives firms must first conduct and finance R&D. In relation to relative cost, it is often argued that direct support implies heavier administrative costs than indirect support, and in terms of welfare impact, many economists highlight the risk that indirect support favors projects with high private returns not high social returns while direct support seems to be linked to projects with considerable social returns.[4] Table 1 presents an overall view of the main advantages and disadvantages of each instrument in terms of its cost, efficiency and welfare impact.

The extensive empirical literature evaluating the impact of financial support on private investment in R&D mostly (1) evaluates the capacity of a specific measure to increase private R&D investment and (2) is at a microeconomic level. Only four studies analyze the impact of both direct and indirect support at the macroeconomic level.[5] However, macroeconomic investigation of financial support would seem very useful in many respects: to evaluate the global effect of R&D policies, to discuss the complementarity of instruments and the pertinence of the policy mix, and to understand their cross-border effects. The small number of macroeconometric works mean much remains to be done.

The literature mostly ignores the possibility of an external (out-of-country) impact of R&D policies, i.e, a country's R&D investment is considered only to be affected by the home country environment and R&D policies. However, (Tobler, 1970, p.234) first law of geography reminds us that "everything is related to everything else, but near things are more related than distant things", i.e, a country's R&D investment may well be affected by the environment and policy decisions of other countries (and vice-versa). Distance is understood as proximity, not necessarily geographical distance, such as the intensity of trade or scientific collaboration for instance. Given the nature of knowledge creating activities and the existence of localized knowledge externalities, it might be expected that private R&D investment in country *i* could be affected by private R&D investment and the R&D policy incentives of other countries.

The main objective of this paper is to investigate more comprehensively the global effects of direct and indirect support policies by considering both temporal and spatial dependence of R&D activities. Although temporal dependence[6] has been modeled in previous works, spatial dependence has been ignored. The presence of spatial dynamics in panel data models generates important spatial spillovers effects that condition the standard results. We provide new empirical evidence based on data for 25 OECD countries in the period 1990–2009. In terms of internal effects, we show that, for both instruments, there exists a non-linear relationship between their effect on the business-funded R&D intensity (hereafter "private R&D intensity") and their level of use. This suggest the possibility of both leveraging and crowding-out effects of these policies according to their exploitation by countries. The spatial component of our work provides evidence that private R&D intensity generates positive spatial spillovers. However, it appears that policies implemented by "neighboring" countries have the opposite impact to national policies. In other words, R&D policies implemented by different countries could be substitutes.

The paper is organized as follows. In Section 2, we present the theoretical macroeconomic effects of financial support policies; Section 3 investigates and briefly reviews the empirical literature

[4] Although the allocations made by public authorities are often questioned for their efficiency.

[5] Guellec and Van Pottelsberghe de la Potterie (2003), Shin (2006), Falk (2006) and Montmartin (2013).

[6] The introduction of temporal dependence in empirical works is related to the strong adjustments costs of R&D investment that do not allow firms to react fully to environmental changes within a period.

on these effects. Section 4 develops dynamic panel data models and extensions that introduce spatial effects. Section 5 presents the empirical methodology applied to the dataset of 25 OECD countries observed during 20 years, and the results of different specification including a variety of spatial effects. Section 6 concludes the paper.

2. Theoretical and empirical analysis of the effects of direct and indirect support at the macroeconomic level

2.1. On the internal (in-country) effect of R&D financial support

2.1.1. The first side of the internal effect: the individual effect of each instrument

The seminal paper by David et al. (2000) provides an interesting conceptual framework to analyze the different channels through which R&D public policies influence the macroeconomic behavior of firms in relation to R&D investment. In a simple microeconomic framework where R&D investment is considered as an asset acquisition decision, it is clear that direct subsidies or fiscal incentives reduce the marginal cost of R&D projects and provide incentives for firms to increase their levels of investment in R&D. However, the market imperfections and externalities that influence R&D investment behavior (see Montmartin and Massard, 2014) are likely to have a strong modifying influence on the macroeconomic effects of such policies.

On the positive side, it can be argued that subsidized (directly or not) R&D activity generates learning and training effects for subsidized firms that are willing to increase their efficiency by conducting their own R&D programs. Public support available for durable research equipment or other R&D fixed costs can help firms to conduct successive own R&D projects at lower incremental costs which will increase the expected internal rates of return on its R&D investments. Direct support can also generate another positive externality for subsidized firms if taken as a positive signal of future product demand. However, although these positive effects can reinforce the macroeconomic effects of financial support for R&D, there are some potential negative effects. The first concerns the individual behavior of firms in terms of their exploitation of support. It is possible that part of support might be used to finance R&D projects that would have been financed anyway, or might not be used to increase R&D expenditure. Here, we refer to the possibility that these policy instruments can be (partial) substitutes for private R&D funding. The second effect refers to the distortions between firms and industries generated by policy instruments. Although these measures may encourage firms and sectors that benefit from them to increase their R&D investments, they create distortions *vis à vis* non-subsidized firms and sectors, which influence the macroeconomic effects of these measures.[7]

The third problem refers to the influence of this support on the price of R&D inputs which are extremely inelastic over the short and medium terms. We could expect significant R&D policies to increase demand for R&D inputs (and especially labor which is strongly inelastic) implying an increase in R&D costs, thereby reducing the profitability of R&D investment.

Two natural questions arise from these diverse sources of externalities. The first is whether the positive externalities are higher than the negative externalities, and the second is whether these effects are of the same magnitude in relation to direct and indirect support. The first question requires empirical work; the second can draw on existing theory. Fundamentally, direct support generates more distortions than indirect support (due to the base of application of these measures). Consequently, it is more likely to generate (compared on a same amount basis) higher complementary but also more crowding-out effects than indirect support. The "crowding-out" effects of indirect support should be less important than the crowding-out effects of direct support because indirect support means that: (1) firms should invest before receiving the tax subsidies (less potential substitution effect) and (2) distortion effects between firms and industries should be low if these measures apply to all sectors/and firms (which is not the case for direct support).[8] The "complementary" effects of direct support should be more important than the complementary effects of indirect support because direct support means: (1) that firms can more easily cover the initial fixed costs of R&D (by receiving cash-in advance or sharing the cost burden), (2) that signaling effects are more important due to the selective process, and (3) greater cooperation and knowledge transfer.

2.1.2. The second side of the internal effect: the externalities between instruments

So far, we have discussed the potential individual externalities that direct and indirect support generate. Another important aspect related to the macroeconomic impact of R&D policies is taking account of the potential interaction between each instruments. In the introduction to this paper, we mentioned the numerous differences between direct and indirect support. We would expect that such differences in design and timing would create complementarity effects because direct and indirect support target different firms or at least different projects due to different incentive mechanisms. Such idea is supported by Busom et al. (2012) who show that some characteristics of firms determine their uses of each instrument. Busom et al. argue that generally tax incentives are used more by large firms or historic R&D performers, while SMEs (small and medium-sized enterprises) with financial constraint and no history of performing R&D are more likely to use R&D subsidies.

If the idea of complementarity between different instruments is rational, the idea of substituability is similarly possible. Indeed, taking into account the high administrative costs related to applying for a grant or the possibility of grant allocation bias toward top R&D performers, it is easy to see that both types of support mainly benefit large firms. Lokshin and Mohnen (2009) note that, tax credits seem more effective at increasing SMEs' investment in R&D compared to large firms' R&D investment. Thus, it is possible to that R&D policies are not complementary to increased private investment in R&D but rather are substitutes because they increase crowding-out effects. Even if we assume that both supports are not used by same firms, we can imagine that an increase in indirect support might displace the incentives to apply for a public grant, and therefore reduce the quality of grant awarded firms and the effectiveness of the policy.

2.2. On the external (out-of-the country) effect of R&D direct subsidies and fiscal incentives

In the previous subsection, we suggested some theoretical elements related to the internal effects of both types of support. Obviously, given the specificities of R&D activities, it is straightforward to consider the possibility of external effects of private R&D support. We define the external effects of R&D subsidies and tax incentives as the total macroeconomic effect that the R&D subsidies and tax incentives of other countries generate for a specific country.

[7] e.g., subsidized firms may have a higher probability of quickly and successfully commercializing innovations which may reduce the productivity expected from the R&D projects of non-subsidized firms.

[8] Of course, some of these distortions might be positive which would increase the complementary of direct support.

The traditional economic literature on fiscal competition (Tiebout, 1956; Musgrave, 1959; Oates, 1972) provides interesting elements to asses the potential external effects that fiscal incentives (and to some extent direct support) can generate. Indeed, the main conclusion of this literature is that coordination among jurisdictions in the definition of fiscal policies is desirable when they concern activities that exceed the bounds of individual jurisdictions' interests because they generate important externalities. The idea is that if governments non-cooperatively set levels of tax rates, they will not internalize the existence of externalities and will choose a non-optimal tax rate. This idea seems plausible if R&D activities are implicated. Indeed, we can envisage potential tax competition among countries to attract R&D investments and new knowledge as the result of the strategic choice of governments or fiscal optimization by private firms. These assumptions seem more likely since several indicators suggest that the organization of R&D activities is increasingly rationalized and internationalized (Kuhlmann and Meyer-Krahmer, 2001). If we assume that mobility of R&D investment although not perfect is at least possible between "neighboring" countries, then we can also assume that the level of R&D fiscal incentives in a country *i* generates a negative externality for private investment in R&D in (at least) neighboring countries. If such negative externalities exists, then non-cooperative governments are likely to choose higher tax incentives compared to the level that a social planner would choose.

Obviously, this idea of R&D competition among countries can be extended to direct subsidies, and generate inefficient levels of direct support. But, in the case where such competition effects would be marginal, we can also imagine the potential existence of complementarity rather than substituability between R&D policies implemented by different jurisdictions. Similar to internal externalities, we can suppose that direct support implemented by a government can directly benefit firms located in other jurisdictions (via grant programs based on cooperation with foreign firms) or indirectly benefit them via a second order external effect. The learning and training effects that increase subsidized firms' R&D efficiency, in turn can generate a positive external effect for the foreign firms that cooperate with subsidized firms. The same positive externalities can be generated also by indirect support measures, especially for multinational firms.

3. Empirical estimates of internal and external effects of direct and indirect support

3.1. The empirical estimates of the first side of internal effect

3.1.1. The individual effect of direct support

Before discussing the macroeconomic studies evaluating the effects of direct support on business-funded R&D, we need to introduce the notion of additionality and substitutability for this R&D policy instrument. Since direct support is accounted for in publicly financed R&D, the elasticity of business-funded R&D with respect to direct support measures directly the net effect of these measures. Consequently, a positive (negative) elasticity refers to the notion of additionality (substitutability). An absence of significance or an elasticity closer to 0 means that we have a "neutral" effect of direct support on business-funded R&D. Table 2 presents the empirical models used to estimate the impact of direct support on private investment in R&D. These evolved over time from the static (taking no account of the adjustment process related to firms' investments in R&D) to the dynamic model. Nevertheless, this important difference seems not to influence the results. Overall, the macroeconomic studies highlight one core result: there is not substitutability effect of direct support on private investment in R&D. The main difference is related to the existence of a leveraging (or additionality) effect of this policy instrument. Indeed, among the nine papers evaluating this effect, four find a neutral (or insignificant) effect, three find a leveraging effect, and two report contrasting results (depending on the country studied). Consequently, it is not obvious to decide which assumption, between neutral and leveraging effect, should be retained.

There are many elements that might explain these contrasting results. One is that the effects presented in Section 2 are not accounted for in the same manner in all studies. In Capron and Van Pottelsberghe de la Potterie's study, country data are based on aggregating sectoral data, to evaluate the extent of the sectoral distortions caused by direct support. The comparison between weighted[9] and unweighted marginal effects highlight significant negative distortions between industries due to direct support. Indeed, the unweighted effect is lower than the weighted effect for all countries studied. Another theoretical explanation is provided by David and Hall (2000) who suggest that most macroeconomic studies do not take into account the impact of direct support on the cost of R&D inputs. Goolsbee (1998) uses American data and, shows that an increase in direct subsidies has a significant effect on the salary rises of both engineers and researchers. According to Golsbee, studies that not take this price-effect into account overestimate the effect of direct support by 30–50%. Wolff and Reinthaler (2008) study carried out on a panel of 15 OECD countries between 1981 and 2002 seems to corroborate this idea. Indeed, they demonstrate that the coefficient of direct support is much larger if the dependent variable is private R&D investment rather than number of researchers[10]. In the same vein, we note that macroeconomic studies using a relative measure of direct support ((Falk, 2006) and (Montmartin, 2013)) find a neutral or insignificant effect. These last elements together with the contrasting empirical evidence provided by microeconomic studies[11] reinforces the idea that direct support does not generate leveraging effect on private investment in R&D.

3.1.2. The individual effect of indirect support

We first introduce the notion of additionality and substitutability for this R&D policy instrument. Since fiscal incentives are accounted for in privately financed R&D, the elasticity of business-funded R&D with respect to indirect support does not directly measure the net effect of fiscal incentives. Indeed, in order to assess the net effect of this policy instrument, which economists call the "bang for the buck" (BFTB), we need to take account of the cost (in terms of fiscal revenue lost to the public authority). If the BFTB is higher than 1, this means that $1 of revenue lost generates more than $1 of R&D investment, i.e, indirect support has an additionality effect on private investment in R&D. Nevertheless, measuring this net effect at the macroeconomic level has been impossible due to the unavailability of sufficient time series data on the macroeconomic cost of indirect support. Consequently, macroeconomic studies often evaluate the elasticity of private R&D investment to the user cost of R&D (which is influenced by the tax incentives). Although this elasticity is an imperfect measure of the BFTB, economists generally agree that an elasticity higher (lower) than 1 gives a positive (negative) indication concerning the capacity of indirect support to generate an additionality effect on private investment in R&D.

There are few empirical studies that evaluate the macroeconomic effect of indirect support on the private investment in R&D.

[9] After estimating the marginal effects for each industry, they weight these effects using the direct national subsidies allocated to each industry. Thus, for each country, we obtain the weighted average of the marginal effects of each industry.

[10] Lokshin and Mohnen (2013) using microeconomic data show a price-effect of tax incentives.

[11] According to Capron and Van Pottelsberghe de la Potterie (1997) and David and Hall (2000) half of microeconomic studies reviewed report additionality effect of direct support and half report a substitutability effect.

Table 2
Empirical review.

Author(s)/year	Dimension of data	Econometric model and estimator	Short-term elasticity (*marginal effect) to direct support (Long-term)	Short-term elasticity to indirect support (Long-term)	Internal complementarity of financial support	External complementarity of financial support	Other significant variables
Levy and Terleckyj (1983)	US aggregate time series (1949–1981)	Static model GLS estimator	*Strongly significant	No studied	No studied	No studied	Not indicated
Lichtenberg (1987)	US aggregate time series (1956–1983)	Static model GLS estimator	[0.045; 0.122]	No studied	No studied	No studied	Not indicated
Levy (1990)	9 OECD countries (1963–1984)	Static model FGLS estimator	*Negative for 2 countries and positive for 5 countries (1)	No studied	No studied	No studied	Not indicated
Capron and Van Pottelsberghe de la Potterie (1997)	7 OECD countries (1973–1990)	AR(1) model IV estimator (2SLS)	*Negative for 3 countries and positive for 1 country	No studied	No studied	No studied	Total sales (+)
Bloom et al. (2002)	9 OECD countries (1979–1997)	AR(1) model IV estimator (2SLS)	No studied	−0.144* (−1.08*)	No studied	No studied	No other variables are significant
Guellec and Van Pottelsberghe de la Potterie (2003)	17 OECD countries (1983–1996)	First difference AR(1) model IV estimator (3SLS)	0.072* (0.078*)	−0.281* (−0.306*)	Direct support is substitute to indirect support	No studied	Valued added (+), Public R&D (except Higher education (−))
Falk (2006)	21 OECD countries (1975–2002), five year average, unbalanced panel	First difference AR(1) model GMM estimators	0.03 (0.13)	−0.24* (−1.04*)	No studied	No studied	Public R&D (Higher education only (+)), patent protection (+)
Shin (2006)	Korea aggregate time series (1982–2002)	AR(1) model GMM estimators	0.111* (0.134*)	−0.271* (−0.899*)	No studied	No studied	Real interest rate (−), GDP (+), public R&D (+)
Wolff and Reinthaler (2008)	15 OECD countries (1981–2004), unbalanced	AR(1) model CLSDV estimator	0.22 (3.14)	No studied	No studied	No studied	No other variables are significant
Wilson (2009)	51 US states (1981–2004)	AR(1) model LSDV and CLSDV estimator	No studied	−1.41* (−2.34*)	No studied	Tax credit of state i is substitute to tax credit of other state $j \neq i$ at the country level	State GDP (+), Federal R&D (−), National GDP (−).
Montmartin (2013)	25 OECD countries (1990–2007), unbalanced	AR(1) model CLSDV estimator	−0.07 (−0.805)	0.114* (−1.31*)	Direct support is substitute to indirect support	No significant impact of direct and indirect support of country $j \neq i$ on country i.	Interest rate (−)

Notes: (1) The estimates reported for Levy (1990) are taken from Capron (1992).
* Significance is at least at 10%.

Table 3
Definition of variables.

Variable name	Definition of the variable	Data source
Dirdefi	R&D expenditures funded by the private sector as a percentage of GDP.	OECD
Interetlt	Long-term nominal interest rate in percentage point.	IMF
Dirdpub	R&D expenditures executed by the public sector as a percentage of GDP.	OECD
Sub	Corresponds to the ratio of Government funded expenditures on R&D in the business sector divided by business expenditures in R&D (BERD) private sector.	OECD
Bindex	B-index for the large company group.	Thomson (2009) OECD

This is obviously because these instruments are more recent than R&D subsidies – no significant fiscal measures were implemented before the 1980s. On the whole, macroeconomic studies evaluating the effect of indirect support provide more controversial results than those evaluating direct support. All studies show that indirect support significantly influences private investment in R&D,[12] and the estimated elasticities are relatively heterogeneous. Based on our survey, four of the six macroeconomic studies considered, report long-run elasticity of privateR&D with respect to indirect support higher than 1, suggesting an additionality effect. Note however that in two cases the elasticity is very close to 1 (and not always significant). The other two studies report different results. The study by Shin (2006) on Korea reports a long-run elasticity slightly lower than 1, while the study by Guellec and Van Pottelsberghe de la Potterie (2003) reports a long-run elasticity much lower than 1. We think this latter result might be partially explained by the specification and estimation methods used. Indeed, Guellec and Van Pottelsberghe de la Potterie (2003) is the only paper to use a non-GMM (Generalized Method of Moments) estimator on a first-difference AR(1) model. GMM estimators may not be the best estimators when the sample size ratio N/T tends to 1 and the persistence of R&D data over time suggest the need to work on first-difference. Given the problems related to measurement of tax incentives at the macroeconomic level and the heterogeneity

[12] Which is not surprising in the sense that, as already mentioned, the effect of tax incentives is entirely accounted for in private R&D investment (in contrast, only substituability or additionality effects are accounted for in direct support).

of empirical results, it is difficult to draw conclusions about the capacity of indirect support to generate a leverage effect on private investment in R&D.

3.2. The empirical estimates of the second side of internal effect and external effects

Although these concepts are not new in the theoretical literature, they have received very little attention in empirical studies. These effects are of prime importance to assess the net efficiency of financial support for private R&D at the macroeconomic level.

Table 2 shows that only two papers try to measure the presence of internal complementarity between instruments at the macroeconomic level. Both study OECD countries in different time periods and conclude that within a jurisdiction (here a country), direct and indirect support are substitutes stimulating private investment in R&D. In other words, it appears that if a country raises the level of indirect support, it decreases the incentive effects of direct support and vice-versa. This very interesting fact for countries using both instruments has very little theoretical foundation so far. Some elements (already discussed) can be advanced to explain such inter-effects but do not constitute a satisfactory rationales for their existence.

Concerning the external effects of R&D policies, only two papers provide interesting results. The first, from Wilson (2009), evaluates the sensitivity of firms' R&D investment located in one American state, to in-state and out-of-state tax credits (from neighboring states). His results show that if firms react positively to in-state tax credit, they also react negatively to the out-of state tax credits. More precisely, this reaction is estimated to be of the same magnitude, implying a zero effect of these "local" tax credits at the macroeconomic level. Using OECD country data, Montmartin (2013) reports an absence of influence of out-of-country financial support on private R&D investment in the focal country. This suggests that out-of-country policies do not influence the effects of the in-country financial support for private R&D. Consequently, the author concludes that there is an absence of a significant external effect of financial support at country level. Note that, these two conflicting results are obtained at different geographical levels. Therefore, they may suggest that the existence of an external complementarity or substituability depends on the geographical unit retained. A simple explanation might be the geographical limits to firms' capacity to react to R&D incentives.

4. Dynamic panel data models

The empirical R&D literature focuses on a set of dynamic panel data models. In this section we present the models that we run for our empirical estimates, from a dynamic model to a general dynamic spatial model. We use i to denote the spatial unit (in our case, country) and n to denote the total number of countries ($i=1, 2, \ldots, n$). The time unit t and T, denotes the total number of observations in the temporal dimension ($t=1, 2, \ldots, T$). We consider a dynamic panel data model in vector form for the spatial units at time t:

$$y_t = \tau y_{t-1} + x_t\beta + \mu + \eta_t \iota_n + \varepsilon_t, \tag{1}$$

with $\varepsilon_t \sim \mathcal{N}(0, \sigma_\varepsilon^2 I_n)$ and $\mu' = [\mu_1, \mu_2, \ldots, \mu_n]$, ι_n a $(n \times 1)$ vector and:

$$y_t = \begin{bmatrix} y_{1t} \\ y_{2t} \\ y_{3t} \\ \vdots \\ y_{nt} \end{bmatrix}; \quad x_t = \begin{bmatrix} 1 & x_{21t} & \cdots & x_{k1t} \\ 1 & x_{22t} & \cdots & x_{k2t} \\ 1 & x_{23t} & \cdots & x_{k3t} \\ \vdots & \vdots & \ldots & \vdots \\ 1 & x_{2nt} & \cdots & x_{knt} \end{bmatrix}; \beta = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \vdots \\ \beta_k \end{bmatrix},$$

where y_{t-1} vector is the temporally lagged dependent variable which captures the inertia present in the time series. Model (1) captures cross-section (or spatial) heterogeneity among countries, μ_i ($i=1, 2, \ldots, n$), and time-period heterogeneity η_t. The spatial-specific effects can be treated as fixed effects or random effects. In the fixed effects model, a dummy variable is introduced for each spatial unit, in the random effects model, μ_i is treated as a random variable i.i.d. with zero mean and variance σ_μ^2. Following the spatial literature, we take this individual effect as fixed effects in all models (for more details of the discussion on these methods in spatial panel data, see Elhorst, 2012).

The panel data literature extensively discusses this model compared to its static version, i.e, when $\tau=0$ (see Hsiao, 2003; Baltagi, 2005). Estimation of the fixed effects in static panel model is based on eliminating the intercept β_1 and the dummy variable μ_i from the regression equation (called *demeaning* procedure). The slope coefficient β (without the intercept) in the demeaning equation can be estimated by OLS, and it is known as the Least Square Dummy Variable (LSDV) estimator. Thereafter, the intercept β_1 and dummy variables μ_i can be recovered (Baltagi, 2005). However, when $\tau \neq 0$ we introduce a temporally lagged dependent variable into the model, the OLS estimator of the slope coefficients in the demeaned equation is inconsistent if T is fixed, regardless of the size of n. The problem with the demeaning technique, known as *Nickell's bias*, is that it creates a correlation of order $(1/T)$ between the demeaned lagged variable, y_{it-1} (after the demeaning), and the demeaned error term (Nickell, 1981; Hsiao, 2003).

The econometric literature has developed a number of consistent estimators which use methods with instrumental variables (Anderson and Hsiao, 1982) and GMM (Arellano and Bond, 1991; Arellano and Bover, 1995; Blundell and Bond, 1998). The instrumental variables estimator suggested by Anderson and Hsiao (1982) estimates a model in first differences and uses as instrument the dependent variable lagged by two periods. We can distinguish between two types of GMM estimator for the dynamic panel data model, i.e, the first differences GMM estimator and the system GMM estimator. The first one procedure uses lagged variables in level as instruments, whereas the second procedure uses a system of equations in both first differences and level.

Another procedure that can be used to estimate a dynamic panel data model is to bias-correct the LSDV estimator, obtaining the corrected least square dummy variable, CLSDV (Kiviet, 1995; Kiviet, 1999; Bun and Kiviet, 2003). The advantage of this method is twofold, on the one hand the LSDV estimator often has smaller variance than others, and on the other hand, correcting the LSDV estimator's bias allows us to provide a consistent estimation for all panel sizes. Elhorst (2008) shows that the CLSDV estimator of τ and β can be obtained by maximizing the log-likelihood function of the model, conditional upon the first observation, with respect to τ, β and σ_ε^2.

Other alternative methods apply an ML procedure based on the unconditional likelihood function of the model (Hsiao et al., 2002). Regression models that include temporally lagged variables are often estimated conditional upon the first observations. However, if the data generating process is stationary, the initial values provide an important information about this process (Nerlove, 1999). Then, taking into account the density function of the first observation of each time-series, the unconditional likelihood function is obtained.

So far, we have discussed two of the problems inherent in modeling panel data: temporal dependence (through consideration of serially lagged dependent variable), and the unobservable cross-section effects (through fixed effects). However, we need also to include the spatial dependence among countries at each temporal point. This dependence can be introduced into model (1) obtaining

Table 4
Summary statistics (pooled).

Variable	Obs.	Mean	Std. dev.	Min.	Max.
Dirdefi (% GDP)	500	0.96	0.66	0.004	2.96
Interetlt	500	7.95	6.73	1.00	66.94
Dirdpub (% GDP)	500	0.67	0.25	0.016	1.34
Sub (% BERD)	500	8.28	7.92	0.053	94.40
Bindex	500	0.94	0.11	0.57	1.08

the so-called dynamic spatial panel data models. We focus on the dynamic spatial Durbin model (*dynSDM*) defined by:

$$y_t = \tau y_{t-1} + \rho W y_t + x_t \beta + W x_t \theta + \mu + \eta_t \iota_n + \varepsilon_t. \quad (2)$$

with $\varepsilon_t \sim \mathcal{N}(0, \sigma_\varepsilon^2 I_n)$. The parameter ρ captures the contemporaneous spatial dependence of the endogenous variable. The term W is the spatial weight matrix. The spatial weight is an $n \times n$ positive matrix, pre-specified by the researcher, and describes the arrangement of the cross-sectional units in the sample (Anselin, 1988). The elements of W, w_{ij}, are non-zero when i and j are hypothesized to be neighbors, and zero otherwise. By convention, the diagonal elements w_{ii} are equal to zero, i.e., the self-neighbor relation is excluded. Wx_t represents the spatial lagged explanatory variables. Also, the inclusion of time lagged variable with the spatial endogenous variable, Wy_t, generates the possibility of spatial effects in short-run and long-run.

To estimate dynamic panel data with spatial interactions, there are different alternatives that extend the conditional or unconditional Maximum Likelihood procedures. Yu et al. (2008) consider the log-likelihood function, taking account of the endogeneity of the Wy_t in the Jacobian term. The estimator that is derived from this log-likelihood function is called the Quasi Maximum Likelihood (QML); 'quasi' refers to the fact that the error terms are not assumed to be normally distributed. Yu et al. (2008) show that the QML estimator is biased and propose a bias-corrected QML. Alternatively, Elhorst (2010) suggests a different procedure, ML-based estimators taking account of the initial condition. The ML estimator has a similar performance of bias-corrected QML in terms of bias and root mean squared error when T is equal to or greater than 15.

Some empirical studies that introduce spatial weights use point estimates of one or more spatial models to test the hypothesis about the importance of spillover effects. However, LeSage and Pace (2009) point out that this could lead to erroneous conclusions, and it is necessary to take into account the partial derivative of the impact from changes to the explanatory variables to interpret correctly the different model specifications.

The relevance of spatial spillovers comes from the presence of Wy as an explanatory variable. Under a cross-section Durbin model, $y = \rho W y + x\beta + W x\theta + \varepsilon$, the matrix of partial derivatives of y with respect to the $k-th$ explanatory variable of x in unit 1 up to unit n can be represented as:

$$\begin{bmatrix} \frac{\partial y}{\partial x_{1k}} & \cdots & \frac{\partial y}{\partial x_{nk}} \end{bmatrix} = \begin{bmatrix} \frac{\partial y_1}{\partial x_{1k}} & \cdots & \frac{\partial y_1}{\partial x_{nk}} \\ \vdots & \ddots & \vdots \\ \frac{\partial y_n}{\partial x_{1k}} & \cdots & \frac{\partial y_n}{\partial x_{nk}} \end{bmatrix},$$

$$= (I_n - \rho W)^{-1} \begin{bmatrix} \beta_k & w_{12}\theta_k & \cdots & w_{1n}\theta_k \\ w_{21}\theta_k & \beta_k & \cdots & w_{2n}\theta_k \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1}\theta_k & w_{n2}\theta_k & \cdots & \beta_k \end{bmatrix},$$

$$= (I_n - \rho W)^{-1} \left[\beta_k I_n + \theta_k W \right], \quad (3)$$

where w_{ij} is the $(i, j) - th$ element of W, β_k is the $k-th$ element of the vector β, and θ_k is the $k-th$ element of the vector θ.

The expression in (3) is the total effect and it can be broken down into direct and indirect effects. The*direct effect* captures the effect in own country of the unit change in explanatory variable. Since this effect is particular to each country, LeSage and Pace (2009) propose to report this effect by the average of the diagonal elements of the matrix of partial derivatives. The *indirect effect*, known as spatial spillover, is reported as the average of the row sums of non-diagonal elements of the expression (3). The significance of these effects can be obtained using Monte Carlo simulation of shocks in the error term.

The direct and indirect effects can be easily extended to dynamic panel data. The advantage of using a temporal dynamic is that we can obtain the direct and indirect spatial effects in the short- and long-runs. To obtain the short-run effects we ignore τ. The matrix of partial derivatives of y with respect to the $k-th$ explanatory variable of x in unit 1 up to unit n at a particular point in time can be seen as:

$$\begin{bmatrix} \frac{\partial y}{\partial x_{1k}} & \cdots & \frac{\partial y}{\partial x_{nk}} \end{bmatrix}_t = (I_n - \rho W)^{-1} [\beta_k I_n + \theta_k W]. \quad (4)$$

To obtain the long-run effects we assume that $y_t = y_{t-1} = y^*$:

$$\begin{bmatrix} \frac{\partial y}{\partial x_{1k}} & \cdots & \frac{\partial y}{\partial x_{nk}} \end{bmatrix}_t = [(1-\tau) I_n - \rho W]^{-1} [\beta_k I_n + \theta_k W]. \quad (5)$$

The results reported in (4) and (5) can be used to determine *short-run and long-run direct effects*, and *short-run and long-run indirect effects* (spatial spillover). For more details see Elhorst (2014).

5. Empirical methodology

5.1. Data and descriptive statistics

The dataset includes information on 25 OECD countries[13] over a time period of 20 years from 1990 to 2009, yielding a total of 500 observations (see Tables 4 and 5 for details). The data are mostly from the OECD and the IMF, apart from the B-index which was gathered from Thomson (2009) paper which proposes B-index values for 25 OECD countries. The B-index is a well-known general measure of countries' R&D tax generosity. Detailed information on this indicator and its limitations can be found in Warda (1997, 2005) and (Thomson, 2009, 2012). We use two OECD datasets to construct the spatial weights. STAN provides information on bilateral trade (aggregation of all industry sectors) for four years: 1995, 2000, 2005, and 2008. REGPAT provides data on collaborations, based on international patent applications (Patent Cooperation Treaty, PCT); in this case, we have annual data for the whole study period (Table 3).

[13] Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Korea, Germany, Finland, France, Greece, Hungary, Ireland, Italy, Japan, Mexico, Norway, New-Zealand, Netherlands, Poland, Portugal, Spain, United Kingdom, United-States and Sweden

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Table 5
Summary statistics. Evolution over time.

Variable	1990–1993	1994–1997	1998–2001	2002–2005	2006–2009
Dirdefi (% GDP)	0.83	0.87	0.97	1.02	1.11
Interetlt	13.28	10.41	6.79	4.69	4.57
Dirdpub (% GDP)	0.59	0.63	0.66	0.71	0.76
Sub (% BERD)	10.01	9.25	7.42	7.01	6.91
Bindex	0.98	0.97	0.96	0.91	0.88

Since our panel data contains about 6% of missing observations, we have an unbalanced data set. Normally, missing values are not a problem for panel data estimations using traditional techniques but spatial econometrics need balanced panel data in order to take into account the spatial dependence at each point of time. Spatial econometrics assumes a connected matrix between all cross-section units, and missing data for any year means that this condition in not satisfied. A strategy to avoid this problem is to use a multiple imputation technique (Rubin, 1987) and to replace the missing values by multiple sets of plausible values. We apply this technique to obtain a full balanced set of panel data.[14] Table 4 presents the basic statistics after multiple imputation.

Table 4 shows that average business-funded R&D intensity (*Dirdefi*) equals 0.96% with a maximum of 2.93% for Sweden in 2001, and a minimum of 0.04% for Mexico in 1990. R&D expenditure by the public sector in terms of GDP (*Dirdpub*) reaches 0.67% on average with a maximum of 1.34% for Sweden in 2009 and 0.01% for Mexico in 1990.

Table 5 shows the evolution of variables defined above using the four-year averages. Growth of business-funded R&D intensity reaches a maximum in 2006–2009. Direct subsidy rate is measured as government funded expenditure on R&D in the business sector as a percentage of business expenditure in R&D (BERD). It is decreasing over the whole period from 10% to reach a minimum value of 6.9% in the period 2006–2009. On the contrary, the fiscal subsidy rate measured by 1 minus the B-index is increasing over the whole period from 2%(1–0.98) to reach a maximum value of 12% in the period 2006–2009.

In order to properly specify the models described in Section 3, we begin with a pre-estimation analysis of the data. Table 6 shows the common tests for unit roots in heterogeneous panel data. As we can see, nearly all series (using logarithm transformation) are integrated of order 1. An exception is *Dirdpub* where the IPS and ADF tests reject the null hypothesis of unit root but Pesaran (2007) CADF test cannot reject that the series has a unit root. As a consequence, the variables of our panel data models are the first differences of the logarithm, i.e, the results are explained in terms of growth rate.[15]

5.2. *Dynamic panel models without spatial effects*

Table 7 presents the estimations of non-spatial dynamic panel models using two potential unbiased types of estimator (GMM and CLSDV). These two estimators provide estimated values for the time lag coefficient (τ) which are in the bounds of the true value of τ[16] (given by OLS and LSDV estimates, for further details see Bond, 2002). Nevertheless, due to the size of our sample, the asymptotic properties of the estimators, the time lag estimates and the strict exogeneity of our explanatory variables (see Endogeneity tests presented in Appendix Table A.3), we are more confident about the CLSDV results (Judson and Owen, 1999).

5.2.1. *The basic model*

Based on the preceding sections, we model the core relationship between private R&D intensity and the explanatory variables as:

$$\triangle ldirdefi_{i,t} = \tau\triangle ldirdefi_{i,t-1} + \beta_2\triangle interetlt_{i,t} + \beta_3\triangle lsub_{i,t} + \beta_4\triangle ldirdpub_{i,t-1} + \beta_5\triangle lbindex_{i,t-1} + \mu_i + \eta_t + \epsilon_{i,t}, \quad (6)$$

where $\triangle$ denotes first differences and l is the logarithm. This is the first model estimated in this paper (see MODEL 1 in Table 7). The other models estimated are sophistications of this functional relationship derived by including non-linear effects and/or crossed-variables (see MODELs 2 and 3 in Table 7).

The first two columns in Table 7 present the estimations of the basic specification. They highlight the fact that (the growth rate of) private R&D intensity appears relatively persistent over time. Indeed, the speed at which the growth rate of private R&D intensity adjusts to changes is estimated at around 57− 58 % which implies that the long-run[17] effect of exogenous variables should be slightly less than twice their short run-effect.

We first concentrate on the impact of the “macroeconomic environment variables” which are nominal long term interest rate and public R&D intensity. The nominal interest rate negatively affects private R&D intensity. The estimated coefficient implies that an increase of 100 bp in the nominal interest rate reduces the growth of private R&D intensity by approximately 1pp in the long-run implying a long-run elasticity of about −1. This indicates that the private R&D intensity is strongly influenced by the macroeconomic financial conditions. The second macroeconomic environment variable is public R&D investment in terms of GDP. The relationship between public and private R&D has been extensively discussed by the economic literature, see David et al. (2000) and David and Hall (2000) for a review. Using a time lag in order to account for intertemporal knowledge spillovers between public and private R&D, our results show a significant positive effect of public R&D intensity. The long-run elasticity of public R&D intensity to private R&D intensity is estimated at around 0.43. This result highlights strong positive inter-temporal knowledge externalities between both R&D sectors. This last result is in line with Guellec and Van Pottelsberghe de la Potterie (2003).

Returning to our core interest, i.e, the effect of R&D policy variables, all public policy variables affect private R&D intensity significantly. An important point of the estimation in Table 7 is the suggestion of a clearly opposite effect between direct and indirect support. Indeed, while an increase in direct support negatively influences private R&D intensity, the effect is reversed for indirect support. More precisely, the long-run elasticity of private R&D intensity to direct support is estimated at around −0.08. In other words, if the direct subsidy rate increases by 1%, then the private R&D intensity decreases by 0.08% in the long-run. This result

[14] We assume an autoregressive process for each country separately, i.e, the missing values are dependent on the values in the dataset (NMAR, not missing randomly).
[15] Additionally, we conduct the cointegration test proposed by Westerlund (2007) using the set of variables in Table 6. The results presented in Appendix Table A.1 suggest that we cannot reject the null hypothesis of no cointegration.
[16] OLS and LSDV estimates are reported in Table A.2 in the Appendix with different robustness checks.
[17] Long-run effects are calculated as the ratio between short-run effects (i.e., estimated β−coefficients) and the 1 minus estimated τ−coefficient.

Table 6
Unit root test to variables in logarithm.

Method		$H_0: I(1)$ $H_1: I(0)$		$H_0: I(2)$ $H_1: I(1)$		Conclusion
Unit root specific for each country		Statistic	p-value	Statistic	p-value	
	IPS W-stat	−1.16	0.13	−7.06	0.00	$I(1)$
Dirdefi (% GPD)	ADF: Fischer χ^2	0.17	0.43	4.79	0.00	$I(1)$
	Pesaran's CADF test	2.86	0.99	−1.92	0.03	$I(1)$
	IPS W-stat	1.52	0.93	−9.32	0.00	$I(1)$
Interetl	ADF: Fischer χ^2	−0.54	0.71	7.09	0.00	$I(1)$
	Pesaran's CADF test	−0.71	0.24	−3.93	0.00	$I(1)$
	IPS W-stat	−3.44	0.00	–	–	$I(0)$
Dirdpub (% GDP)	ADF: Fischer χ^2	9.63	0.00	–	–	$I(0)$
	Pesaran's CADF test	0.12	0.55	−4.89	0.00	$I(1)$
	IPS W-stat	−1.18	0.12	−11.90	0.00	$I(1)$
Sub (% BERD)	ADF: Fischer χ^2	−0.78	0.78	4.01	0.00	$I(1)$
	Pesaran's CADF test	0.89	0.81	−4.70	0.00	$I(1)$
	IPS W-stat	0.59	0.72	−12.97	0.00	$I(1)$
Bindex	ADF: Fischer χ^2	−1.52	0.94	3.30	0.00	$I(1)$
	Pesaran's CADF test	−0.89	0.19	−5.43	0.00	$I(1)$

Notes: IPS (Im, Pesaran and Shin,2003). For Pesaran (2007) test we report the standardized Z-tbar statistic and its p-value. The tests to $H_0: I(1)$ included a constant and trend. The tests to $H_0: I(2)$ included a constant.

Table 7
Dynamic panel models without spatial effects.

Variable	Model 1		Model 2		Model 3	
	GMM	CLSDV	GMM	CLSDV	GMM	CLSDV
$\Delta ldirdefi_{-1}$	0.379^{***}	0.434^{***}	0.373^{***}	0.429^{***}	0.366^{***}	0.419^{***}
$\Delta interetlt$	-0.008^{***}	-0.005^{**}	-0.008^{***}	-0.006^{**}	-0.009^{***}	-0.008^{***}
$\Delta lsub$	-0.042^{***}	-0.045^{***}	-0.034^{***}	-0.037^{***}		
$\Delta lsub \times sub$					-1.009^{***}	-1.000^{***}
$\Delta lsub \times sub^2$					3.966^{***}	3.787^{***}
$\Delta ldirpub_{-1}$	0.317^{***}	0.245^{***}	0.310^{***}	0.237^{***}	0.288^{***}	0.233^{***}
$\Delta lbindex_{-1}$	-0.196^{***}	-0.198^{***}	-0.251^{***}	-0.248^{***}		
$\Delta lbindex_{-1} \times lbindex$					-3.765^{***}	-3.176^{***}
$\Delta lbindex_{-1} \times lbindex^2$					4.623^{***}	3.819^{***}
$\Delta interact$			0.589^{***}	0.581^{***}	1.097^{***}	1.020^{***}
constant	-0.038^{**}		-0.039^{**}		-0.033^{**}	

Notes: *, ** and *** denotes significance at 10%, 5% and 1%. Dep. variable is log Dirdefi %GDP (first difference). Terms Δ and l denotes first diff. and log. All tests are based on robust std. errors. Time effects are included but not reported.

highlights a slight crowding-out effect of direct support on private R&D intensity. Concerning indirect support, the long-run elasticity of private R&D intensity to the B-index is estimated at around −0.32. That is, if the B-index decreases by 1% (which translates into an increase of fiscal incentives), then private R&D intensity will increase by 0.35% in the long-run. This result clearly highlights a positive effect of indirect support on the private R&D intensity. Nevertheless, this positive effect does not mean that fiscal incentives generate a leveraging effect because we cannot evaluate the marginal effect of fiscal incentives using the B-index.

Our results concerning indirect support are in line with those in Guellec and Van Pottelsberghe de la Potterie (2003), and, in some sense, with those obtained by Falk (2006). However, our results for direct support contrast with the existing literature (which highlights either a significant positive effect or a neutral effect). This difference is mainly explained by the relative measure of direct support used in this paper. As Goolsbee (1998) and Wolff and Reinthaler (2008) point out, it is necessary in macroeconomic studies to use a relative measure for direct support in order to control for the price-effect on R&D inputs which seems to be very important and causes an upward skew in estimations of the coefficient of direct support. This idea is reinforced when we analyze the specification and variables used in previous studies. Guellec and Van Pottelsberghe de la Potterie (2003) explain the amount of private R&D by the amount of direct support and find a strong positive effect of direct support. Falk (2006) explains private R&D intensity by "direct subsidy intensity" (amount of direct support/GDP) and finds a neutral effect of direct support. Thus, our negative effect could be simply due to the fact that unlike Falk (2006), we use different relative measures for private R&D (private R&D intensity) and for direct support (amount of direct support/ amount of private R&D executed) which is likely to take better account of the aforementioned price-effect.

5.2.2. Externalities between direct and indirect support and non-linear effects

An important question for public authorities that rely on a combination of direct and indirect support, is related to their complementarity for increasing private investment in R&D. The results in Guellec and Van Pottelsberghe de la Potterie (2003) show that direct and indirect measures substitute for each other since it appears that an increase in either direct or indirect measures diminishes the positive effect of the other upon private investment in R&D. In order to investigate this further, we extend the Model 1 by integrating a crossed variable of both direct and indirect support which we call *interact* ($\Delta lbindex_{-1} \times \Delta lsub$). The estimation results are presented in the columns 3 and 4 in Table 7. They confirm the results in Guellec and Van Pottelsberghe de la Potterie (2003) and show that direct and indirect support are substitutes for boosting the intensity of private R&D. In our case, however,

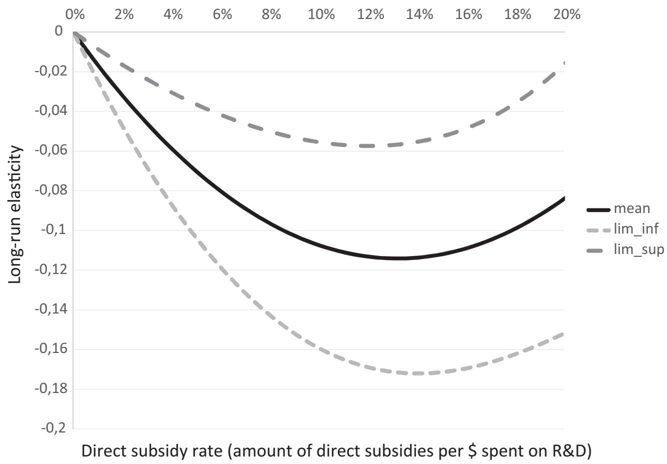

Fig. 1. Estimated long-run effect of direct subsidies on private R&D intensity.

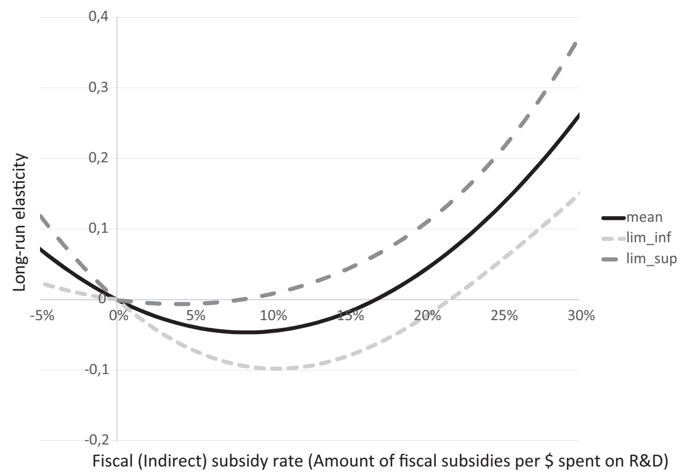

Fig. 2. Estimated long-run effect of fiscal incentives on private R&D intensity.

the estimated coefficient of direct support is negative (whereas it is positive in Guellec and Van Pottelsberghe de la Potterie, 2003). Hence, an increase in the dynamic of fiscal subsidization implies that the windfall effect of direct support will also increase and that an increase in direct support will reduce the positive effect of indirect support.

So far, we have only considered the possibility of a linear effect between private R&D intensity and R&D public support. It might be that the capacity of each policy to increase private R&D intensity is non-linear with its level of use, i.e, the rate of subsidy. We therefore test the following relationships:

$$\beta_{\Delta lsub} = \delta_1 sub + \delta_2 sub^2,$$
$$\beta_{\Delta lbindex_1} = \theta_1 bindex + \theta_2 bindex^2.$$

The last two columns in Table 7 report GMM and CLSDV estimates of the Model 2 with non-linear effect of both direct and indirect support. All the policy variables are strongly significant and validate our assumption about non-linear effect of public support for R&D and the presence of spillovers between direct and indirect support.

Concerning R&D subsidies, our results clearly highlight the existence of a convex relationship between private R&D elasticity with respect to direct support and the direct subsidy rate.

Fig. 1 reports (for the 90% central values of observed subsidy rate) the long-run elasticity of private R&D intensity with respect to direct support according to the level of the direct subsidy rate. This figure is based on the estimates of Model 3 CLSDV in Table 7 using the delta method (with second order Taylor expansion) to construct confidence intervals. Our results suggest that, on average, elasticity decreases with the direct subsidy rate up to a threshold of 13%, then increases with the subsidy rate and becomes positive above a threshold of approximately 26%. However, the empirical distribution of the subsidy rate is concentrated at between 1.38% (p5) and 17.03% (p95), suggesting that for all OECD countries, R&D subsidies generate a partial crowding-out effect on business-funded R&D intensity (see Fig. 1). Indeed, the direct subsidy rate is higher than 26% only for Poland (1990–2001) and Mexico (1996 and 1997).

In relation to indirect support, our results show the existence of a convex relationship between private R&D elasticity with respect to indirect support, and the B-index value. In order to simplify reading and comparison of our results, we present the non-linear effect of indirect support according to the fiscal subsidy rate (1 minus the B-index is a measure of the fiscal subsidy rate)[18].

Fig. 2 reports for the 90% central values of observed subsidy rate) the long-run elasticity of private R&D intensity with respect to indirect support, according to the level of the fiscal subsidy rate. It shows that, on average, elasticity decreases with the fiscal subsidy rate, up to a threshold of 10%, then increases with the fiscal subsidy rate and becomes positive above a threshold of approximately 17%. For low fiscal subsidy rates (high values of the B-index), elasticity is negative, highlighting a negative effect of fiscal incentives on business-funded R&D. We can see that, on average, fiscal incentives generate a positive effect on business-funded R&D if the indirect subsidy rate is higher than 17%. The empirical distribution of the fiscal subsidy rate is concentrated between −5% (p5) and 30% (p95), suggesting that some OECD countries with high fiscal subsidy rates seem to benefit from their policies, while for the other countries[19] the effect seems to be slightly negative. It should be noted however that countries applying the less generous fiscal systems for R&D do not seem to be penalized and are even in a better situation than countries with small fiscal subsidy rates. From a global perspective, it seems that for most OECD countries, fiscal incentives have a relatively low influence on the business-funded R&D intensity. However, the recent tendency of OECD countries to significantly increase fiscal incentives could change the overall impact of these policies in the future quite significantly.

5.3. The introduction of spatial effects

A problem with the results presented so far is that they implicitly assume that a country's R&D investment is influenced only by its own policy mix. Given the nature of knowledge creating activities and the growing internationalization of R&D activities, we might assume that the private R&D intensity of a country i could be impacted by the private R&D intensity of its neighbors and their R&D policy incentives. The presence of cross-section dependence in the residuals obtained from previous estimations (see Table A.4 in the Appendix) indicate this possibility and justify to use alternative estimation methods to take into account the dependence existing between countries.

[18] We again use Model 3 CLSDV in Table 7 and the delta method (with second order Taylor expansion) to obtain the long-run elasticity of private R&D investment with respect to the B-index denoted β^*. Multiplying β^* by $-(1-B)/B$, we obtain the elasticity of private R&D investment with respect to the fiscal subsidy rate that is presented in Fig. 2

[19] which represents the majority of OECD countries because only seven countries has experienced fiscal subsidy rates higher than 17%: Canada, Czech Republic, Hungary, France, Mexico, Spain and Portugal.

Table 8
Dynamic spatial durbin models.

Variable	*dynSDM*1		*dynSDM*2		*dynSDM* 3	
	W (trade)	W (patent)	W (trade)	W (patent)	W (trade)	W (patent)
Main effects						
$\Delta ldirdefi_{-1}$	0.372^{***}	0.371^{***}	0.367^{***}	0.363^{***}	0.359^{***}	0.349^{***}
$\Delta interetlt$	-0.005^{***}	-0.005^{***}	-0.005^{***}	-0.005^{***}	-0.007^{***}	-0.007^{***}
$\Delta lsub$	-0.044^{***}	-0.044^{***}	-0.036^{***}	-0.036^{***}		
$\Delta lsub \times sub$					-1.029^{***}	-0.974^{***}
$\Delta lsub \times sub^2$					3.862^{***}	3.662^{***}
$\Delta ldirpub_{-1}$	0.256^{*}	0.258^{**}	0.247^{*}	0.248^{**}	0.241^{*}	0.241^{*}
$\Delta lbindex_{-1}$	-0.193^{***}	-0.198^{***}	-0.247^{***}	-0.260^{***}		
$\Delta lbindex_{-1} \times bindex$					-3.286^{***}	-3.214^{***}
$\Delta lbindex_{-1} \times bindex^2$					3.958^{***}	3.843^{***}
$\Delta interact$			0.608^{***}	0.584^{***}	1.066^{***}	1.060^{***}
Spatial effects						
$W\Delta ldirdefi$	0.139^{**}	0.321^{**}	0.161^{**}	0.323^{**}	0.147^{**}	0.272^{**}
$W\Delta interetlt$	0.014^{*}	-0.038^{**}	0.013^{*}	-0.043^{**}	0.011^{*}	-0.044^{**}
$W\Delta lsub$	0.006	0.063	0.017	0.077		
$W\Delta lsub \times sub$					0.140	−0.108
$W\Delta lsub \times sub^2$					−0.698	21.729
$W\Delta ldirpub_{-1}$	−0.047	0.150	−0.042	0.086	−0.052	0.072
$W\Delta lbindex_{-1}$	−0.027	−0.091	−0.116	1.047^{*}		
$W\Delta lbindex_{-1} \times bindex$					−2.939	−0.348
$W\Delta lbindex_{-1} \times bindex^2$					3.556	2.053
$W\Delta interact$			0.589	15.427^{***}	1.221	15.239^{***}
AIC	−1049	−1050	−1046	−1055	−1044	−1055
BIC	−954	−955	−931	−940	−887	−899

Notes: *, ** and *** denotes significance at 10%, 5% and 1%. Dependent variable is log Dirdefi %GDP (in first difference). Terms Δ and l denotes first diff. and log. All tests are based on robust std. errors. Time effects are included but not reported. *AIC*: Akaike's inf. crit.

The cross-section dependence is introduced via a spatial weighting matrix, W, as a convenient way to describe the underlying structure that generates links between units of analysis. The elements of W measures the strength of the relationships between any pair of countries. There are different alternatives criteria to define the spatial weights. In our case we try to capture the economic distance so that space should not be understood literally.

Generally, the selection of W is an a priori for the researcher. Geographical proximity can be introduced as a general criterion to capture neighborhood, but we do not consider this criterion to necessarily be a good choice depending on the particular characteristics of the particular problem. For example, in our case, we have Japan, Australia and New Zealand which are geographically far from other countries. This means that geographical distance is not a good approximation to capture the countries with which they interact. In our view, the best option is the criterion of trade or patent. These channels are probably most important to capture the interdependency of policies between "nearby" countries. Also nearly half of our countries' nearest (in terms of distance) neighbors are also the nearest neighbors using patent or trade criteria.

The spatial matrix W involves two choices: the definition of the neighborhood and the weight between each neighbor. We introduce the spatial dependence using two alternative criteria. The first uses the idea of proximity between countries based on strength of bilateral trade, and each weight is formed by defining the relation between two countries i and j in the following way:

$$w_{ij} = \frac{1}{2T}\sum_{t\in T}\left(\frac{export_{ij,t}}{\sum_j export_{ij,t}} + \frac{import_{ij,t}}{\sum_j import_{ij,t}}\right), \tag{7}$$

where $export_{ij,t}$ represents the total amount of country i's exports toward country j (at time t), and $import_{ij,t}$ represents the amount of country i's imports from country j during that same period. The proximity between two countries is measured by the average of their bilateral commercial relations of all T periods.

The second criterion considers the intensity of technological relationships. To construct these weights, we use collaboration data from international patent applications (Patent Cooperation Treaty, PCT). The intensity of technological collaboration between two countries i and j can be defined as:

$$w_{ij} = \frac{\frac{1}{T}\sum_{t\in T} p_{ij,t}}{\sum_j \left[\frac{1}{T}\sum_{t\in T} p_{ij,t}\right]}, \tag{8}$$

where $p_{ij,t}$ represents the number of collaborations between the countries i and j during the period t for PCT patent applications. Thus, the proximity between two countries is measured by the relative average intensity of their collaboration for international patent applications during T periods.

To break down the connection between all countries and to avoid possible endogeneity issue of W, we apply a binary transformation of the weights. For each criterion, we apply the following condition:

$$w_{ij} = \begin{cases} 1 & \text{if} \quad \sum_j w^o_{ij} \leq 0.75 \\ 0 & \text{otherwise} \end{cases},$$

where w^o_{ij} is the ordered weight in descending form, for the $i-th$ country. This transformation allows us to reduce the connectivity of the matrices into an average of six neighbors for bilateral trade and around four neighbors for patent collaboration relationships. Finally, we apply row normalization of the spatial weight matrix.

Using these two spatial weight matrices, we extend the previous models and report estimates of their spatial Durbin version in Table 8. The estimates report the existence of positive spatial dependence between OECD countries in terms of private R&D intensity. Our results report that spatial dependence is more than two times higher based on scientific collaboration intensity

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Table 9
Direct and indirect effects (Short-term). Spatial durbin models.

Variable	*dynSDM1*		*dynSDM2*		*dynSDM3*	
	W (trade)	W (patent)	W (trade)	W (patent)	W (trade)	W (patent)
Direct effect						
$\Delta interetlt$	-0.005^{***}	-0.005^{***}	-0.005^{***}	-0.004^{***}	-0.008^{***}	-0.006^{***}
$\Delta lsub$	-0.042^{***}	-0.044^{***}	-0.034^{***}	-0.036^{***}		
$\Delta lsub \times sub$					-1.023^{***}	-0.964^{***}
$\Delta lsub \times sub^2$					3.851^{***}	3.249^{***}
$\Delta ldirpub_{-1}$	0.266^{*}	0.266^{*}	0.258^{*}	0.258^{*}	0.252^{*}	0.251^{*}
$\Delta lbindex_{-1}$	-0.195^{***}	-0.197^{***}	-0.250^{***}	-0.288^{***}		
$\Delta lbindex_{-1} \times bindex$					-3.280^{***}	-3.240^{***}
$\Delta lbindex_{-1} \times bindex^2$					3.963^{***}	3.857^{***}
$\Delta interact$			0.608^{***}	0.257	1.036^{***}	0.750^{***}
Indirect effect						
$\Delta interetlt$	-0.013^{*}	-0.028	-0.012^{*}	-0.031^{**}	0.012^{**}	-0.033^{**}
$\Delta lsub$	-0.008	0.067	0.019	0.068		
$\Delta lsub \times sub$					0.325	0.162
$\Delta lsub \times sub^2$					-1.450	14.125
$\Delta ldirpub_{-1}$	-0.065	0.095	-0.069	0.013	-0.090	-0.002
$\Delta lbindex_{-1}$	0.043	0.001	-0.039	0.888^{***}		
$\Delta lbindex_{-1} \times lbindex$					-2.139	0.616
$\Delta lbindex_{-1} \times lbindex^2$					2.566	0.570
$\Delta interact$			0.444	11.623^{***}	0.973	11.813^{***}

Notes: *, ** and *** denotes significance at 10%, 5% and 1%. Dependent variable is log Dirdefi %GDP (in first difference). Terms Δ and l denotes first diff. and log.

compared to bilateral trade intensity which confirms the intuition that scientific collaboration generates significant positive externalities that increases the productivity of private R&D. This first element highlights the need to take account of spatial dependence even at the OECD country level. Looking at the results of the two weight models, we prefer the estimates using the "patent" spatial weight matrix because they fit the data better (lower AIC and BIC), however both models provide similar core results. The results for short-run direct and indirect effects are presented in Table 9.

5.3.1. Results for direct effects

We begin our analysis by comparing the direct effects obtained with and without inclusion of spatial dependence (Tables 7 and 9). The sign of estimated coefficients is the same in Tables 7 and 9 and overall there is not a huge difference in their values. Nevertheless, the speed of adjustment of private R&D intensity is estimated to be slightly higher when we introduce spatial dependence at around 64% (against an estimate of 58%) implying a lower gap between short- and long-run effects. Therefore, the long-run elasticities of private R&D intensity with respect to each independent variable is slightly lower when spatial dependence is included. This implies that ignoring spatial dependence tends to overestimate the true effect of public R&D support (between 0% and 3% for indirect support and between 5% and 13% for direct support). Consequently, overall, the direct effects estimated by the Spatial Durbin Models are in line with those provided by non-spatial model and confirm all the previous results including (1) a positive influence of fiscal incentives and a negative influence of direct subsidies,[20] (2) a nonlinear effect for both policies according to their level of use, and (3) a substitution effect between R&D subsidies and fiscal incentives.

5.3.2. Results for indirect effects

Although numerous direct effects are significant, the estimates reported in Table 9 highlight that few exogenous variables in neighboring countries influence private R&D intensity in the focal country. Concentrating on the best specification (DynSDM 2) using the "patent" spatial weight matrix, we observe that only three indirect effects are significant (and only one at the 5% level). The first is related to the difference in the long-run nominal interest rate. The spatial model estimates that an increase of 100 bp of the long-run nominal interest rate in all neighboring regions reduces growth of private R&D intensity in the focal country by approximately 3pp in the short-run. This implies that financial conditions in other countries more strongly influence the private investment intensity in the home country than do home national financial conditions. Many elements can explain these results. Here, we concentrate on one potential explanation. Currently, in the world, multinational companies are responsible for more than 90% of private R&D investment in the world (source: EU Industrial R&D investment Scoreboard 2013).

These companies develop global strategies for their R&D activities which are undertaken in different countries. In a context of increasing financial market integration, we can think that private investment in R&D of these companies (and hence global investment in R&D) is more sensitive to global financial market conditions rather than the conditions in one specific country. Our assumption seems plausible since our data show a positive correlation between the first difference of the long-run nominal interest rate and its spatial-lag counterpart ($corr = 0.2825$).

The second significant indirect effect is related to the level of fiscal incentives in neighboring countries in long run. In the fourth column of Table 9, we estimate that a decrease of B-index of 1% (an increase in fiscal incentives) in all neighboring regions decreases private R&D intensity in the focal country of approximately 0.89% in the short-run (and 1.4% in the long-run). This indirect effect is clearly higher than its direct counterpart and has the opposite sign implying a negative (direct + indirect) total effect of indirect support. Obviously, some caution is needed in interpreting this result but it nevertheless tends to confirm our assumption of fiscal competition/optimization. It is also in line with the results in Wilson (2009) showing the ineffectiveness of local tax credits in United States at the macroeconomic level, to increase private investment in R&D. It is interesting to note that the opposite applies to direct support (but the indirect effect is not significant).

[20] Recall previous remarks on the leveraging effect of both types of support.

Indeed, the indirect effects reported in Table 9 shows that an increase in direct support in all neighboring regions increases private R&D intensity in the focal country and overcomes the negative direct effect of national R&D subsidies implying a positive (but insignificant) total effect of direct support.

The last significant indirect effect is related to the spatial lag of the interact variable[21]. We notice that this variable $W\Delta interact$ does not correspond to the crossed variable of the spatial lag of each support ($W\Delta interact \neq W\Delta lbindex_{-1} \times W\Delta lsub$). This implies that we cannot interpret this variable directly in terms of substituability between direct and indirect support implemented in neighboring countries. Nevertheless, we can deduct some elements from the correlation between $W\Delta interact$ and $W\Delta lbindex_{-1} \times W\Delta lsub$ which is 0.6334. As the coefficients of $W\Delta interact$, $W\Delta lbindex_{-1}$ and $W\Delta lsub$ are all positive, this reflects complementarity among both direct and indirect support from neighboring countries in terms of their influence on own country R&D intensity. In other words, if neighboring countries increase their level of direct support, it increases the negative impact of indirect support from neighboring countries on own country R&D intensity.

These comments highlight the importance of taking account of the spatial dependence to assess the macroeconomic effect of R&D policies. Indeed, without that we only consider internal/direct effect of policies whereas it seems that external/indirect effects could be at least as large.

6. Conclusions

This paper provides new empirical evidence on the macroeconomic effects of R&D subsidies and fiscal incentives on business-funded R&D intensity using a database of 25 OECD countries over the period 1990–2009. We developed theoretical concepts and discussed empirical results in order to determine the core functional relationships to investigate. This first step highlighted that the empirical literature does not fully answer questions related to (1) the internal impact of public support for R&D, (2) the externalities between direct and indirect support, (3) the external effects of these policies. The second step focused on appropriate econometric methods to test these elements. More precisely, we developed dynamic spatial panel models.

In terms of internal (in-country) effects, our results show that tax incentives increase business-funded R&D intensity while the reverse applies to R&D subsidies. However this difference does not imply that subsidies are less efficient than fiscal incentives for increasing business-funded R&D. R&D subsidies are deducted in business-funded R&D accounting but not fiscal incentives, and overall, our results point more to a small crowding-out effect for both types of support. A clearer result is found for the shape of the impact of R&D subsidies and fiscal incentives. We show that there is a convex relationship between the effect of each instrument on the business-funded R&D intensity and the level of use of each instrument. In other words, the existence of a leveraging or crowding-out effect (especially for fiscal incentives) is directly related to the amount received for each $ spent on R&D. In relation to the externalities between R&D subsidies and fiscal incentives, our results are in line with previous studies. We find that within a country, R&D subsidies and fiscal incentives are substitutes for stimulating business-funded R&D intensity. This invalidates the common assumption of complementarity of these two policies in terms of incentives and firm's use.

[21] i.e the spatial lag of the crossed variable of direct and indirect support.

The most important and new contribution of this paper is its consideration of potential external effects of R&D policies and more generally of spatial dependence between private R&D activities in the OECD countries. Our results highlight significant and positive spatial dependence in terms of private R&D intensity suggesting the existence of strong spillovers between private R&D firms. In terms of the external effects of public support, our estimates highlight the possibility of a substitution effect between in-country and out-of-country R&D policies. In other words, the effects of national R&D policies on national private R&D intensity can be nullified by the effects of external R&D policies. More specifically, there is a substitution effect between internal and external fiscal incentives whereas this substitution effect is present but not significant in the case of direct subsidies. This demonstrates the importance of taking account of spatial dependence of public policies to assess their macroeconomic effects. Focusing only on internal effects could potentially lead empiricists to conclude the opposite to what is the true impact of R&D policies.

From a public policy perspective, our findings provide interesting elements for the definition of R&D support policies (especially to optimize their impact).

The first is related to the empirical non-linear relationship between the effect of each instrument and its level of use. This result suggests that (1) a macroeconomic leverage effect on private R&D can be achieved only if the policy represents an important level of subsidization for firms, and (2) a partial macroeconomic crowding-out effect is likely to emerge if the policies represent a low level of subsidization for firms. In most OECD countries, the level of subsidization induced by their R&D subsidies and fiscal incentives is far behind the level able to generate a leverage effect but is at a level that generate a partial crowding-out effect. Thus, it might explain in part why we observe that those EU countries with the highest level of private R&D investment in R&D are also those countries where public support is inferior to the European or OECD average.

The second element is related to the total (internal and external) effect of R&D subsidies and fiscal incentives. Indeed, our results suggest that the total (internal and external) elasticity of private R&D intensity with respect to direct support is (at least) less negative than its internal counterpart. The total (internal and external) elasticity of private R&D intensity with respect to indirect support is clearly less positive than its internal counterpart. In other words, if governments do not take account of spatial interdependencies when defining their R&D policies, they will likely favor indirect over direct support even if, in the long-run, this choice will not be the most effective. Looking at the reality and the tendency of governments to substitute direct subsidies for fiscal incentives, this implication is significant.

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Appendix: Different tests

Tables A.1–A.4 .

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Table A.1
Cointegration test to variables in logarithm of Table 6.

Statistics	Value	Z-value	p-value	Robust p-value
G_t	−1.684	3.989	1.00	0.49
G_a	−1.475	7.492	1.00	0.93
P_t	−6.953	3.497	1.00	0.18
P_a	−1.542	5.120	1.00	0.38

Notes: The results are based on Westerlund (2007) cointegration tests. Robust p-value obtained using bootstrap with 499 replications. H_0 : No cointegration. The tests included a constant and one time lag.

Table A.2
Robustness checks (based on MODEL 2).

Variable	OLS	LSDV	CLSDV	CLSDV1	CLSDV2	CLSDV3	CLSDV4
$\Delta ldirdefi_{-1}$	0.481***	0.373***	0.429***	0.418***	0.506***	0.422***	0.416***
$\Delta lcredit$				0.047			0.050
$\Delta interetlt$	−0.005	−0.006**	−0.006**	−0.005**	−0.005**	−0.005**	−0.006**
$\Delta lsub$	−0.037	−0.036***	−0.037***	−0.037***	−0.028**	−0.037***	−0.038***
$\Delta ldirpub_{-1}$	0.232*	0.250*	0.237***	0.234***		0.209***	0.239***
$\Delta lbindex_{-1}$	−0.242*	−0.244***	−0.248***	−0.246***	−0.265***	−0.243***	−0.253***
$\Delta interact$	0.439	0.579***	0.581**	0.581***	0.738***	0.618***	0.597**
Constant	−0.033*	−0.011					
Time dummies	yes	yes	yes	yes	yes	no	yes
Obs.	450	450	450	450	450	450	425

Notes: *, ** and *** denotes significance at 10%, 5% and 1%. Dependent variable is log Dirdefi %GDP (in first difference). Terms Δ and *l* denotes first diff. and log. All tests are based in robust std. errors. *lcredit* represents the domestic credit to private sector as a percentage of GDP from IMF data.

Table A.3
Endogeneity tests.

Variable	C-test		Hansen test	
	Statistic	p-value	Statistic	p-value
$\Delta Interetlt$	0.81	0.37	1.19	0.55
$\Delta Dirdpub$	0.27	0.60	0.087	0.77
ΔSub	0.18	0.67	0.16	0.92
$\Delta Bindex$	0.39	0.53	0.80	0.67

Notes: All variables are in logarithm. The results are based on the difference between Sargan–Hansen tests.

Table A.4
Average cross-section correlation to residuals.

Estimator	CD-Test		Corr.	Abs(corr.)
	Statistic	p-value		
GMM|MODEL1	−1.83	0.067	−0.025	0.194
CLSDV|MODEL1	−1.78	0.076	−0.02	0.192
GMM|MODEL2	−1.80	0.072	−0.024	0.195
CLSDV|MODEL2	−1.74	0.082	−0.024	0.192
GMM|MODEL3	−1.91	0.057	−0.026	0.187
CLSDV|MODEL3	−1.78	0.075	−0.024	0.185

Notes: The results are based on CD test (Pesaran, 2004).

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