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Cooperation or non-cooperation in R&D: how should research be funded? *

Marie-Laure Cabon-Dhersin,[†] Romain Gibert[‡]

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Abstract

This article compares two research funding policies in a cooperative or non-cooperative R&D setting: subsidising private research (Spr) and subsidising public research (Spu). We show that the Spr policy induces better performance than the Spu approach in terms of overall net surplus whether firms cooperate or not in R&D. Nevertheless, subsidising public research leads to greater R&D investment overall provided that the knowledge externalities from the public to the private research sector are not too high. The Spu policy is more effective in terms of research efforts when firms cooperate and subsidies are low.

Key words: R&D Cooperation, R&D spillovers, Knowledge public externalities, Subsidies, Public policy

Code JEL: C7, H2, H4, L3, L5, O3.

1 Introduction

Research and development activities benefit both the firms that undertake them and society as a whole because of the positive externalities produced. These externalities, also known as knowledge or technology spillovers, stem from the partial appropriation by rival firms of the knowledge generated by the investments of others. Although this is beneficial for society as a whole, the incentive for firms is to underinvest in R&D and adopt a free-rider strategy. The difference between the social and private benefits of innovation is widely acknowledged as a fact by both economists and politicians.

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Governments have several public policy tools at their disposal to support R&D efforts. Firstly of course, they can establish a judicial framework that protects innovation (patents, licences): firms are given a temporary monopoly during which to exploit their innovation. States can also offer financial support, directly (by funding selected firms) or indirectly (through fiscal incentives based on specific research criteria). Finally, cooperation agreements in R&D between potentially rival firms (horizontal agreements) increase R&D efforts by internalising spillovers. In light of the social benefits of these deals, a large number of Western countries have weakened anti-trust regulations for firms signing R&D agreements (Treaty of Rome, 1957; exemption 85.3, National Cooperative Research and Production Act, 1984, 1993).

Over the past 15 years or so, political initiatives in many OECD countries have simultaneously combined several of these strategies to encourage innovation (Martin, 2016). Indeed, governments increasingly reserve subsidies for firms engaging in R&D collaboration. One example of this type of policy is the creation of *Pôles de compétitivité* (research clusters) in France since 2004, bringing firms and public bodies with similar research interests into close physical proximity to collaborate on R&D projects. In France between 2007 and 2011, 888 projects have been funded in this way for a total cost of one billion euros, in partnership with local government agencies.

Academic investigations in the industrial organisation literature have focussed on each R&D support measure separately. The most studied topic since the 1980s has probably been the mechanisms of R&D cooperation (d'Aspremont and Jacquemin, 1988; Amir, 2000; Amir et al., 2002, 2003; Brod and Shivakumar, 1997; Katz, 1986; Kamien et al., 1992; Norman and Pepall, 2004). This work indicates that beyond a certain level of technological appropriation (i.e. above a certain spillover threshold), cooperative R&D efforts dominate over non-cooperative efforts. Furthermore, R&D investments increase with the amount of spillover when firms cooperate whereas it decreases when there is no cooperation. Analyses of the advantages of cooperation have been extended to include public-private partnerships (Poyago-Theotoky, 2009; Poyago-Theotoky et al., 2002; Beath et al., 2003). A number of empirical studies have shown that research produced by public laboratories or universities is beneficial for the private research sector (Jaffe, 1989; Audretsch et al., 2002; Autant-Bernard, 2001; Cohen et al., 1994; Veugelers and Cassiman, 2005; Boufaden and Plunket, 2007).

Secondly, a substantial strand of the literature has investigated public subsidies or fiscal incentives for innovation in the presence of R&D spillovers (Romano, 1989; Inci, 2009; Atallah, 2014; Heggedal, 2015). Among more recent empirical studies, Gelabert et al. (2009) have investigated the impact of public subsidies on R&D investments. The authors highlight the fact that public support for research helps firms that struggle to appropriate their research (i.e. those with high spillovers) more than it does those with a high level of appropriation (low spillovers). The

latter thus use the subsidies to lower the cost of research that they would have in any case undertaken. In the literature, this mechanism is known as an eviction effect.

In spite of the current trend towards public policies encouraging the creation of research clusters as the primary means to stimulate innovation, there have been few investigations that bring together these two segments of the literature, namely research cooperation (between firms but also between the public and private sectors) and subsidy allocation. Hinlopen (1997, 2000, 2001) has investigated the theoretical effects of subsidies (financed by taxation) on R&D efforts for cooperating and non-cooperating firms. On the basis of empirical work, Gussoni and Mangani (2010) argue that this effect is significantly stronger for cooperating firms in a context of low appropriability (high spillovers). However, the only theoretical work in which the role of public bodies in research is considered, is the recent paper by Cabon-Dhersin and Taugourdeau (2017) which investigates the organization and the distribution of research activities between nearby public and private laboratories in a cooperative setting.

In this article, we will attempt to clarify the link between public subsidies and R&D cooperation involving the public sector or not. The aim therefore is to understand what public funding policies encouraging R&D cooperation can do to tackle the problem of underinvestment in innovation. We first of all propose an analytical framework in which to investigate R&D cooperation between competing firms receiving subsidies that depend on their R&D efforts. We then include a public research sector body, whose aim is to maximise social welfare, generating knowledge public externalities for the private sector. The question is then whether subsidising private research is more effective than subsidising public research is, in both a cooperative and a non-cooperative context.

The results of this theoretical work are that subsidising private research is more effective in terms of overall net surplus (production and consumption surplus) whether firms cooperate or not in R&D. However, subsidising public research increases the overall amounts invested in research (both public and private) provided the knowledge externalities of the public sector are not too high. This research policy is more effective in terms of research efforts when firms cooperate and subsidies are sufficiently low.

The following section presents our analytical model, which is then used to obtain equilibrium results for the two types of funding policy. Finally, in a third section, we compare and discuss the results before concluding.

2 The model

We present first of all the analytical framework before restating what the results of the model are without subsidies. This outline will allow us to compare the different

public founding policies studied in the rest of the article.

2.1 Analytical framework

We consider two competing firms investing in R&D to lower their production costs and they produce separately. The model involves two stages:

- The R&D stage: the firms choose how much to invest in R&D based on the possibility or not of cooperation (the cooperative, C, and non-cooperative, NC, scenarios), and the availability or not (NS) of subsidies for private (Spr) or public (Spu) research.
- The production stage: regardless of the funding policy, the firms engage in Cournot competition (i.e. on the amount of output they produce).

The demand function is linear and given by:

$$P(Q) = a - Q$$

where the total level of production is $Q = q_1 + q_2$, with $Q \leq a$.

The rest of the analysis follows the approach proposed by Hinloopen (2000), which is based on the seminal work of Kamien et al. (1992).

Thereby, the *effective* R&D investment of firm i corresponds to the sum of its own effort, x_i , and part of firm j 's, βx_j , with $\beta \in [0, 1]$ being the level of spillover. The *effective* R&D effort available to firm i is thus:

$$X_i = x_i + \beta x_j, \quad i \neq j, i, j \in \{1, 2\}$$

This *effective* effort reduces firm i 's production costs,

$$C_i(q_i, x_i, x_j) = (c - x_i - \beta x_j)q_i, \quad i \neq j, i, j \in \{1, 2\}$$

with $a > c > 0$.

Note that the R&D cost function is quadratic (leading to diminishing returns): $\gamma(1 + \beta)x_i^2$, with $\gamma > 0$. This is different from the usual approach (d'Aspremont and Jacquemin, 1988) in that it allows for *internal* spillovers. In effect, the (realistic) supposition is that spillovers occur during the R&D process (via meetings, publications, seminars, observations...) rather than after it (*external* spillovers)¹.

¹The R&D cooperation models proposed by d'Aspremont and Jacquemin (1988) (AJ) and Kamien et al. (1992) (KMZ) have been compared several times. In contrast with the KMZ model,

For the sake of simplicity and with no loss of generality, we will assume that $\gamma = 1$, which ensures that all the variables are non-negative. The profit function of firm i can be written²:

$$\pi_i(q_i, q_j, x_i, x_j) = (a - q_i - q_j)q_i - (c - x_i - \beta x_j)q_i - (1 + \beta)x_i^2 \quad (1)$$

with $i \neq j, i, j \in \{1, 2\}$

By backward induction, the first and second order conditions yield the Nash-Cournot equilibrium:

$$q_i(x_i, x_j) = \frac{a - c + (2 - \beta)x_i + (2\beta - 1)x_j}{3} \quad (2)$$

Before investigating the different research funding policy strategies available to government, we rapidly present the well-known results showing the benefits of co-operation in R&D (in the absence of subsidies).

2.2 The benchmark model without subsidies

Following d'Aspremont and Jacquemin (1988) and Kamien et al. (1992), we can calculate the equilibrium R&D efforts and thereby deduce the amounts produced at the Subgame Perfect Nash equilibrium, for firms that cooperate or not in R&D.

2.2.1 Non-cooperation in R&D

In a non-cooperative scenario (NC), the firms choose their level of R&D investment independently. The profit function (1) becomes:

$$\pi_i^{NC}(x_i, x_j) = \left(\frac{a - c + (2 - \beta)x_i + (2\beta - 1)x_j}{3} \right)^2 - (1 + \beta)x_i^2 \quad i \neq j, i, j \in \{1, 2\} \quad (3)$$

Equilibrium levels of R&D efforts are given by maximizing (3) with respect to x_i . The R&D research effort can be deduced by considering a symmetric solution, $x^{NC} = x_i = x_j$.

AJ's does not consider diminishing returns for research when calculating spillovers, which are outside of the research process. This tends to make the R&D process in the AJ model more productive and to increase the level of the equilibrium results. One can switch between the two models by replacing γ with $(1 + \beta)\gamma$ (see Amir (2000), Amir et al. (2008)).

²All second order conditions are always satisfied for all solutions of all cases (NC, C, Spr, Sps, NS). They are available from the authors upon request.

$$x^{NC} = \frac{(2 - \beta)}{(1 + \beta)(9 - (2 - \beta))}(a - c) \quad (4)$$

By substitution, this gives the amount produced at equilibrium in non-cooperative scenario:

$$q^{NC} = \frac{3}{9 - (2 - \beta)}(a - c) \quad (5)$$

2.2.2 Cooperation in R&D

The cooperative scenario (C) only differs from the non-cooperative one at the R&D stage, the production step is identical to that in the NC scenario. In the research stage, firms choose the research effort that maximises their profit:

$$\Pi^C = \sum_{i=1}^2 \left\{ \left(\frac{a - c + (2 - \beta)x_i + (2\beta - 1)x_j}{3} \right)^2 - (1 + \beta)x_i^2 \right\} \quad i \neq j, i, j \in \{1, 2\} \quad (6)$$

By symmetry, the first order conditions yield the equilibrium solution corresponding to the coordinated R&D efforts:

$$x^C = \frac{1}{9 - (1 + \beta)}(a - c) \quad (7)$$

and

$$q^C = \frac{3}{9 - (1 + \beta)}(a - c) \quad (8)$$

2.2.3 Comparisons: some well-known results

The following proposition highlights the benefits of cooperation in R&D when the spillover level is high:

Proposition 1 *With no subsidies (NS Policy),*

$$\begin{aligned} x^{NC} > x^C, \quad Q^{NC} > Q^C, \quad \text{and} \quad \pi^{NC} < \pi^C \quad \text{if} \quad \beta < 0.5 \\ x^{NC} < x^C, \quad Q^{NC} < Q^C, \quad \text{and} \quad \pi^{NC} < \pi^C \quad \text{if} \quad \beta > 0.5 \end{aligned}$$

We can also deduce the effect of spillovers on R&D efforts:

Lemma 1 $\forall \beta \in [0, 1]$, the following hold:

$$\frac{\partial x^{NC}}{\partial \beta} < 0 \quad \text{and} \quad \frac{\partial x^C}{\partial \beta} > 0$$

The higher the level of spillover is, the more cooperative effort in R&D is high; conversely, non-cooperative R&D effort decreases in β , which highlights the disincentive effect of technology leaks on research efforts.

3 The two research funding policies

We now introduce the two funding public policies. The first involves directly funding private research by allocating a subsidy for each unit invested in R&D (Spr). In the second, public laboratories are subsidised (Spu) to stimulate private R&D through the knowledge externalities of the public research.

The game proceeds as follows: in the first stage, the government sets the subsidy level that maximises the social welfare function. Depending on the R&D subsidy, the different research bodies simultaneous set their R&D efforts in the second stage, either cooperatively or noncooperatively (C and NC scenarios). Finally, depending on the subsidy and the R&D investment, the firms independently determine their production in Cournot competition.

3.1 Subsidising private sector research: the Spr policy

This policy consists in subsidising each firm's R&D effort. Each firm receives a subsidy s for each unit invested in R&D³: $S(x_i) = s.x_i$. The government subsidy is calculated so as to maximise the social welfare function:

$$SW = \underbrace{\frac{Q^2}{2}}_{\text{Consumer surplus}} + \underbrace{(\pi_i + \pi_j)}_{\text{Producer surplus}} - \underbrace{s.(x_i + x_j)}_{\text{Social cost of the subsidy}} \quad (9)$$

Of course, the firms' profits include the subsidies received for R&D:

$$\pi_i(q_i, q_j, x_i, x_j) = P(Q)q_i - C_i(q_i, x_i, x_j) - (1 + \beta)x_i^2 + s.x_i \quad i \neq j, i, j \in \{1, 2\}$$

This implies that the subsidy term disappears from the social welfare function (Equation (9)). However, these subsidies affect social welfare and equilibrium outputs indirectly through the R&D efforts, which depend directly on the subsidy level.

³A common feature of this subsidy is that it is unconditional, that is, its level is not related to the success of research project as in Atallah (2014).

In the last stage of the game (solved by backward induction), each firm i chooses the output that maximises its objective function, including the output of its rival:

$$\frac{\partial \pi_i}{\partial q_i}(q_i, q_j, x_i, x_j) = 0 \quad (10)$$

The first and second order conditions yield Equation (11).

$$q_i(x_i, x_j) = \frac{a - c + (2 - \beta)x_i + (2\beta - 1)x_j}{3} \quad (11)$$

This allows equilibrium calculations to be performed in the R&D stage and thus deduce what the optimal subsidy level is for the NC and C scenarios.

3.1.1 The non-cooperative scenario with subsidies to the private research sector

In the second stage, the firms choose the level of investment that maximises their profit:

$$\pi_i(x_i, x_j) = (q_i(x_i, x_j))^2 - (1 + \beta)x_i^2 + s.x_i \quad i \neq j, i, j \in \{1, 2\} \quad (12)$$

The solution of this equation is unique and symmetric, such that the two firms invest the same amount in R&D, i.e. $x_i = x_j = x_{Spr}^{NC}$, and have the same equilibrium level of output, q_{Spr}^{NC} :

$$x_{Spr}^{NC} = \frac{(2 - \beta)(a - c) + 4.5s}{(9 - (2 - \beta))(1 + \beta)} \quad (13)$$

$$q_{Spr}^{NC} = \frac{3(a - c) + 1.5s}{9 - (2 - \beta)} \quad (14)$$

We can already see that the subsidy has a positive effect on the firms' R&D efforts and their outputs.

In the first stage, the government sets the optimal level of the subsidy granted to firms. The welfare function is:

$$SW_{Spr}^{NC} = \frac{(Q_{Spr}^{NC})^2}{2} + 2\pi_{Spr}^{NC} - 2s(x_{Spr}^{NC}) = 4(q_{Spr}^{NC})^2 - 2(1 + \beta)(x_{Spr}^{NC})^2$$

Differentiating with respect to s gives:

$$\frac{\partial SW_{Spr}^{NC}}{\partial s} = 8q_{Spr}^{NC} \frac{\partial q_{Spr}^{NC}}{\partial s} - 4(1 + \beta)x_{Spr}^{NC} \frac{\partial x_{Spr}^{NC}}{\partial s}$$

The subsidy increases social welfare by increasing the equilibrium output (q_{Spr}^{NC}) and thus consumer surplus. However, the subsidy decreases social welfare because of the social cost of the increase in R&D efforts. The optimal level of subsidy balances out these two effects:

$$s_{Spr}^{NC} = \frac{6\beta}{9 - 2(1 + \beta)}(a - c) \quad (15)$$

This gives the values x_{Spr}^{NC} , Q_{Spr}^{NC} , π_{Spr}^{NC} , and SW_{Spr}^{NC} at the subgame-perfect Nash equilibrium. These are listed in Table (1).

3.1.2 The cooperative scenario with subsidies to the private research sector

In the cooperative scenario, the firms coordinate their research efforts so as to maximise the sum of profits:

$$\Pi_{Spr}^C = \sum_{i=1}^2 \{ (q_i(x_i, x_j))^2 - (1 + \beta)x_i^2 + s.x_i \} \quad (16)$$

The symmetric solution, $x_{Spr}^C = x_i = x_j$, gives a unique equilibrium solution for the coordination of R&D efforts as a function of s ,

$$x_{Spr}^C = \frac{(1 + \beta)(a - c) + 4.5s}{(1 + \beta)(9 - (1 + \beta))} \quad (17)$$

from which the two firms' output as a function of s can be deduced:

$$q_{Spr}^C = \frac{3(a - c) + 1.5s}{9 - (1 + \beta)} \quad (18)$$

The positive effect of the subsidy is stronger when the firms coordinate their R&D efforts, if the level of spillover is high enough:

$$\frac{\partial x_{Spr}^C}{\partial s} > \frac{\partial x_{Spr}^{NC}}{\partial s} > 0 \quad \text{and} \quad \frac{\partial q_{Spr}^C}{\partial s} > \frac{\partial q_{Spr}^{NC}}{\partial s} > 0 \quad \text{if} \quad \beta > 0.5$$

The optimal subsidy level, s_{Spr}^C can be obtained by maximising the social welfare function:

$$\frac{\partial SW_{Spr}^C}{\partial s} = 8 \frac{\partial q_s^C}{\partial s} q_s^C - 4(1 + \beta) \frac{\partial x_s^C}{\partial s} x_s^C = 0$$

such that:

$$s_{Spr}^C = \frac{2(1+\beta)}{9-2(1+\beta)}(a-c) \quad (19)$$

All the values at equilibrium are listed in Table (1).

At this stage of the analysis, we can advance two propositions:

Proposition 2 $\forall \beta \in (0, 1]$,

$$x_{Spr}^{NC,C} > x^{NC,C}, \quad Q_{Spr}^{NC,C} > Q^{NC,C}, \quad \text{and} \quad \pi_{Spr}^{NC,C} > \pi^{NC,C}$$

In both scenarios (C and NC), the welfare-optimal level of the R&D subsidy increases private investment in R&D, the consumer surplus and the producer surplus (Proposition 2). This is the same result as that of Hinloopen (1997, 2000), who considered a subsidy financed by a tax on profits. He also finds the same equivalence as in Proposition 3. This implies that financing by taxation does not alter the results obtained here in terms of R&D efforts and equilibrium outputs. However, our results differ in terms of the equilibrium profit: while with a tax-financed subsidy, the firms are indifferent to the presence (or absence) of cooperation, this is no longer the case in our model. The result presented in Proposition 3 shows that cooperative strategies will not be adopted by subsidised firms (because of their low profitability), when the spillover level is high (> 0.5).

Proposition 3 $\forall \beta \in (0, 1]$,

$$\begin{aligned} x_{Spr}^{NC} &= x_{Spr}^C \\ Q_{Spr}^{NC} &= Q_{Spr}^C \\ s_{Spr}^C &> s_{Spr}^{NC}, \quad \forall \beta \in [0, 0.5) \quad \text{and} \quad s_{Spr}^C < s_{Spr}^{NC}, \quad \forall \beta \in (0.5, 1] \\ \pi_{Spr}^C &> \pi_{Spr}^{NC}, \quad \forall \beta \in [0, 0.5) \quad \text{and} \quad \pi_{Spr}^C < \pi_{Spr}^{NC}, \quad \forall \beta \in (0.5, 1] \end{aligned}$$

Because the two firms behave identically in the production stage, the government-calculated subsidy encourages firms to supply the R&D effort that maximises the total net surplus. The optimal subsidy leads to the same levels of R&D investment and output regardless of the firms' behaviour in the R&D stage. As a result, the optimal subsidy is higher in the non-cooperative case when the level of spillover is high (to encourage firms to invest substantially in R&D). Since non-cooperating firms benefit more from the subsidy, the profit in the non-cooperative case is higher than in the cooperative one for high spillovers.

The following section investigates the alternative policy of subsidising public research.

3.2 Subsidising public sector research: the Spu policy

In this section, we consider a policy of support for public research. To this end, we introduce a public research body supplying an effort x_{PU} . Instead of subsidising private sector research, the government funds this public effort in welfare-optimal manner. This subsidy is calculated so as to maximise the social welfare function:

$$SW = \underbrace{\frac{Q^2}{2}}_{\text{Consumer surplus}} + \underbrace{(\pi_i + \pi_j)}_{\text{Producer surplus}} - \underbrace{s.(x_{PU})}_{\text{Funding of public research}} \quad (20)$$

The company benefits indirectly from the public subsidy through the knowledge externalities, αx_{PU} with $\alpha \in (0, 1)$, generated by the public research sector⁴. The firms' profit is now written:

$$\pi_i(q_i, q_j, x_i, x_j) = P(Q)q_i - (c - x_i - \beta x_j - \alpha x_{PU})q_i - (1 + \beta)x_i^2 \quad i \neq j, i, j \in \{1, 2\}$$

The new game proceeds as follows:

- first stage: the public laboratory receives a subsidy. The government chooses the subsidy level that maximises social welfare (Equation 20).
- second stage: the two firms decide how much to invest in R&D, x_{Spu} , while simultaneously, the public laboratory sets its research effort, x_{PU} , so as to optimise social welfare.
- third stage: the two firms set their output levels under Cournot competition.

As before, by backward induction, each firm i chooses the output level that maximises its objective function, accounting for its rival's output and the public research effort:

$$q_i(x_i, x_j, x_{pu}) = \frac{a - c + (2 - \beta)x_i + (2\beta - 1)x_j + \alpha x_{PU}}{3} \quad (21)$$

with $i = \{1, 2\}$

We can now carry out equilibrium calculations in the R&D stage and thus deduce the optimal subsidy levels in the NC and C scenarios.

⁴This set-up is similar to some of the models used in the mixed markets literature (Gil-Molto et al., 2011; Kesavayuth and Zikos, 2013).

3.2.1 The non-cooperative scenario with subsidies to the public research sector

In the R&D stage, we simultaneously determine the R&D investments of the two firms (for a given public research effort) and the research effort of the public laboratory (for a given level of private R&D investment).

First of all, the profit equation from the previous stage,

$$\pi(x_i, x_j, x_{PU}) = (q_i(x_i, x_j, x_{PU}))^2 - (1 + \beta)x_i^2$$

can be used to determine the level of R&D investment that maximises the two firms' profits.

The solution to this equation is unique and symmetric since the two firms adopt the same behaviour at equilibrium, i.e. $x_i = x_j = x_{Spu}$. The best-response function is thereby:

$$x_{Spu}^{NC} = \frac{(2 - \beta)(a - c + \alpha x_{PU})}{(1 + \beta)(9 - (2 - \beta))} \quad (22)$$

This equation shows that the public research effort boosts private research investment, particularly if β is low and α high.

Simultaneously, the welfare-optimal public research effort for a given x_{Spu} satisfies:

$$\frac{\partial SW}{\partial x_{PU}} = 8 \frac{\partial q}{\partial x_{PU}} q - s = 0$$

The best-response function of the public research body is then:

$$x_{PU} = \frac{9}{8\alpha^2}s - \frac{a - c}{\alpha} - \frac{(1 + \beta)}{\alpha}x_{Spu}^{NC} \quad (23)$$

Equation (23) shows that the public effort is negatively correlated with private R&D effort. Indeed, since the government's aim in fixing x_{PU} is to maximise social welfare, the public sector increases its research effort to offset any decreases in private investment. Conversely, the social value of compensating in this way for a lack of private R&D increases the more the private effort decreases. This effect is reinforced by a high spillover level (β) and low public externalities (α).

The R&D efforts in the second stage are obtained from the best-response functions (Equations (22) and (23)), as a function of the subsidy level:

$$x_{Spu}^{NC} = \frac{(2 - \beta)}{8\alpha(1 + \beta)}s \quad (24)$$

$$x_{PU}^{NC} = \frac{9 - (2 - \beta)}{8\alpha^2}s - \frac{a - c}{\alpha} \quad (25)$$

Comparing the impacts of the subsidy on the public and private research sectors shows that:

$$\frac{\partial x_{PU}^{NC}}{\partial s} > \frac{\partial x_{Spu}^{NC}}{\partial s} > 0, \quad \forall \alpha \in (0, 1), \beta \in [0, 1]$$

The direct positive effect of the subsidy on the public research effort is greater than its indirect effect on the private effort. We can also see that the presence of a public body does not solve the problem of encouraging private innovation when the level of spillover increases:

$$\frac{\partial x_{Spu}^{NC}}{\partial \beta} < 0 \quad \forall \alpha \in (0, 1), \quad \beta \in [0, 1]$$

Substituting Equations (24) and (25) into Equation (21) with $x_{Spu}^{NC} = x_i = x_j$ yields the output level:

$$q_{Spu}^{NC} = \frac{3}{8\alpha}s \quad (26)$$

At end of the second stage, the profit of both firms as a function of the public research effort is:

$$\pi_{pr}^{NC}(s) = (q_{Spu}^{NC}(s))^2 - (1 + \beta)(x_{Spu}^{NC}(s))^2 = \frac{9(1 + \beta) - (2 - \beta)^2}{64(1 + \beta)\alpha^2}s^2 \quad (27)$$

This already shows that the profits and the firms' outputs and R&D efforts all increase with the subsidy level and decrease as public externalities (α) increase. This latter tendency can be explained by the public sector's investment choices as a function of α . For the public sector indeed, the externality discourages (encourages) research efforts if and only if the subsidy is high (low):

$$\frac{\partial x_{PU}^{NC}}{\partial \alpha} < 0 \quad \Leftrightarrow \quad s > \frac{4\alpha}{9 - (2 - \beta)}(a - c) = \bar{s}_{NC}$$

Equation (23) summarises this intuition. Public externalities have a dual effect on the public effort. The first effect, positive, reflects the aim of the public research sector (to maximise social welfare). This aim translates into supporting private

efforts through the effect of public externalities on lowering production costs. The second effect, negative, reflects the social cost of the public research effort, which increases with s :

$$\frac{\partial x_{PU}^{NC}}{\partial \alpha} = \underbrace{-\frac{9}{4\alpha^3}s}_{<0} + \underbrace{\frac{(a-c) + (1+\beta)x_{Spu}^{NC}}{\alpha^2}}_{>0}$$

Consequently, if the negative effect is stronger, public externalities (α) discourage public research efforts. Thus, high subsidy levels ($> \bar{s}_{NC}$) lead to an investment incentive problem in the public research sector.

3.2.2 Welfare-optimal subsidy level

In the last stage of the game, the optimal subsidy level is obtained by maximising the welfare function, namely (as a function of s):

$$SW_{Spu}^{NC}(s) = 4(q_{Spu}^{NC}(s))^2 - 2(1+\beta)(x_{Spu}^{NC}(s))^2 - s.x_{PU}^{NC}(s)$$

Maximising social welfare in terms of s gives,

$$\frac{\partial SW}{\partial s} = 8\frac{\partial q_{Spu}^{NC}}{\partial s}q_{Spu}^{NC} - 4(1+\beta)\frac{\partial x_{Spu}^{NC}}{\partial s}x_{Spu}^{NC} - s\frac{\partial x_{PU}^{NC}}{\partial s} - x_{PU}^{NC} = 0$$

and thus:

$$s_{Spu}^{NC} = \frac{16\alpha(1+\beta)}{18(1+\beta) - (2-\beta)(5\beta+2)}(a-c) > \bar{s}_{NC} \quad (28)$$

The optimal subsidy is greater than \bar{s}_{NC} , which implies that α has a negative effect on public research efforts.

Substituting the optimal subsidy into the preceding equations gives the equilibrium results of the three stage game listed in Table (1).

3.3 The cooperative scenario with subsidies to the public research section

Let us now consider that rather than maximise their individual profits during the R&D stage, the firms choose the research effort that maximises the sum of profits.

$$\Pi_{Spu}^C = \sum_{i=1}^2 \left\{ \left(\frac{a-c + (2-\beta)x_i + (2\beta-1)x_j + \alpha x_{PU}}{3} \right)^2 - (1+\beta)x_i^2 \right\} \quad (29)$$

Solving the game as before, we obtain:

$$\frac{\partial \Pi_{Spu}^C}{\partial x_i} = 0 \quad \Leftrightarrow \quad x_{Spu}^C = \frac{(a-c) + \alpha x_{PU}^C}{9 - (1 + \beta)} \quad (30)$$

The level of output at the end of the second stage is then:

$$q_i(x_{Spu}^C, x_{PU}^C) = \frac{(a-c) + (1 + \beta)x_{Spu}^C + \alpha x_{PU}^C}{3} \quad (31)$$

with $i = \{1, 2\}$

Equations (30) and (23), with a private effort x_{Spu}^C , give the R&D efforts as a function of the subsidy, s :

$$x_{Spu}^C(s) = \frac{s}{8\alpha} \quad (32)$$

$$x_{PU}^C(s) = \frac{9 - (1 + \beta)}{8\alpha^2} s - \frac{a-c}{\alpha} \quad (33)$$

Comparing the results with and without cooperation shows that the effect of the subsidy on the private research sector is stronger in cooperative scenario (C), provided the spillovers are high enough:

$$\frac{\partial x_{Spu}^C}{\partial s} > \frac{\partial x_{Spu}^{NC}}{\partial s} > 0 \quad \text{if } \beta > 0.5$$

However, the effect is opposite for the public research effort:

$$\frac{\partial x_{PU}^{NC}}{\partial s} > \frac{\partial x_{PU}^C}{\partial s} > 0 \quad \text{if } \beta > 0.5$$

For a given α , the subsidy has a greater effect on private efforts when the firms cooperate in R&D than when they do not, and less of an effect on public research efforts when the spillover level is high. This policy therefore has opposite effects on the public and private sectors: when it favours private research (high spillovers) it hinders public research and vice versa.

For the public effort, the result is the same as in the NC scenario: public externalities discourage research efforts if and only if the subsidy is above a certain threshold:

$$\frac{\partial x_{PU}^C}{\partial \alpha} < 0 \quad \Leftrightarrow \quad s > \frac{4\alpha}{9 - (1 + \beta)}(a-c) = \bar{s}_c$$

This threshold above which the incentive for the public sector is to reduce its research effort is higher the stronger the public externalities are. The reasoning is similar to the one followed for the NC scenario. The threshold subsidy is higher in the cooperative case, $\bar{s}_c > \bar{s}_{nc}$, if and only if $\beta > 0.5$. Otherwise, $\bar{s}_c < \bar{s}_{nc}$.

Equations (31), (32) and (33), can be used to show that the output levels are the same as in the NC scenario (Equation 26), even though the research efforts differ:

$$q_{Spu}^C(s) = \frac{3}{8\alpha}s$$

Here, we see that the public research effort compensates for the drop in private output between the NC and C scenarios, thereby maximising the total net output.

At the end of the second stage, the expression for the two firms' profit as a function of the public sector effort is similar to the one in the non-cooperative case:

$$\pi_{Spu}^C(s) = (q_{Spu}^C(s))^2 - (x_{Spu}^C(s))^2 = \frac{9 - (1 + \beta)}{64\alpha^2}s^2 \quad (34)$$

For a same level of subsidy s ,

$$\pi_{Spu}^{NC}(s) > (<) \pi_{Spu}^C(s) \quad \text{if } \beta > (<) 0.5$$

which can be explained by a higher level of private investment in the cooperative R&D scenario when the spillovers are high enough (> 0.5).

We can therefore calculate the optimal subsidy in terms of social welfare,

$$\frac{\partial SW}{\partial s} = 8 \frac{\partial q_{Spu}^C(s)}{\partial s} q_{Spu}^C(s) - 4(1 + \beta) \frac{\partial x_{Spu}^C(s)}{\partial s} x_{Spu}^C(s) - s \frac{\partial x_{PU}(s)}{\partial s} - x_{PU}(s) = 0$$

which is solved by:

$$s_{Spu}^C = \frac{16\alpha}{18 - 3(1 + \beta)}(a - c)$$

Substituting the optimal subsidy into the relevant equations gives the Subgame Perfect Nash equilibrium show in Table (1), from which we draw the following propositions:

Proposition 4 $\forall \beta \in (0, 1]$,

$$x_{Spu}^{NC,C} > x^{NC,C}, \quad Q_{Spu}^{NC,C} > Q^{NC,C}, \quad \text{and} \quad \pi_{Spu}^{NC,C} > \pi^{NC,C}$$

These equilibrium results show that the presence of a public research body generating knowledge externalities leads by itself to better results in terms of all criteria than a policy with no subsidies (NS), in both cooperative and non-cooperative scenarios.

We can compare the equilibrium results for the NC and C scenarios in the presence of a public research body.

Proposition 5 $\forall \alpha \in (0, 1)$, at equilibrium, the following relations hold:

$$\begin{aligned} s_{Spu}^{NC} &> (<) s_{Spu}^C \quad \text{if } \beta < (>) 0.5 \\ x_{PU}^{NC} < x_{PU}^C, \quad \forall \beta \in [0, 1] \quad \text{and} \quad x_{Spu}^{NC} < (>) x_{Spu}^C \quad \text{if } \beta > (<) 0.5 \\ Q_{Spu}^{NC} &< (>) Q_{Spu}^C \quad \text{if } \beta > (<) 0.5 \\ \pi_{Spu}^{NC} &\leq \pi_{Spu}^C \quad \forall \beta \in [0, 1] \end{aligned}$$

Proposition 5 highlights the benefits (in terms of R&D efforts and producer and consumer surplus) of coordinating R&D efforts in the presence of a public research body when the spillover level is high (> 0.5) (see Figure 1). An interesting feature is the impact of public externalities on the equilibrium results. In the private sector, if the government adjusts the subsidy so as to maximise social welfare, results do not depend on the level of public externalities, being completely offset by the subsidy. Indeed, the latter increases with the strength of the public knowledge externalities. One should recall however that too much funding of the public sector leads it to reduce its research effort monotonically when α increases. This effect is observed in both non-cooperative and cooperative scenarios.

The following lemma clarifies what the disincentive effect of the public externalities are on the research effort of the public body in the two scenarios:

Lemma 2 *Comparison of the impact of public externalities on public research effort in cooperative and non-cooperative research scenarios:*

$$\frac{\partial x_{PU}^{NC}}{\partial \alpha} < \frac{\partial x_{PU}^C}{\partial \alpha} < 0 \quad \text{if } \beta > 0.5$$

An increase in public and private externalities (spillovers) is less of a disincentive to the public research effort when the firms cooperate. In terms of social welfare, the public sector supplies less of an effort in the cooperative case when spillovers are high, which limits the negative impact of α on the public research effort. This confirms the notion that cooperative strategies improve the research effort when a public research body is involved. But this also highlights the problem public laboratories have appropriating their research, a problem that is not solved by this funding policy.

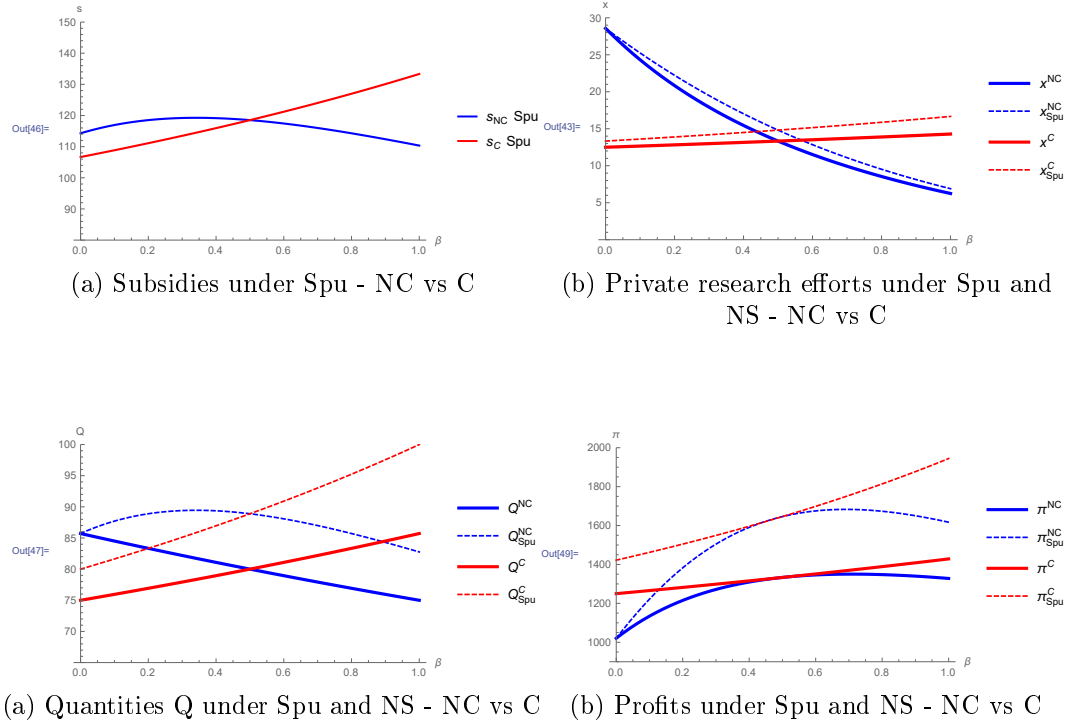


Figure 1: Comparisons between Spu policy and NS

4 Comparing the two funding policies

We now look to compare the two public policies, Spr and Spu, whose objective is to encourage innovation. Considering first the total R&D efforts, these are denoted XT and account for all research investment, including public investment as part of the Spu policy (see Table 1).

Proposition 6 *Funding the public research sector (Spu) stimulates research investment more than funding the private sector (Spr) does, provided the public externality (α) is not too high:*

$\forall \beta \in [0, 1]$,

$$XT_{Spu}^{NC} \geq (\leq) XT_{Spr}^{NC} \quad \text{if} \quad \alpha \leq (\geq) \alpha^{NC} = \frac{3\beta(2-\beta)(9-2(1+\beta))}{4((1+\beta)(20-7\beta)-9(2-\beta))} \in (0, 1)$$

$$XT_{Spu}^C \geq (\leq) XT_{Spr}^C \quad \text{if} \quad \alpha \leq (\geq) \alpha^C = \frac{(1+\beta)(9-2(1+\beta))}{4(9-(1+\beta))} \in (0, 1)$$

This proposition (illustrated in Figure 2) emphasises the fact that the Spu policy generates more total investment in research than the Spr one does when the public externality is sufficiently low. The reason for this is simple: the total research effort decreases as the public externality (the portion of public research that benefits firms) increases, whether the firms cooperate or not: the disincentive effect of the externality on the public research effort dominates. Furthermore, the positive effect of the subsidy on the total efforts decreases when α increases. In this context, for identical spillovers levels, low welfare-optimal subsidies lead to a higher total research investment under Spu than under Spr. Indeed, the following lemma shows that for low public externalities (α), the optimal subsidy level under Spu is lower than under Spr.

Lemma 3 $\forall \beta \in [0, 1]$, comparing the welfare-optimal subsidy levels shows that:

$$s_{Spu}^{NC} \leq (\geq) s_{Spr}^{NC} \quad \text{if} \quad \alpha \leq (\geq) \alpha_s^{NC} = \frac{(3\beta)(18(1+\beta) - (2+5\beta)(2-\beta))}{8(9-2(1+\beta))} \in (0, 1)$$

$$s_{Spu}^C \leq (\geq) s_{Spr}^C \quad \text{if} \quad \alpha \leq (\geq) \alpha_s^C = \frac{(1+\beta)(18-3(1+\beta))}{8(9-2(1+\beta))} \in (0, 1)$$

The conclusion is that low welfare-optimal subsidies to public research lead to more overall investment in research than subsidies to private sector research can. This paradoxical result is explained by the disincentive effect of the public externality. Similarly, cooperative strategies outperform non-cooperation in terms of total research efforts under the Spu policy, but not under the Spr policy.

Proposition 7 $\forall \beta, \alpha \in (0, 1)$, the producer surplus and the consumer surplus are always higher under the Spr than under the Spu policy, whether the firms cooperate or not (NC and C scenarios).

These last two propositions can help guide public policy. An Spr approach seems preferable in terms of total surplus (consumer and producer surplus), but the success of this policy does not rely on cooperation between the firms. Nonetheless, an Spu approach stimulates more total investment in R&D provided the public sector properly appropriates its research (by protecting and/or commodifying its discoveries for example). If subsidies are allocated to the public sector, then R&D cooperation needs to be encouraged, in particular when spillovers are high. This approach is then less costly than subsidising innovating firms would be.

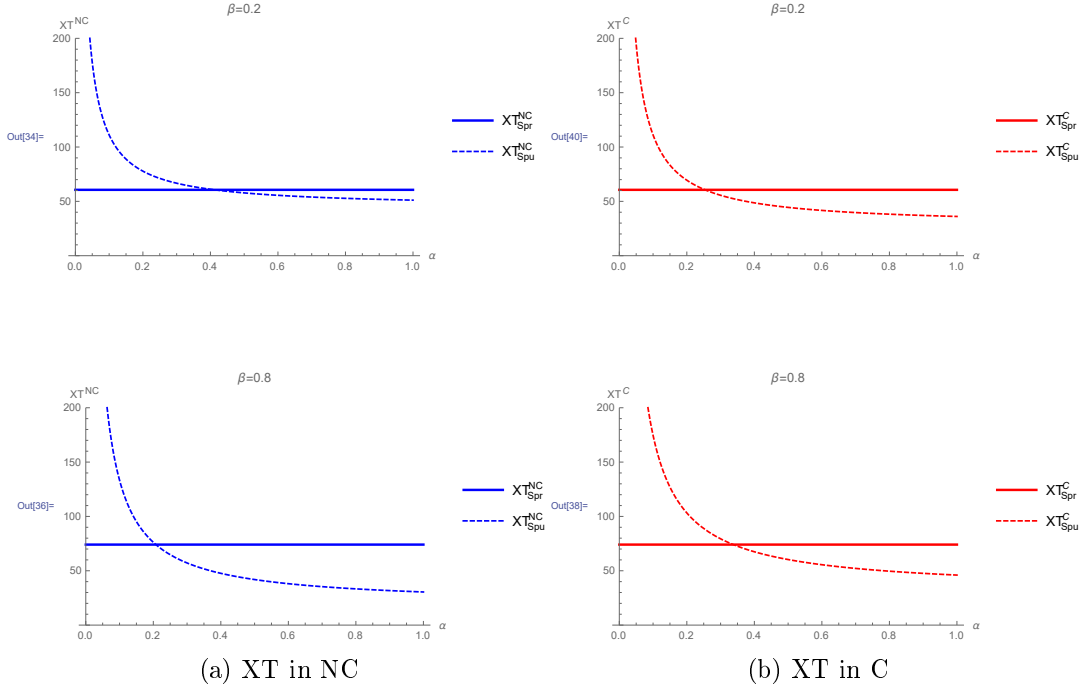


Figure 2: Total R&D efforts under Spr and Spu policies as a function of the public externality, α

5 Conclusion

In conclusion, the main results of this study are

1. Policies of subsidising private or public sector research (Spr or Spu) are both strictly more effective than R&D cooperation alone.
2. The success of the Spr policy does not hinge on the presence of cooperation during the R&D stage. Except for the producer surplus (higher in the NC case when spillovers are high), when research is subsidised, cooperation and non-cooperation perform equally in economic terms.
3. Subsidising private sector innovation is more effective than subsidising public research in terms of social welfare (producer and consumer surplus). However, the Spu policy leads to a greater research effort overall provided the public sector properly handles the release of its discoveries (low public externality). Under this condition, the Spu approach has a lower social cost than directly subsidising firms does. Cooperation in R&D is then preferable to non-cooperation.

	Spr policy		Spu policy	
	NC	C	NC	C
s	$\frac{6\beta}{X}A$	$\frac{2(1+\beta)}{X}A$	$\frac{16\alpha(1+\beta)}{Y}A$	$\frac{16\alpha}{W}A$
x_{PU}	-		$\frac{3\beta(2-\beta)}{\alpha Y}A$	$\frac{(1+\beta)}{\alpha W}A$
x_{pr}	$\frac{2}{X}A$		$\frac{2(2-\beta)}{Y}A$	$\frac{2}{W}A$
$XT = 2x_{pr} + x_{PU}$	$\frac{4}{X}A$		$\frac{(2-\beta)(4\alpha+3\beta)}{\alpha Y}A$	$\frac{(1+\beta)+4\alpha}{\alpha W}A$
Q	$\frac{6}{X}A$		$\frac{12(1+\beta)}{Y}A$	$\frac{12}{W}A$
π	$\frac{9-4(1-2\beta)}{X^2}A^2$	$\frac{9}{X^2}A^2$	$\frac{4(1+\beta)(9(1+\beta)-(2-\beta)^2)}{Y^2}A^2$	$\frac{4(9-(1+\beta))}{W^2}A^2$
SW	$\frac{4}{X}A^2$		$\frac{8(1+\beta)}{Y}A^2$	$\frac{8}{W}A^2$

Table 1: Welfare-optimal subsidy, Individual R&D efforts, Total R&D efforts, Output, Profit, Total surplus
 $A = (a - c)$, $X = 9 - 2(1 + \beta)$, $Y = 18(1 + \beta) - (2 + 5\beta)(2 - \beta)$, $W = 18 - 3(1 + \beta)$

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