The Intellectual Spoils of War? Defense R&D, Productivity, and International Spillovers

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Abstract. We examine the impact of government funding for R&D—and defense-related R&D in particular—on privately conducted R&D, and its ultimate effect on productivity growth. We estimate longitudinal models that relate privately funded R&D to lagged government-funded R&D using industry-country level data from OECD countries and firm level data from France. To deal with the potentially endogenous allocation of government R&D funds we use changes in predicted defense R&D as an instrumental variable. In many OECD countries, expenditures for defense-related R&D represent by far the most important form of public subsidies for innovation. In both datasets, we uncover evidence of "crowding in" rather than "crowding out," as increases in government-funded R&D for an industry or a firm result in significant increases in private sector R&D in that industry or firm. On average, a 10% increase in government-financed R&D generates a 5% to 6% additional increase in privately funded R&D. We also find evidence of international spillovers, as increases in government-funded R&D in a particular industry and country raise private R&D in the same industry in other countries. Finally, we find that increases in private R&D induced by increases in defense R&D result in productivity gains.

JEL: D24, O32, O33, O38, O47

Acknowledgements: We thank the Economic and Social Research Council for their financial support through the Centre for Economic Performance. Patrick Warren has provided truly outstanding research assistance. Pierre Azoulay, Josh Lerner, Heidi Williams, and participants in many seminars have given helpful comments. Mirko Draca kindly made his data on US defense procurements available to us, which was invaluable. We are also grateful to Sharon Belenzon and David Thesmar for useful discussions and sharing their data with us.

1 Introduction

While a large body of empirical research has argued that R&D is a key source of firm productivity growth, the question of exactly which policies governments should adopt to foster R&D investment is still largely an open question.[1] In this paper, we study the impact of government funding for R&D on privately conducted and financed R&D, and its ultimate effect on productivity growth. We use two complementary longitudinal datasets—a country-industry-year-level dataset for OECD countries and a firm-year-level dataset for France—to address two related questions. First, we estimate the effect of government-funded R&D on private R&D—namely, R&D conducted and financed by private businesses. We are interested in whether government-funded R&D in a given country and industry (or to a given firm) displaces or fosters private R&D in the same country and industry (or firm). Having found evidence of a positive effect (i.e., "crowd in" rather than "crowd out"), we next estimate how investment in R&D affects productivity. For both types of analysis, we assess whether the benefits of public R&D investment are limited to a single country or spill over across multiple countries.

[1] The literature focuses on two types of R&D policies. First, there are fiscal policies towards R&D such as Hall (1993), Bloom, Griffith, and Van Reenen (2002), Moretti and Wilson (2014), Dechezlepretre et al. (2019). Second, there is a body of empirical research on the effect of public R&D on private R&D (e.g. David, Hall, and Toole, 2000; Lach, 2002; Goolsbee, 1998; Wallsten, 2000; Dimos and Pugh, 2016). Examples of papers with a causal identification strategy include Azoulay et al. (2019a); Bronzini and Iachini (2014); Howell (2017); Slavtchev and Wiederhold (2016); Guellec and van Pottelsberghe de la Potterie (2001) and Pless (2019).

To isolate the causal effect of government-funded R&D, we use quasi-exogenous variation in defense-related R&D. Defense-related R&D is an important but relatively understudied component of public policy on R&D. It represents a key channel through which governments seek to shape innovation (Lichtenberg, 1995, Draca 2013). In the US, annual government defense-related R&D expenditures amounted to about $78.1 billion in 2016, 57.2% of all government-funded R&D (Congressional Research Service, 2018). While defense-related R&D is motivated by goals that are not mainly economic, it is often the most important *de facto* industrial policy used by the federal government to affect the speed and direction of innovation in the economy. The amount of public money flowing into defense R&D dwarfs the amount spent on other prominent innovation policy tools in the US. For example, the total budget of the National Science Foundation or the overall value of the federal R&D tax credit in a typical year are less than one tenth of federal outlays for defense-related R&D (National Science Foundation 2006). Defense R&D is the single most important component of government-funded R&D in the UK and France as well, and a major component of government-sponsored R&D in many other developed economies.

We begin our empirical analysis using a unique dataset that we constructed by linking detailed information on defense-related and non-defense related government-funded R&D to information on private R&D, output, employment, and salaries in 26 industries in all OECD countries over 23 years. We estimate models that relate privately funded R&D in a given country, industry, and year to government-funded R&D in the previous year, conditioning on a full set of country-industry and industry-year fixed effects.

We complement this industry-level analysis with a firm-level analysis based on a longitudinal sample of firms that engage in R&D collected by the French Ministry of Research from 1980 to 2015. This is the only available dataset we know of that disaggregates public defense

R&D subsidies by firms across the whole economy. One advantage of using firm-level data is that we observe which firms within an industry actually receive public R&D funds and which do not. The longitudinal nature of the data allows us to control for firm fixed effects, absorbing all time invariant unobserved differences across firms that may be systematically correlated with the propensity to invest in R&D. We compare the same firm to itself in different moments of time, and identification stems from the exact timing of the public R&D award.

We use predicted defense R&D as an instrumental variable to isolate exogenous variation in public R&D. This instrument combines nationwide changes to defense R&D with fixed allocations across industries. Annual aggregate changes in defense spending reflect political and military priorities that are largely independent of productivity shocks in different domestic industries. Wars, changes of government, and terrorist attacks have had major influences on defense spending. In the US, for example, military R&D spending ramped up under President Reagan; fell back after the end of the Cold War and rose again after 9/11. Importantly for our identification strategy, the impact that nationwide exogenous changes in military spending have on defense related R&D varies enormously across industries, because some industries (e.g., aerospace) rely more heavily on defense-funding than others (e.g., textiles).

The sign of the effect of government-funded R&D on privately funded R&D could be positive or negative, depending on whether government-funded R&D crowds out or crowds in privately-funded R&D. Crowding out may occur if the supply of inputs to the R&D process (specialized engineers, for example) is inelastic within an industry and country (Goolsbee, 1998). In this case, the only effect of an increase in government-funded R&D is to displace private R&D with no net gains for total R&D. Crowding in may occur if (i) R&D activity involves large fixed costs and, by covering some of the fixed costs, government-funded R&D makes some marginal private sector projects profitable; (ii) government-funded R&D in an industry generates technological spillovers that benefit other private firms in the same industry; and/or (iii) firms face credit constraints.

Empirically, we find strong evidence of crowding-in across both the OECD and French datasets. Increases in government-funded R&D generated by variation in defense R&D translate into significant increases in privately funded R&D expenditures, with our preferred estimates of the elasticity equal to about 0.5. Our estimate implies that defense-related R&D is responsible for an important part of private R&D investment in some industries. For example, in the US "aerospace products and parts" industry, defense-related R&D amounted to $3,026 million in 2002 (nominal). Our estimates suggest that this public investment results in $1,948 million of additional private investment in R&D. Considering the total amount spent by the US government, we estimate that private R&D investment in the US is $85 billion higher than the counterfactual with no government-funded defense R&D. Using our estimates, we calculate that dollar-for dollar, publicly funded R&D generates twice as much overall R&D compared to R&D tax credits.

Our estimates also indicate that cross-country differences in defense R&D might play an important role in determining cross-country differences in overall private sector R&D investment. For example, we estimate that if France increased its defense R&D to the level of the US as a fraction of its GDP (admittedly a large increase), private R&D in France would increase by 10.3%.

We also find evidence of spillovers *between* countries.[2] Increases in government funded R&D in one country appear to increase private R&D spending in the same industry in other countries. For example, an increase in government-funded R&D in the US chemical industry induced by an increase in US defense spending in the chemical industry raises the industry's private R&D in the US, but it also raises private R&D in the German chemical industry. This type of cross-border spillover is consistent with the presence of industry-wide technological or human capital spillovers.

In the final part of the paper, we turn to the effect of R&D on productivity. We uncover a positive effect of private R&D on TFP. Our preferred model suggests that an increase in the defense R&D to value added ratio of one percentage point causes an 8.3% increase in the yearly growth rate of TFP (e.g., from 0.98 percent per annum to 1.06 percent). We view this as a significant but not overwhelming effect. It suggests that a small fraction of US economic growth is accounted for by investment in defense R&D. For example, defense R&D in the US increased by a third between 2001 and 2004 following the 9/11 attack. We estimate that, holding taxes constant, this translated into a 0.005 percentage point increase of the annual TFP growth rate, or a 1.5% increase.

Overall, our estimates suggest that cross-country differences in defense R&D play a role in explaining cross-country differences in private R&D investment, speed of innovation, and ultimately in productivity of private sector firms. We caution that our estimates do not necessarily

[2] International spillovers of R&D are studied by Hall, Mairesse, and Mohnen (2010); Coe and Helpman (1995); Pottelsberghe and Lichtenberg (2001); Keller (2004); and Bilir and Morales (2015).

imply that it is desirable for all countries to raise defense R&D across the board. Our finding that government-funded R&D results in increased private R&D does not necessarily imply that defense R&D is the most efficient way for a government to stimulate private sector innovation and productivity. There are other possible innovation policies available to governments (see Bloom, Van Reenen and Williams, 2019, for a survey).

2 Conceptual Issues, Econometric Models and Identification

2.1 How Government R&D May Affect Private R&D

We focus on the effect of government-funded R&D on private R&D activity. Specifically, we are interested in the direct effect for or a firm of receiving government-funded R&D on the recipient's own private R&D investment.

The direction of such effect is unknown a priori. If increases in government-funded R&D crowd out private R&D, the effect will be negative. In the case of complete crowding out, the only effect of the policy is to displace private R&D, with no net gain in total R&D. This would be the case if the supply of inputs in the R&D process in any given industry was perfectly inelastic in the short run. A key input in this respect is likely to be specialized scientists and engineers and the elasticity of their supply to a country-industry depends on their mobility across industries and countries. With inelastic supply to a country-industry, increases in public funds for R&D come at the expense of declines in private R&D.

If, on the other hand, increases in government funded R&D crowd in private R&D, the effect will be positive. In this case, more public R&D stimulates even more private R&D. There are at least three possible reasons for why this might be the case.

First, in the presence of large fixed costs, public R&D may make marginal private projects feasible. In most industries, R&D activity is characterized by large fixed costs in the form of labs, research, human capital accumulation, set up costs, etc. It is realistic to think that some of these fixed costs can be used for multiple projects. For example, lab infrastructure set up for a specific project can, in some cases, be used for other projects as well. Similarly, a scientist's human capital acquired while working on a specific project—the intellectual understanding of a specific literature, for example, or her mastery of a scientific technique—can be helpful in other projects. By paying for some of the fixed costs, government-funded R&D may make profitable for private firms' projects that otherwise would not have been profitable. Similarly, if government-funded R&D results in process innovation, it is conceivable that this innovation can indirectly benefit private R&D. Second, if firms are credit constrained, the public provision of R&D might relax these financial constraints.

Finally, government-financed R&D investment by one firm may make other firms in the same industry more productive because of technology or human capital spillovers (e.g., Moretti, 2004 and 2019). In this case, an increase in government-financed R&D directly raises R&D in the firm that receives the government contract and may indirectly raise R&D in other firms in the same industry or same locality. Spillovers could also be negative in the case of strategic substitutability, as rival firms could free ride off the R&D of the supported firms (e.g., Bloom, Schankerman, and Van Reenen, 2013).

An implication that is relevant for our empirical analysis is that in the presence of R&D spillovers within an industry the estimated coefficient from industry-level data does not need to be identical to the coefficient from firm-level data in equation. Broadly, we expect industry coefficients should be larger if crowd-in induces rival firms to do more R&D (e.g., due to strategic complementarity) or smaller if rivals do less R&D (e.g., due to strategic substitutability).

2.2 Econometric Models

In our analysis of OECD data, the level of observation is an industry-country-year, and we assume that privately funded R&D expenditures in industry i in country k at time t, R_{ikt}, can be written as

$$\ln R_{ikt} = \alpha^{OECD} \ln S_{ik(t-1)} + \beta^{OECD} \ln Y_{ikt} + \lambda X_{kt} + d_{ik} + d_{it} + \upsilon_{ikt} \tag{1}$$

where $S_{ik(t-1)}$ is government-funded R&D expenditures; Y_{ikt} *is* output; X_{kt} is a vector of country by year observables; and d_{ik} and d_{it} are a set of industry by country and industry by year fixed effects. In our baseline models, X_{kt} includes country-specific linear trends and GDP at $t-1$, thus controlling for country-specific long run trends and business cycles as these demand side effects are likely to affect innovation.

In our analysis of the French data, the level of observation is the firm-year and firm f's R&D can be written as:

$$\ln R_{fit} = \alpha^{FRA} \ln S_{fi(t-1)} + \beta^{FRA} \ln Y_{fit} + d_f + d_t + \upsilon_{fit} \tag{2}$$

where we include a set of firm fixed effects (d_f) to absorb all sources of time-invariant heterogeneity across firms. Since in this specification we only have one country, we do not include X_{kt} and d_{ik} as these are absorbed by the time dummies and firm fixed effects respectively.

We derive equations (1) and (2) in the context of a simple model in Appendix A, where we also discuss the assumptions needed. The focus of our analysis is on estimating the coefficients α^{OECD} and α^{FRA} that relate changes in government-funded R&D in a given year to changes in private R&D in the following year.

To account for the possible correlation of residuals in each year across industries in a given country and across countries in a given industry, standard errors for OECD data are multi-way clustered by country and industry pair and country by year pair. In the regressions based on the French data, we cluster at the 2-digit industry for industry-level regressions; and 3-digit industry for firm-level regressions.

2.3 Identification

Government R&D policies are unlikely to be random and may be set endogenously as a function of shocks to firms in the private sector. Our models yield inconsistent estimates if the timing and amount of public R&D is correlated with *unobserved* time-varying determinants of private R&D. This may happen, for example, if governments tend to use public funds to help firms in sectors that are struggling and are experiencing declines in private R&D. In this case, changes in public R&D would be negatively correlated with unobserved determinants of private R&D, introducing a negative bias in our estimates of the coefficient α in equations (1) and (2). The opposite bias arises if governments tend to use public funds to help firms in sectors that are thriving and are experiencing increases in R&D over and above those experienced by the same sector in other countries. If governments disproportionately help "winners", the correlation between $S_{ik(t-1)}$ and υ_{ikt} (and $S_{fik(t-1)}$ and υ_{fikt}) is positive and OLS overestimates the true effect. If governments disproportionately help "losers" (compensatory policies), the correlation between $S_{ik(t-1)}$ and υ_{ikt} (and $S_{fik(t-1)}$ and υ_{fikt}) is negative and OLS overestimates the true effect.

A second possible reason why the OLS estimates of equations (1) and (2) may be biased is the presence of measurement error in our measure of public subsidies. In the presence of classic measurement error in S, attenuation bias may arise.

To deal with these two issues, we use an instrumental variable that is a function of variation in defense R&D subsidies. Defense R&D is by far the largest component of government R&D in many countries, e.g., United States, United Kingdom, and France. Defense R&D also causes the biggest variations in public R&D over time, and there is a large variation across countries, ranging from pacifist countries like Japan or neutral countries like Austria, to defense-heavy countries like the United States and South Korea. This ensures that our instrument has a strong first stage.

Defense R&D is usually motivated by geopolitical, not economic, considerations (Mowery, 2010), raising the possibility of using actual R&D defense subsidies as the instrument for government funded R&D. However, we are concerned that while most of the variation in defense R&D is motivated by geopolitical considerations, variation in defense R&D may also include an endogenous component. This would be the case if changes in the timing and amount of defense R&D allocated to some industries and firms respond at least in part to shocks to the supply or demand of private R&D in those industries or firms. While variation in R&D defense subsidies is almost certainly more exogenous than variation in overall public R&D, we cannot rule out the existence of an endogenous component.

For this reason, we use *predicted* defense R&D subsidies as instrumental variable instead of actual defense R&D subsidies. Predicted defense R&D subsidies isolate variation in defense R&D subsidies based on the combination of lagged defense R&D subsidies to a given industry and the overall total defense R&D spending. While the use of predicted instead of actual defense R&D subsidies may weaken the power of the instrument in the first stage, it strengthens its validity. In practice, our first stage has good power and is robust to various changes in the assumptions we use to construct the instrument.

The exact definition of predicted public defense R&D differs slightly for the OECD and the French dataset due to differences in level of aggregation and variable definitions. The details on how we construct the instrument are in Appendix B.

a) OECD. For the OECD analysis, predicted defense R&D subsidies (DR_{ikt}^{IV}) is defined as

$$DR_{ikt}^{IV} = share_{ik(t-1)}^{l} \cdot \widetilde{def_{kt}}$$

where $\widetilde{def_{kt}}$ is country k's total defense R&D spending in year. The term $share_{ik(t-1)}^{l}$ is a weighted average of one-year lagged government defense R&D in industry *i* as a share of all the government defense R&D in the *United States* and *France*. The weights are country-industry-time specific and depend on the similarity of country k's patent technology class distribution to the distributions of the *United States* and *France*. We use $share_{ik(t-1)}^{l}$ rather than the actual own country share in order to further reduce the risk that the industry distribution of defense R&D subsidies responds to expected country-specific shocks. Using the US and French data also has the practical advantage that defense R&D subsidy data at the country-industry level by year is not available for the other countries.

Our identifying assumption is that variation over time in the amount of *predicted* defense-related R&D experienced by a given industry in a given country is driven by shocks that are orthogonal to private R&D shocks, such as wars, terrorism, geopolitical shocks like the end of the Cold War, and the ideological preferences of the political leaders in power.

It is possible that while the *overall* level of defense spending in a country is orthogonal to the residual υ_{ikt}, the industry composition of defense spending may still be correlated with υ_{ikt}. This would be the case if, for example, French defense spending declined after the end of the Cold War for exogenous reasons, but the decline was smaller in, say, aerospace, for endogenous reasons. Because we are using a weighted average of US and French industry shares for all countries, this is a problem only to the extent that endogenous adjustments to the industry shares reflect unobserved industry-specific time-varying shocks that are shared by the US, France and the relevant country. As tests of this we look at models that exclude the US or France (or both) and find that they all yield similar estimates.

b) France. In the French analysis, the IV for firm-level models is defined as

$$DR_{ft}^{IV} = share_{i4} \cdot \widetilde{def_{\imath 3,t}}$$

where $share_{i4}$ is the annual share of defense R&D subsidies allocated to firm *f*'s main four-digit SIC industry (averaged across all years); and $\widetilde{def_{\imath 3,t}}$ is the level of defense subsidies defined at the three-digit industry level *excluding subsidies going to firm f itself in a particular year*, to avoid a mechanical correlation between the IV and instrumented variable. In some models, we perform an analysis at the three-digit industry level for France. In this case, we use the three-digit industry defense R&D share and the two-digit industry defense R&D subsidy excluding the subsidy to firm *f's* three-digit industry: $share_{i3} \cdot \widetilde{def_{\imath 2,t}}$. We tried using the US shares for the French analysis, but the first stages were weak.

2.4 International Effects

It is possible that increases in government-funded R&D in an industry in a given country affect private R&D investment by firms in the same industry located abroad. For example, an increase in government-funded R&D in the German chemical industry may increase private R&D in the French chemical industry. This would be the case if R&D is a strategic complement between countries, so French chemical firms decide to invest more to keep up in the race; or if there are significant cross-country technological or human capital externalities within the chemical industry. On the one hand, it is possible that the effect is negative. This may happen if the global supply of industry-specific R&D inputs (e.g., chemical engineers) is inelastic, so that their cost increases.

To empirically assess international effects, we use our OECD data to estimate models of the form:

$$\ln R_{ikt} = \alpha^{OECD} \ln S_{ik(t-1)} + \gamma^{OECD} \ln SP_{ik(t-1)} + \beta^{OECD} \ln Y_{ikt} + \lambda X_{kt} + d_{it} + d_{ik} + \upsilon_{ikt} \quad (3)$$

where $SP_{ik(t-1)}$ is a weighted average of government-funded R&D in other countries in the same industry and year with weights measuring the between country i and each other country: $SP_{ik(t-1)} = \sum_j d_{ij} S_{jk(t-1)}$ where d_{ij} is the economic or geographic "distance" between country i and country j (normalized to sum to one for each country i) and $S_{jk(t-1)}$ is, as before, government-funded R&D in industry i in country j.

3 Data and Basic Facts

3.1 OECD Industry-Country Data.

We combine data for OECD countries from the STructural ANalysis (STAN) dataset and the Main Science and Technology Indicators (MSTI) dataset. Our data include 26 countries, 26 industries, and 23 years, from 1987 to 2009. Appendix B describes in detail how we cleaned and merged the data and provides the exact definition of each variable with the corresponding source. Appendix Figure A1 shows how employment is distributed across the industries in our sample.

The definitions of R&D are based on the internationally recognized "Frascati Manual" used by the OECD and national statistical agencies. Our main R&D variable measures industry-level R&D *conducted by businesses* (known as "Business Enterprise R&D" or "BERD"). We will generally refer to BERD as simply "R&D" for brevity. While all BERD is conducted by firms, some of its funding comes from private sector sources while other funding comes from the government. Hence, in the notation of our model, BERD = $R + S$. We refer to the part of BERD that is funded by private sources as "privately-funded R&D," or "private R&D." This is the variable R, the main dependent variable in equations (1) and (2). We refer to the part of BERD that is funded by the government as "government-funded R&D" or "public R&D." This is the variable *S*. A subset of public R&D is defense-related, and we refer to it as "defense R&D." Note that *S* only includes government-funded R&D conducted by private firms and does not include R&D conducted by universities (and other non-profits) and by the government itself (e.g., in government R&D labs). Appendix Table A1 (Panel A) summarizes the variable definition and presents summary statistics.

Facts about R&D. There is wide variation in private R&D, public R&D, and defense R&D across countries, industries, and years. Consider first aggregate R&D as a percent of GDP by country (Appendix Table A2). The most R&D-intensive country is South Korea at 2.7%, followed by Sweden at 2%. The US also has a very high R&D/GDP ratio of 1.9%. At the other end of the spectrum, there are Southern European countries like Greece and Portugal, with ratios of approximately 0.2%.

R&D intensity also varies widely across industries. Appendix Figure A2 shows how *private* R&D is distributed across the industries in our sample; the chemical industry spends the largest share of private R&D in our sample, followed by telecommunications, and automotive.

Public R&D also varies widely across countries and over time. Appendix Table A3 shows that the US and Eastern European nations such as Poland and Slovakia have the highest share of R&D funded by the government (over 15%), whereas the share is under 2% in Switzerland and Japan. In many countries, such as the US, the UK, France, and Canada, the rate of public funding has decreased over time. Some of this is likely to be due to a shift from direct to indirect support to business R&D, such as tax breaks (see Guellec and van Pottelsberghe de la Potterie, 1999). In some of our models, we also control for tax incentives. Appendix Table A4 shows the defense share of government-funded R&D by country. Not surprisingly, the US has the highest proportion of defense-related R&D (57%), followed by Great Britain (35%), and then France (29%). In the data, we observe the defense-related part of the government's total R&D budget from the OECD MSTI. "Total government funded R&D" is all government budget appropriations or outlays of total R&D, i.e., not just the government-funded part of R&D conducted by businesses, but also the part of R&D conducted by government agencies and labs.

The defense share of R&D varies not just across countries, but also within country over time. This is important for the identification of our models, which include country by industry fixed effects. Figure 1 illustrates how the four largest economies in our data experienced very different developments in their shares of defense-related and government-funded R&D to GDP ratios over time. In the United States, defense R&D spending started at a very high level in the late 1980s under Reagan (over 0.8% of GDP) and fell subsequently after the fall of the Berlin Wall in 1989. After 9/11, defense R&D spending ramped up again under the War on Terror and the wars in Afghanistan and Iraq, rising from 0.45% (in 2001) to 0.59% (in 2008) of GDP. In Germany, defense spending is at a much lower level. Like the US, Germany reduced defense spending after the Cold War, with the rise of President Gorbachev and the fall of the Berlin Wall. In 1996, however, Germany and France cofounded a military agency focusing on R&D activities, causing a pick-up in defense R&D in Germany. In contrast to the US, Germany did not ramp up defense spending after 9/11; instead, it continued to downsize its military (European Parliament, 2011). In stark contrast, Japan has an even lower level of defense R&D spending, as its constitution commits the country to pacifism. However, Japan increased its military activities in response to North Korean missile tests in the late 1990s (Hagström and Williamsson, 2009). Finally, France shows a time-pattern relatively similar to Germany—the reduction in defense spending after the end of the Cold War is visible, but in contrast to Germany, France did ramp up defense spending after 9/11.

Overall, the experiences of these four major economies with highly variable levels of defense R&D illustrate how the timing of changes in defense R&D often reflects factors that are largely exogenous to economic and technological conditions, being driven by geopolitical events that are heterogeneous across countries.[3]

Our instrumental variable strategy is predicated on the notion that defense R&D is an important driver of overall government-funded R&D. Appendix Figure A3 presents the series of defense R&D and public R&D by *country* (summed across industries). Clearly, in most cases the two series tend to move together: the average correlation is 0.29 (standard error 0.11). The importance of defense R&D varies widely across industries: Aerospace tends to be the single most important beneficiary of defense R&D. In the OECD data the first stage of our IV relies on the relationship between public R&D and predicted defense R&D. The correlation at the industry level is visually strong (see Appendix Figure A4). In years when defense R&D is high (low), overall government funded R&D tends to be high (low).

3.2 French Firm-level Data

We use firm-level data collected by the French Ministry of National Education, Higher Education and Research ("Ministry of Research") in their annual R&D survey from 1980 through 2015. Appendix B provides details on the survey that seeks to include all large firms that perform

[3] When the conservative center-right party came to power in 1996, Spain saw a rise in military spending and a sharp increase in military R&D spending. The financial crisis in 2008 forced the government to cut the military budget, including R&D contracts (Barbé and Mestres, 2007).

R&D and a rotating sample of smaller firms that perform R&D. We refer to all R&D subsidies originating from Ministry of the Armed Forces and its agencies as "defense R&D subsidies." We refer to the sum of all R&D subsidies (including defense R&D subsidies) originating from any ministry or government agency as "total R&D subsidies" or just "R&D subsidies." We refer to the firm's R&D budget less total R&D subsidies, other national funds, and international funds, as "privately funded R&D."

The sample includes 12,539 firms appearing an average of 6.5 years each, 56% of which appear in more than 5 years.[4] Summary statistics are in Panel B of Appendix Table A1. Of the €833 billion in R&D conducted in our sample, €87 billion was publicly funded, and €57 billion of that was targeted at defense. In industries like aerospace/transport, the dominance of defense subsidies is even clearer, with the industry conducting €119 billion in R&D, of which €38 billion was publicly funded, almost €31 billion specifically for defense. The industries with the largest defense subsidies after aerospace/transport are electronics, technical instruments, machinery, and chemicals.

4 The Effect of Government-Funded R&D on Privately Funded R&D, Jobs and Wages

4.1 Effect of Public R&D on Domestic Private R&D: Estimates Based on OECD Data

Table 1 presents estimates of the relationship between privately funded R&D and lagged public R&D in the OECD industry-country panel. The dependent variable is R&D conducted in the private sector (BERD) that is also financed by the private sector (recall that it excludes government financed R&D). As discussed in the Data section, "Public R&D" is government-

[4] The overall sample includes 40,787 firms. But only 24% of firms appear in five or more years and almost 40% of firms appear just once.

financed R&D performed by private firms. All columns control for a full set of country by industry fixed effects, a full set of industry by year dummies and a set of country-specific linear trends. Standard errors are two-way clustered at the industry-country and country-year level. All models are weighted by the industry-country pair's initial share of employment in total country employment.

Panel A of Table 1 reports OLS estimates. It shows that there is a statistically significant positive correlation between public R&D and private R&D, more consistent with crowding in rather than crowding out. In Panel B, we report 2SLS estimates obtained by using predicted defense R&D as an instrument for public R&D. The first stages of our instrumental variable estimates are generally well identified. Weak instrument diagnostics are reported at the bottom and show that the instruments have good power: the F-Test (Kleibergen-Paap) ranges from 10.02 to 14.66 in our main specifications; and Anderson-Rubin Wald test rejects the null hypothesis of weak instruments in all columns.[5]

The entry in column (1) in panel B of Table 1 indicates a positive effect of public R&D on private R&D. A 10% increase in public R&D subsidies is associated with a 5.6% increase in the

[5] The first stage coefficients are interesting in their own right. A priori, it is unclear whether an increase in predicted defense R&D in an industry will necessarily result in an increase in total government-funded R&D in that industry. Given a budget constraint, it is possible that increases in defense spending are offset by declines in non-defense subsidies, leading to no net effect on total public R&D. Empirically, we find that this is not the case. A 10% increase in predicted defense R&D is associated with a 1% increase in total government-funded R&D, so there is not complete offset (See Appendix Table A4 in Moretti et al (2021)).

industry's privately funded R&D spending in the following year. A comparison with panel A indicates that the point estimate is larger than the corresponding OLS estimate. This could indicate that subsidies are compensatory—targeted at "losers" and/or the presence of measurement error in public R&D.

Other policies. One possible concern is that changes in defense R&D might be correlated with changes in other policies that affect firms' private R&D spending. For example, our estimate would be biased if, say, right-wing governments tend to both increase defense spending for specific sectors and simultaneously adopt pro-business policies for those sectors. In the rest of the table, we probe the robustness of our estimates to additional controls intended to capture variation in public policies. Since our sample size declines from 5,026 to 4,459, in column (2) we replicate the model in column (1) using the smaller sample for comparison.

In column (3) we add controls for industry output and national GDP; the coefficient on public R&D increases slightly to 0.518 (0.204). Recall that our models condition on country-specific linear trends. Adding country-specific *quadratic* trends to absorb non-linear drifts in each country results in significantly larger estimates of the effect of Public R&D. For example, the estimated IV coefficient from the model in column (3) is 0.780 (0.244).

In column (4), we add a measure of R&D tax credits based on data from Thomson (2012). R&D tax credits are an alternative form of government support for R&D used by a number of countries. Over the past 20 years, many governments have started to replace direct R&D subsidies with other fiscal policies such as R&D tax credits (Guellec and van Pottelsberghe de la Potterie, 1999; Moretti and Wilson, 2014). From the point of view of governments, publicly funded R&D and R&D tax credits are likely to be substitutes, making it possible that in practice the two types of public support are negatively correlated. In this case, our estimates might understate the true effect of government-funded R&D. In practice, the magnitude of this bias is unlikely to be large, since R&D tax credits are in most countries part of the national tax code, and unlike the direct R&D subsidies, they are not industry specific. Empirically, the coefficient on public R&D in column (4) appears to decrease to 0.476 (0.190).

Besides businesses, other institutions like universities and government-funded research labs receive subsidies for R&D, which might be correlated with business R&D subsidies. In column (5) we also include R&D subsidies to non-business institutions. Empirically, non-business R&D does not appear to affect private R&D undertaken by businesses significantly, and the coefficient on public R&D rises slightly. R&D subsidies might also be correlated with other business favoring policies, for example taxes on businesses, which might also affect private R&D directly (e.g., Akcigit et al. 2022). In column (6) we control for business tax revenues as a proportion of GDP (tax revenue data is from OECD and includes taxes on income, profits and capital gains of corporates). There is a weakly negative effect of taxes, but the point estimate on public R&D subsidies is robust to this addition.

Procurement and Future Demand. Another concern is that increases in defense R&D spending might be correlated with increases in expected future demand for output, since the military is often the main customer of defense companies. Consider the example of the F-35—one of the largest single defense programs in the US. It started with DARPA's ASTOVL program, which provided R&D subsidies to Lockheed Martin to do research on short/vertical takeoff and landing of aircraft. Ultimately, Lockheed Martin was the prime contractor for the production of the F-35. If after receiving the ASTOVL subsidy Lockheed Martin increased its private R&D investment not only as a function of the subsidy but also because it anticipated winning the contract for the production of the F-35, then our models would overestimate the effect of public

R&D on private R&D. Intuitively, our model would attribute to public R&D an effect that is in part driven by an increase in future demand. Note that in order for this to be a failure of our identification assumption, it is not enough that defense R&D in a given industry and country at time *t* is correlated with future procurement contracts. It also needs to be the case that firms in that industry and country invest in private R&D *at time t* not just as a function of the public subsidy but also because they expect to win future production contracts. While in the case of Lockheed Martin this may have been true, it is unclear how much current R&D expenditures firms may find optimal to incur for uncertain future contracts that may or may not materialize.

For our purposes, the question is how common cases like the F-35 are example. More precisely: how much of the changes in defense R&D funding observed in our data across industries-country pairs is correlated with changes in expectations of future procurement spending? Historically, large increases in government defense procurement have been typically targeted toward existing, rather than new technologies, while most R&D is likely to be directed at new technologies – see Milward (1977). This may suggest that the F-35 example is more the exception than the rule, at least historically.

Ultimately, this is an empirical question. To investigate the extent of the problem in our setting, in Appendix Table A5 we perform placebo tests based on components of defense spending that should be unrelated to R&D subsidies paid to businesses: defense procurement excluding R&D; and military wage bill excluding R&D. We use either using a narrow or a broad definition of R&D, so we end up with four placebo instruments. The idea is that changes in defense procurement excluding R&D in an industry are a direct measure of changes in product demand faced by firms in that industry. If our models are correctly specified, they should not result in changes in R&D. Similarly, changes in military wage bill excluding R&D are probably a good proxy for change in product demand, but should not directly result in changes in R&D. Thus, if our models are properly specified, the four placebo instruments should not be predictive of public or private R&D. Finding a significant correlation between the placebo instruments and public or private R&D would suggest that our IV estimates might be driven by demand effects coming from procurement spending, or by a correlation of defense spending with other policies that encourage economic growth and therefore R&D. The results in Appendix Table A5 indicate that the effect of non-R&D defense procurement and non-R&D military wage bill on public and private R&D is not statistically different from zero.

We also estimated versions of equation (1) that directly control for (i) current and future non-R&D military spending; or (ii) current and future output. The estimates are similar to the baseline estimates in Table 1. (See Appendix Table A5 in Moretti et al. (2021)). Overall, we conclude that the weight of the evidence appears to be more consistent with the effects of public R&D on private R&D reflecting forces of supply rather than demand.

4.2 Effect of Public R&D on Domestic Private R&D: Estimates Based on French Data

Table 2 contains the estimates for the French dataset. Compared to the estimates based on the OECD data, the firm-level French data allow for a much finer level of detail, since we observe which firms within an industry actually receive public R&D and which do not. In terms of identification, firm-level data allow us to estimate models that include firm fixed effects, therefore accounting for all time-invariant heterogeneity across firms. Identification comes from comparing the level of private R&D in the same firm observed before it receives a government R&D subsidy and after it receives a government R&D subsidy.

Panel A presents the industry-level results for France and panel B presents the firm-level results. We present industry-level results for comparison to the OECD industry-country data in

Table 1, although it should be noted that the French data allow for a finer degree of industry disaggregation (169 sectors). Column (1) of panel A shows the OLS estimates. The coefficient suggests a positive correlation between privately funded business R&D and lagged government subsidies but is smaller in magnitude than the OECD results in Table 1. Column (2) reports the corresponding IV estimate using defense spending predicted from more aggregate industry trends as an instrument for defense R&D subsidies. The first stage F-statistic is F = 11.56. (First stage coefficients are reported in Appendix Table A7 in Moretti at al. (2021)). The IV estimate is significant and much larger than the OLS estimate, just like the OECD results. The IV coefficient of 0.346 is not significantly different from the comparable OECD coefficient of 0.511 in column (2) of Table 1 Panel B (p-value of difference = 0.20).

Recall that defense spending at the industry level is not available in OECD industry data for most countries, but we do have it in France. Consequently, we include it directly on the right-hand side of the private R&D equation in the columns (3) and (4) of Table 2. The coefficient on defense subsidies is positive and significant for the OLS and IV specifications, although again the IV coefficient is larger: 0.150 (0.041). Note that a 10% increase in total subsidies is obviously a larger amount of money than a 10% increase in defense subsidies alone, which explains the smaller elasticity in column (4) compared to (2).

The firm-level analysis in panel B is based on a longitudinal sample of 12,586 firms observed for several years, for a total sample size of 81,201 firm-years. Panel B shows similar patterns to the results in panel A. In column (2), the IV coefficient is 0.119 (0.069), while in column (4), it is 0.374 (0.215). The IV estimates again lead us to reject the null of crowd-out: increases in public R&D result in more investment in private R&D, not less. Based on entries in column (2), a 10% increase in R&D subsidies is associated with a 1.2% increase in the firm's privately funded

R&D spending in the following year. This confirms that even after controlling for firm fixed effects, defense R&D subsidies appear to be crowding in private R&D spending.

A comparison with panel A of Table 2 indicates that industry-level coefficients are smaller than firm-level coefficients when we use defense R&D subsidies (columns (3) and (4)), but the reverse is true for total R&D subsidies (columns (1) and (2)). Coefficients from industry-level data do not need to be identical to coefficients from firm-level data in the presence of technology spillovers from R&D within an industry. Industry coefficients should be larger if crowd-in induces rival firms to do more R&D (strategic complementarity). However, it might be that rivals do less R&D if there is strategic substitutability (e.g., free riding), for example, meaning that industry coefficients would be less than their firm-level counterparts (Bloom, Schankerman, and Van Reenen, 2013). We will investigate spillover effects at the international level in more detail below.

OLS vs. IV. Overall, there is little evidence of upward bias in the OLS estimates in Tables 1 and 2. In fact, the OLS estimates are consistently below the IV estimates. In the context of our discussion in Section 2, there are three possible non-mutually exclusive explanations. First, this finding is consistent with compensatory government policies, whereby governments tend to subsidize industries that are underperforming in terms on R&D investment. For example, Criscuolo et al. (2019) find evidence of compensatory policies in the case of UK investment subsidies. In our data, there is some evidence that public R&D policies tend to be compensatory in OECD countries. To see whether public R&D subsidies tend to be directed toward industries that are struggling or thriving, we used our OECD data to estimate simple VAR models that relate changes in public R&D to changes in industry output in a given country and year (controlling for changes in country GDP). Results for models with ten lags are in Appendix Figure A5. Panel A indicates that public R&D subsidies increase after a negative industry output shock. While this evidence needs to be interpreted merely as suggestive, it appears more consistent with compensatory government policies. By contrast, Panel B shows that industry output reacts positively to lagged public R&D subsidies, as we would expect.

Alternatively, the finding of IV estimates being larger than OLS estimates may reflect attenuation bias from measurement error. Or it may reflect local average treatment effects. If the effect of public R&D is heterogeneous and it varies across firms and sectors, our IV estimates identify the effect for compliers. If the effect on private R&D for sectors and firms that experience an increase in government R&D due to an increase in defense R&D subsidies is larger than the effect for sectors and firms that experience an increase in government R&D due to an increase in non-defense R&D subsidies, then our IV estimates may be larger than our OLS estimates even if OLS estimates are unbiased.

4.3 Magnitude of the Estimated Effect

Taken together, the estimates in Tables 1 and 2 indicate that increases in public R&D translate into increases in private R&D expenditures. This is true both when we focus on industry changes across the whole OECD or within France and when we focus on within-firm changes in France. This crowd-in is consistent with the existence of agglomeration economies—whereby increases in government R&D raise the returns for private companies in the same country and industry—or large fixed costs or credit constraints.

Our preferred elasticity for the OECD dataset is 0.518 (Table 1, panel B, column (3)), suggesting that a 10% increase in government subsidies in a given year is expected to result in a 5% increase in private sector R&D the following year. Our preferred elasticity at the firm level in the French dataset is 0.119 (Table 2, panel B, column (2)). At the mean values of public and private R&D in France, this implies that €1 of additional public funds for R&D translates into €0.85 of extra R&D funded by the private sector. As noted above, the smaller firm level effects compared to industry level effects could be due to positive within industry spillovers.

Our findings imply that in some industries, defense-related R&D is responsible for a significant portion of private R&D investment. For example, in the US "aerospace products and parts" industry, defense-related R&D amounted to $3,027 million in 2002 (nominal). Our estimates suggest that this public investment results in $1,948 million of additional investment in private R&D. If we take the total amount spent by the US government, we estimate that private R&D investment is $85 billion higher than the counterfactual with no government-funded defense R&D.

Interestingly, differences in defense-related R&D can account for some of the differences in private R&D across countries. For example, our estimates indicate that if France increased its defense R&D to the level of the US as a fraction of GDP (admittedly a very large increase: roughly a factor of 2.2), private R&D investment would increase by 10.3%. Our estimates also indicate that if Germany increased its defense R&D to the level of the US as a fraction of GDP (an even larger increase), private R&D investment would increase by 72%.

In order to understand how the estimated effect of public R&D subsidies compares to the effect of alternative innovation policies, we compare public R&D subsidies to R&D tax credit policies. We consider the impact on total R&D of abolishing the US tax credit and reallocating the saved public funds to direct government grants.[6] On the most recent data, the federal tax credit costs $11.3 billion. Using the user-cost elasticity of around unity in Table 1, we estimate that the

[6] Other thought experiments are possible. But this one sidesteps the issue of what is the impact of R&D on productivity and what is the distorting effects of raising public funds.

credit raises R&D by $14.2 billion. By comparison, the crowd-in elasticities of Table 1 imply that spending the $11.3 billion saved from abolishing tax credits on grants would raise total R&D by $30.7 billion. This is over twice as much as the effect generated by R&D tax credits. Appendix C provides the details of these calculations, considers a range of robustness tests and concludes that direct grants are likely no worse value for money than tax incentives and generally seem to perform better.

4.4 Effect on Employment and Wages

We now examine the effect of increases in public R&D investment on employment and wages. This is important because an increase in private R&D *expenditures* does not necessarily equal an increase in R&D *activity*. If the supply of R&D workers is completely inelastic in the short run, increased R&D spending could simply result in higher wages, with little or no effect on employment and innovation (Goolsbee, 1998). On the other hand, if R&D workers can move across industries or across countries so that supply to a specific country and industry is fairly elastic, we might find significant increases in R&D personnel and limited increases in their wages. The effects on demand for non-R&D personnel in the industry depend on whether R&D generates technologies that substitute for or complement such labor.

Appendix Table A6 reports estimates of models where the dependent variable is employment or wages. Specifically: in column (3), the dependent variable is the number of workers directly engaged in R&D activities; in column (4) it is the number of workers not engaged in R&D activities; and in column (5) it is the average salary of R&D workers—measured as the cost of R&D personnel over divided by R&D personnel. OLS estimates using the OECD data uncover significant elasticities of employment of R&D workers and the average salary of R&D workers and significant positive but much smaller elasticities on the employment of non-R&D

workers. The large employment effects and smaller wage effects for R&D workers are consistent with an elastic labor supply, possibly indicating that it might be easy for R&D workers to relocate to the affected industry from other industries or countries.

For France, the estimated elasticities on employment of R&D workers in column (3) are similar to those for R&D expenditures in column (2), indicating that employment of French scientists increases proportionally to increases in R&D expenditures. At the same time, the employment effects are much larger than the wage effects, indicating a more elastic labor supply of researchers from possibly abroad compared to the average OECD country. IV estimates for French 3-digit industries have a similar pattern as OLS estimates, but estimates based on OECD data and French firm level data are too imprecise to draw firm conclusions.

4.5 International Effects

So far, we have estimated the direct effect of government-funded R&D in an industry and country on private R&D activity in the same industry and country. We now consider the possibility that government-funded R&D in an industry and country may have an additional, indirect effect on private R&D investment in *other* countries.

In panel A of Appendix Table A7, we regress private R&D on lagged domestic public R&D and lagged neighbors' public R&D, measured as a weighted average of public R&D in other countries in the same industry and year, with weights reflecting various measures of geographic and economic proximity (equation (3)). Column (2) uses the difference in GDP per capita as a distance measure, column (3) the geographic distance in kilometers between the capital cities, column (4) the difference in skill intensity as measured by the share of the population with tertiary education, column (5) the similarity of patent technology classes (out of 15 different technology classes), column (6) the difference in R&D intensity as measured by R&D/GDP. We instrument domestic public R&D but not neighbors' public R&D, which we assume to be exogenous to domestic firms. (The OLS coefficients are in Appendix Table A8).

The coefficient of interest is the one on neighbors' public R&D. It is positive and statistically significant in all columns but column (4), which uses skill intensity, indicating that if one country increases its public R&D, firms in nearby countries in the same industry increase their investment in private R&D after controlling for public R&D received from their own government. The positive effect is consistent with significant crowd-in between close countries when proximity is defined by income, geography, technology, FDI flows, and R&D intensity.

Panel B uses business R&D (not government-funded R&D) to compute the international spillover pool to test whether private R&D undertaken in a foreign country can also generate spillover effects. Here the coefficients in columns (5) and (6) are negative, providing evidence of international displacement between firms that are technological close or have similar R&D intensity. The coefficients in the other columns are not statistically different from zero. Thus, private R&D investment by firms in an industry and country appear to have either no effect, or in some cases to discourage competitors in the same industry in other countries from undertaking their own R&D.

In panel C we include both international public R&D and international business R&D simultaneously. In all but one specification, elasticities on international public R&D are positive while elasticity on international private R&D are negative and significant. The elasticities on the international public R&D and international private R&D appear of the same order of magnitude in absolute value, indicating that they have a quantitatively similar percentage effect, although of opposite sign.

Overall, we conclude that private and public R&D generate rather different spillover effects on R&D behavior. While there are positive spillover effects from public R&D subsidies, private R&D leads to either no spillover effects or crowding out. One possible explanation could be the fact that governmental subsidies may be associated with requirements to make research findings public; or that research supported by the government tends to be more basic research.

5 The Effect of R&D on Productivity

We now turn our attention to quantifying the effect of R&D investment on productivity. In the OECD data, we measure productivity as industry-country-year TFP. We assume that growth of TFP in industry *i* in country *k* at time *t*, A_{ikt}, can be approximated by:

$$\Delta \ln A_{ikt} = \rho \left(\frac{R+S}{VA}\right)_{ik(t-1)} + \gamma \Delta X_{ikt} + \Delta u_{ikt} \tag{4}$$

where *VA* is value added; ρ is the gross rate of return to R&D capital. In the French firm-level data, we have no information on capital stock or value added. Thus, our dependent variable is labor productivity defined as output per worker, $\left(\frac{Y}{L}\right)_{fikt}$:

$$\Delta \ln \left(\frac{Y}{L}\right)_{fikt} = \rho \left(\frac{R+S}{Y}\right)_{fik(t-1)} + \Delta u_{fikt} \tag{5}$$

We derive equations (4) and (5) in Appendix A.

In practice, variation in value added and output per worker reflect both variation in physical productivity as well as variation in the prices of output. This is a common issue in the estimation of production functions. In our context, this problem is likely to be serious because shocks to the demand for defense products (geopolitical shocks, leadership changes, etc.) are likely to results in shocks to the price of defense-related products. The defense industry is highly concentrated and has significant barriers to entry, at least in the short run. This means that the supply curve is almost certainly not infinitely elastic in the short run. An upward sloping supply curve implies that when product demand increases, our measure of TFP increases even if productivity does not change. As standard in this literature, we deal with this problem by using industry-year specific price deflators.

In Table 3, we estimate equations (4) and (5) by regressing changes in productivity on lagged total R&D intensity. Total R&D is measured as the sum of private R&D (*R*), public R&D (*S*) and R&D from any other source. The OLS coefficient on R&D of column (1) indicates a positive correlation between lagged R&D intensity and subsequent TFP growth. Column (2) adds country dummies and shows that the coefficient is essentially the same as in column (1). We find a similar coefficient of 0.097 (0.031) for the IV estimate in column (3), which is very similar to the OLS estimate. Column (4) reports the reduced form estimate. In this model the independent variable is defense R&D divided by value added, which has a both positive and statistically significant effect. We conduct a similar exercise for French three-digit industries in column (5). The OLS estimate is positive, just like the one for the OECD industry-country panel, but of smaller magnitude—0.026 (0.004). In column (6) we repeat this exercise on the French firm-level data. We uncover a coefficient of 0.040 (0.004), slightly larger than the corresponding industry-level elasticity. Unfortunately, the IV estimates corresponding to columns (5) and (6) are unidentified as the first stages have insufficient power (the F-statistics at the industry and firm level are 0.96 and 0.10 respectively).

The magnitude of the estimated effects in Table 3 is economically significant. Using the estimate for the OECD industry-country panel in column (4), for example, a permanent increase in the predicted defense R&D to value added ratio of one percentage point is associated with an increase in the annual growth rate of TFP of 0.08 percentage points. Since average annual TFP growth in our sample is around 0.98%, this represents an increase from 0.98% to 1.06% a year (i.e., an increase by 8.3%). Using the OLS estimate in column (5), a similar calculation suggests an increase from an average annual labor productivity growth rate of 0.05% to 0.076% a year in France.

To put this in perspective, consider that our estimates indicate that if France and Germany were to raise their defense spending to the level of the US as a percentage of value added—holding constant everything else and ignoring the additional tax revenues needed—they would experience an increase in the productivity growth rate by 3% and 5%, respectively.

We also note that our estimates quantify the TFP gains occurring within a relatively short horizon. It is likely that the effects are larger when looking at a longer time horizon.

It is possible that there is an additional *indirect* effect in the form of an international technological spillover. This would occur if a country's investment in a given industry ends up benefitting the productivity of firms in different countries due to international knowledge spillovers. To test for this possibility, we use our OECD data to estimate

$$\Delta \ln A_{ikt} = \rho((R+S)/VA)_{ik(t-1)} + \kappa(RP/VA)_{ik(t-1)} + \gamma\Delta X_{ikt} + \Delta u_{ikt} \qquad (6)$$

where $(RP/VA)_{ik(t-1)}$ is the weighted average of R&D/value added in all other countries in the same industry and year, with weights measuring the economic or geographic distance of country k to all other countries. Empirically, we find statistically significant positive international spillovers with IV coefficients ranging between 0.188 (0.068) and 0.304 (0.070) depending on the weights (see Appendix Table A10 in Moretti et al (2021)). However, the first stage is too weak for the estimates to be conclusive.

The 9/11 Shock. We end with an illustration of the magnitudes of various effects arising from our analysis based on a concrete example: the increase in military R&D that occurred in the US after the 9/11 attacks. Using all the linkages in the results above, we calculate that the 9/11 shock induced an increase of the TFP growth rate by 0.005 percentage points, holding taxes constant—

a 1.5% increase. We view this effect as significant but not exceedingly large. In addition, TFP growth in other OECD countries is estimated to rise by 0.028% on average. We provide a detailed explanation of how we quantified these effects in Appendix D.

6 Conclusions

Our results suggest that government R&D "crowds in" rather than "crowds out" private R&D. In addition, we find evidence that an increase in public R&D in one industry and country raises private R&D in the same industry in other countries through a positive spillover effect. Finally, we uncover significant but not overwhelming effects of private R&D investment on TFP growth and therefore economic growth.

In terms of policy implications, our estimates point to a specific tool that governments can use to raise private R&D investment in their jurisdiction. Our estimates indicate that government-funded R&D in general—and defense R&D in particular—are effective at raising a country's total expenditures on innovation in a given industry. The ultimate effect of government-funded R&D on overall R&D significantly exceeds its dollar value because government-funded R&D stimulates additional R&D investment on the part of the private sector. This positive effect of government-funded R&D on private R&D is important not just in itself, but because it generates higher productivity.

This of course does not imply that it is efficient to raise defense R&D or government-funded R&D across the board, since government-funded R&D clearly has an opportunity cost in the form of taxpayer money used plus any welfare loss that inevitably comes from taxation. Our paper does not compare the benefits of government-funded R&D to its costs.[7]

Our findings also indicate that the benefits of public R&D investment do not stop at a country's borders but spill over to other countries. This implies that countries that spend aggressively on government funded R&D—like the US—indirectly support the productivity of countries with less government-funded R&D. This externality indicates the desirability of more international cooperation in government-funded R&D.

References

Akcigit, U., Hanley, D. and Stantcheva, S. (2022), Optimal Taxation and R&D Policies. *Econometrica*, 90: 645-684.

Azoulay, Pierre, Joshua Zivin, Danielle Li, and Bhaven Sampat (2019a) "Public R&D Investment and Private Sector Patenting: Evidence from NIH Funding Rules" *Review of Economic Studies*, 86(1), 117-152.

Azoulay, Pierre, Erica Fuchs, Anna Goldstein and Michael Kearney (2019b) "Funding Breakthrough Research: Promises and Challenges of the ARPA Model", in *Innovation Policy and the Economy*, Volume 19, Josh Lerner and Scott Stern (eds)

[7] The opportunity cost could be high if it cut other forms of public expenses with high returns or if the expected increase in taxes crowd out private investment. Alternatively, the opportunity costs could be low if the federal government financed the increase in public R&D by cutting unproductive or wasteful public expenses. For example, military procurement is widely considered inefficient and ripe with waste and rent seeking.

Barbé, Esther and Laia Mestres (2007) Spain and ESDP Brummer, Klaus (Ed.) *The South and ESD*.

Bilir, L. Kamran, and Eduardo Morales (2020) Innovation in the Global Firm, *Journal of Political Economy*, 128:4, 1566-1625

Bloom, Nick, Rachel Griffith and John Van Reenen (2002) "Do R&D tax credits work? Evidence from a panel of countries 1979-1997" *Journal of Public Economics* 85(1), 1-31

Bloom, Nick, Mark Schankerman and John Van Reenen (2013) "Technology Spillovers and Product Market Rivalry" *Econometrica*, 81 (4), 1347–1393

Bloom, Nicholas, John Van Reenen and Heidi Williams (2019) "Policies to Promote Innovation", *Journal of Economic Perspectives*, 33(3), 163-184

Bronzini, Raffaello and Eleonora Iachini (2014) "Are Incentives for R&D Effective? Evidence from a Regression Discontinuity Approach", *American Economic Journal: Economic Policy*, 6(4), 100-134

Coe, David T. and Elhanan Helpman (1995) "International R&D Spillovers". *EER* 39(5), 859-887

Congressional Research Service (2018) *Government Expenditures on Defense related R&D by the US and other OECD Countries* Washington DC https://fas.org/sgp/crs/natsec/R45441.pdf

Criscuolo, Chiara, Ralf Martin, Henry Overman and John Van Reenen (2019), "Some causal effects of an industrial policy" *American Economic Review* 109(1) 48-85

David, Paul, Bronwyn Hall and Andrew Toole (2000) "Is public R&D a complement or substitute for private R&D? A review of the econometric evidence" *Research Policy*, 29(4-5), 497-529.

Dechezlepretre, Antoine, Elias Einio, Ralf Martin, Kieu-Trang Nguyen and John Van Reenen (2019), "Do Fiscal Incentives increase innovation? An RD Design for R&D" CEP Paper 1413

Dimos, Christos and Geoff Pugh (2016) "The effectiveness of R&D subsidies: A meta-regression analysis of the evaluation literature" *Research Policy*, 45, 797-815

Draca, Mirko (2013) "Reagan's innovation dividend? Technological impacts of the 1980s US defense build-up." CAGE Working Paper Series No. 168.

European Parliament (2011) "The Impact of the Financial Crisis on European Defense", Annex.

Goolsbee, Austan, (1998) "Does Government R&D Policy Mainly Benefit Scientists and Engineers?" *American Economic Review*, 88(2), 298-302.

Guellec, Dominique and Bruno Van Pottelsberghe de la Potterie (2001) "R&D and Productivity Growth: Panel analysis of 16 countries" *OECD Economic Studies*, 33, 103-126

Hall, Bronwyn. 1993. R&D Tax Policy during the 1980s: Success or Failure? Tax Policy and the Economy 1993(7): 1-35, National Bureau of Economic Research

Hall, Bronwyn, Jacques Mairesse, and Pierre Mohnen. 2010. Chapter 24 - Measuring the Returns to R&D. In Handbook of the Economics of Innovation 2: 1033-1082

Howell, Sabrina (2017) "Financing Innovation: Evidence from R&D Grants." *American Economic Review*, 107(4), 1136-64.

Keller, Wolfgang (2004): "International Technology Diffusion" *Journal of Economic Literature*, 42(3), 752–782.

Lach, Saul (2002) "Do R&D subsidies stimulate or displace private R&D? Evidence from Israel" *Journal of Industrial Economics*, 50, 369-90

Lichtenberg, Frank (1995) "The Economics of Defense R&D". In Hartley, K and Sandler, T. (eds) *Handbook of Defense Economics, Volume 1*. Elsevier: New York.

Milward, Alan S. 1977. "War, Economy and Society, 1939-1945. University of California Press.

Moretti, Enrico (2004) "Workers' Education, Spillovers and Productivity: Evidence from Plant-Level Production Functions", *American Economic Review* 94(3)

Moretti, Enrico (2021) "The Effect of High-Tech Clusters on the Productivity of Top Inventors" *American Economic Review*

Moretti, Enrico and Claudia Steinwender and John Van Reenen "The Intellectual Spoils of War? Defense R&D, Productivity and International Spillovers" NBER WP 26483 Revised in December 2021

Moretti, Enrico, and Daniel J. Wilson. 2017. "The Effect of State Taxes on the Geographical Location of Top Earners: Evidence from Star Scientists." *American Economic Review*, 107 (7): 1858-1903.

Mowery, David (2010) "Military R&D and Innovation" in Bronwyn Hall and Nate Rosenberg (eds) *The Handbook of the Economics of Innovation, Volume 2*. Elsevier, London.

National Science Foundation (2006) *National Patterns of R&D Resources* (Annual Series). Division of Science Resources Statistics, Washington DC

Pless, Jacqueline (2019) "Are 'Complementary Policies' Substitutes? Evidence from R&D Subsidies in the UK" MIT mimeo

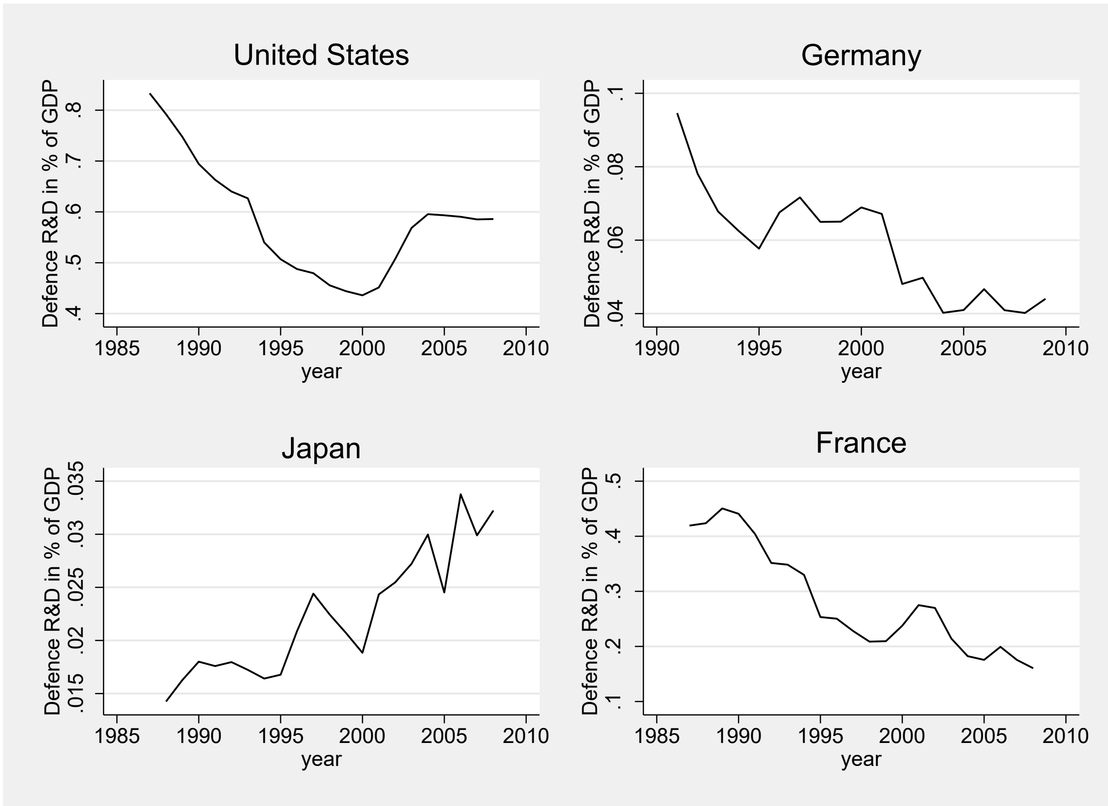
Pottelsberghe De La Potterie, Bruno Van and Frank Lichtenberg (2001). Does Foreign Direct Investment Transfer Technology Across Borders? *Review of Economics and Statistics*, 83(3)

Slavtchev, Viktor, and Simon Wiederhold (2016) "Does the Technological Content of Government Demand Matter for Private R&D? Evidence from US States." *American Economic Journal: Macroeconomics*, 8(2): 45-84.

Thomson, Russell (2012) "Measures of R&D tax incentives for OECD countries", mimeo, Melbourne Institute of Applied Economic and Social Research

Wallsten, Scott (2000) "The effects of government-industry R&D programs on private R&D: the case of the Small Business Innovation Research program" *RAND Journal of Economics*, 31, 82-100.

FIGURE 1: DEFENSE R&D AS PERCENT OF GDP IN THE US, GERMANY, JAPAN AND FRANCE



Notes: This figure shows the defense related, government funded total R&D as a share of GDP. The defense R&D in this figure refers to "all public R&D" which includes all government budget appropriations or outlays of total R&D, i.e. not just the government-funded part of business conducted R&D, but also the government funded part of R&D conducted outside of enterprises.

TABLE 1: EFFECT OF PUBLICLY FUNDED R&D ON PRIVATELY FUNDED R&D – OECD DATA

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable: ln(Privately funded business R&D)						
Panel A: OLS						
ln(Public R&D)$_{t-1}$	0.128**	0.147**	0.143**	0.144**	0.144**	0.145**
	(0.028)	(0.027)	(0.027)	(0.028)	(0.028)	(0.028)
R&D tax credit$_{t-1}$				0.641**	0.725**	0.790**
				(0.295)	(0.300)	(0.307)
ln(Non-bus. public R&D)$_{t-1}$					-0.328	-0.313
					(0.246)	(0.243)
(Corp. tax revenue/GDP)$_{t-1}$						-3.305
						(3.006)
ln(output)$_{t-1}$			0.691**	0.700**	0.630**	0.616**
			(0.171)	(0.170)	(0.184)	(0.178)
ln(GDP)$_{t-1}$			-0.184	-0.201	-0.101	-0.080
			(0.458)	(0.457)	(0.484)	(0.483)
Panel B: IV						
ln(Public	0.561**	0.492**	0.518**	0.476**	0.508**	0.477**

R&D)$_{t-1}$						
	(0.140)	(0.199)	(0.204)	(0.190)	(0.203)	(0.196)
R&D tax credit$_{t-1}$				0.885*	0.993**	1.092**
				(0.470)	(0.496)	(0.485)
ln(Non-bus. public R&D)$_{t-1}$					-0.334	-0.305
					(0.237)	(0.230)
(Corp. tax revenue/GDP)$_{t-1}$						-6.312*
						(3.406)
ln(output)$_{t-1}$			0.412	0.458*	0.364	0.360
			(0.268)	(0.255)	(0.285)	(0.276)
ln(GDP)$_{t-1}$			0.092	0.036	0.161	0.177
			(0.534)	(0.521)	(0.567)	(0.551)
Observations	5,026	4,459	4,459	4,459	4,459	4,459
First stage F-Statistic	14.66	10.30	10.17	10.66	10.02	10.96
Anderson-Rubin	9.630	5.316	5.918	5.503	5.516	5.345
Wald F-test p-value	0.00208	0.0218	0.0156	0.0196	0.0195	0.0215

Notes:. Two-way clustered standard errors at the industry-country and country-year level. The dependent variable is private R&D, i.e., R&D conducted in the business sector (BERD) that is also financed by the private sector (i.e., excludes government financed R&D). "Public R&D" is government-financed R&D performed by private firms. "R&D tax credit" is Warda's B-Index from Thomson (2012) and the coefficient can be interpreted as the elasticity of R&D with respect to its tax adjusted user cost (see Appendix C). "Non-business public R&D" is government-financed R&D performed not by the private sector, e.g. universities or other institutions. "Corporate tax revenue/GDP" is tax revenue from taxes on income, profits, and capital gains of corporates divided by GDP (from OECD). All columns include a full set of country*industry fixed effects and industry*year fixed effects, as well as linear country time trends. Models in Panel B use predicted government funded defense R&D as an instrument for government-financed R&D (see text). "First stage F" is the Kleibergen-Paap rk Wald F-statistic. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. All regressions are weighted by the industry-country pair's initial share of employment in total country employment. ** significant at 5% level, * significant at 10% level.

TABLE 2: EFFECT OF PUBLICLY-FUNDED R&D ON PRIVATELY-FUNDED R&D – FRENCH DATA

	(1)	(2)	(3)	(4)
	OLS	IV	OLS	IV
Dependent variable: ln(Privately funded business R&D)				
Panel A. 3-digit industry				
ln(public R&D+1)$_{t-1}$	0.069**	0.346**		
	(0.011)	(0.092)		
ln(defense R&D+1)$_{t-1}$			0.047**	0.150**
			(0.009)	(0.041)
Observations	4,444	4,444	4,444	4,444
Number of industries	169	169	169	169
First stage F		11.56		23.23
p(firm β=ind β)	0.000	0.013	0.000	0.000
Panel B. Firm-level				
ln(public R&D+1)$_{t-1}$	0.011**	0.119*		
	(0.002)	(0.069)		
ln(defense R&D+1)$_{t-1}$			0.006	0.374*
			(0.005)	(0.215)
Observations	80,692	80,692	81,201	81,201

Number of firms	12,429	12,429	12,586	12,586
First stage F		13.76		12.12
p(firm β = industry β)	0.000	0.001	0.000	0.298

Notes: The dependent variable is private R&D, i.e., R&D conducted in the business sector (BERD) that is also financed by the private sector (i.e., excludes government financed R&D). "Public R&D" is government-financed R&D performed by private firms. All columns include year fixed effects; Panel A (B) includes 3-digit industry (firm) fixed effects. All variables in Panel B are winsorized at the 0.5% tails. "First stage F" is the Kleibergen-Paap rk Wald F-statistic. We use predicted government funded defense R&D as an instrument for government-financed R&D (see text). Standard errors in Panel A (B) are clustered at the 2-digit (3-digit) industry level. ** significant at 5% level, * significant at 10% level. "p(firm β=ind β)" is a test of whether the coefficient in Panel A (industry level) is equal to that in Panel B (firm level).

TABLE 3: EFFECT OF R&D GROWTH ON TFP GROWTH

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	IV	Reduced Form	OLS	OLS
	Annual TFP growth				Annual labor productivity growth	
(Total R&D/value added)$_{t-1}$	0.095**	0.098**	0.097**			
	(0.040)	(0.041)	(0.031)			
(Predicted Defense R&D/value added)$_{t-1}$				0.083**		
				(0.030)		
(Total R&D/ sales)$_{t-1}$					0.026**	0.040**
					(0.004)	(0.005)
Observations	6,102	6,102	6,102	6,102	4,513	82,743
First stage F			14.42			
Country FE	NO	YES	YES	YES	N/A	N/A

Notes: Columns (1)-(4) use OECD data and (5)-(6) are French data. Columns (1) through (4) use two-way clustered standard errors at the industry*country and country*year level, and are weighted with weights equal to the industry-country pair's initial share of employment in total country employment. Columns (5) and (6) use clustered standard errors at the 3-digit industry. All regressions include a full set of year fixed effects. Column (3) presents IV estimates using (defense R&D)/value added as an instrument for R&D/value added. Column (4) presents the reduced form estimate for column (3). ** significant at 5% level, * significant at 10% level.