The Intellectual Spoils of War?

Defense R&D, Productivity and Spillovers

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Abstract. We examine the impact of government funding for R&D on privately performed R&D and its ultimate effect on productivity growth. To deal with the potential endogeneity of where governments choose to allocate R&D funds, we use changes across countries and industries in defense R&D spending. Shocks to defense R&D are mainly driven by geopolitical factors that we argue are largely orthogonal to technology shocks. We uncover strong evidence of "crowding in" rather than "crowding out", as increases in government funded R&D result in significant increases in private sector R&D. Specifically, a 10% increase in government financed R&D generates about 3% more privately funded R&D. Analysis of the wage and employment effects suggests that the increase in private R&D expenditures reflect actual increases in R&D employment, not just higher wages. In turn, increases in R&D in a country and industry pair result in sizeable productivity gains. A permanent one percentage point increase in the ratio of defense related R&D to value added is associated with a 5% increase in the annual TFP growth rate in that country-industry pair (e.g. from 1 to 1.05 percentage points a year). We estimate that the increase in US defense R&D caused by the 9/11 events, for example, generated an increase in the aggregate annual TFP growth rate of 2% in the US (e.g. from 1 to 1.02 percentage points a year). At the international level, we find that increased R&D spending by foreign governments has two offsetting effects on domestic firms. On the one hand, it *deters* R&D spending by domestic firms; on the other hand it creates some beneficial domestic productivity gains through industry-specific knowledge spillovers. On net, the effect of foreign R&D on domestic productivity is significantly positive (but small in magnitude), pointing to the global benefits of national R&D increases.

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1 Introduction

We study the impact of government funding for R&D on privately performed R&D and its ultimate effect on productivity growth. Productivity growth is crucial for improvements in standards of living. Given the central role that productivity plays in explaining economic growth, it is not surprising that the search for the determinants of productivity has been central to modern economics. A large body of empirical research has argued that R&D is a key source of firm productivity growth (e.g. Griliches, 1979; Aghion and Howitt, 1992; Romer, 1991; Acemoglu, 2009), but the question remains of what policies can successfully raise R&D, and whether these policies are socially efficient.

In this paper, we focus on an important but understudied component of public policy on R&D: defense-related R&D. Defense R&D represents a key channel through which governments all over the world shape innovation. In the US, annual defense-related R&D expenditures amount to about $72 billion in 2016 prices, or 57.2% of all government funded R&D.[1] While defense related R&D is motivated by goals that are not purely economic, it is 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 money flowing into high-tech, defence-focused production dwarfs the amount spent on other prominent innovation policy tools.[2] In the UK and France, too, defense R&D is the single most important component of government funded R&D.

We address three related questions. First, we estimate the effect of government funded R&D – and in particular, defense-related R&D – on private R&D (i.e. R&D conducted and financed by private businesses). We are interested in whether government funded R&D in a given country and industry displaces or fosters private R&D in the same country and industry.[3] Having found evidence of a

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[1] Average between 1987 and 2009, computed using our data.

[2] For example, the Federal R&D tax credit costs around $6.5 billion per year while support for basic science through the National Science Foundation is $7 billion (NSF 2006). By contrast, around $16 billion per year is spent on military R&D procurement alone along with another $40-50 billion in spending on high-tech products (Draca, 2012).

[3] There is a body of empirical research on the relationship between public R&D on private R&D (e.g. David, Hall & Toole, 2000; Guellec & Pottelsberghe, 2001; Lach, 2002; Goolsbee, 1998; Wallsten, 2000; Hall, 1993), but identifying causal effects has proven difficult. There is a small number of recent papers that explicitly seek to address the causal effect of public subsidies. The existing papers tend to differ from ours in that they focus on different policy instrument and different outcomes than the ones we are studying in this paper. Jacob and Lefgren (2011) and Azoulay et al (2015) study the causal effect of NIH grants on publications and patenting; Bronzini and Iachini (2014) focus on the effect of R&D subsidies on capital investment by Italian firms; Howell (2015) looks at Department of Energy grants on venture capital funding and

positive effect, we estimate how investment in R&D in a country and industry affects productivity in that country and industry. Finally, we assess whether the benefits of public R&D investment on private R&D and productivity are limited to a country or spill over to other countries.[4]

The effect of defense R&D expenditures on private sector innovation and economic growth has been a hotly debated topic for many years (e.g. see the surveys by Mowery, 2010, and Lichtenberg, 1995). Proponents of the benefits of defense R&D point to the commercial success of major innovations such as jet engines, computers, radars, nuclear power, semiconductors, the GPS and the Internet as evidence that military R&D has been a crucial source of technological development with civilian applications (e.g. Lichtenberg, 1984, 1988; Ruttan, 2006; Mazzucato, 2013).[5] Some even argue that an important reason why US manufacturing became so dominant in the second half of the 20th century was that during the Cold War the Pentagon became the world's most generous investor in technological innovation and this ultimately resulted in superior technologies for American companies and long lasting gains in their competitiveness (Braddon, 1999). More recently, defense R&D is viewed as an important contributor to national economic growth through private sector spin offs and agglomeration economies.[6] Proponents of this view point to Israel as an example of how defense spending has spawned a multitude of commercially successful high tech start-ups.

On the other hand, critics argue that the social returns to defense R&D are low because the secrecy surrounding defense R&D inherently limits the scope of spillovers to civilian firms. Even more fundamentally, critics argue that defense related R&D might *displace* private R&D and therefore could have little impact on the total amount of innovation in a country. Overall, there is much anecdotal evidence on some of the positive and negative effects that defense R&D might play on growth, but little systematic econometric evidence.

We assembled a unique dataset that contains detailed information on defense-related government funded R&D, non-defense related government funded R&D, private R&D, output,

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patents; and Slavtchev, and Wiederhold (2016) study the effect of government procurement on innovation. Bloom, Schankerman and Van Reenen (2013) and Dechezlepretre et al (2016) focus on R&D tax credit policies.

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

[5] Draca (2012) estimates the impact of US defense spending on firm level innovation and found that increases in procurement contracts are associated with a 0.7% increase in patenting and company-sponsored R&D.

[6] An additional benefit of military R&D is the creation of highly specialized human capital that has skills valued by the private sector. The *New York Times* reports that a recent trend is for Silicon Valley companies is to scout the Pentagon's and NSA's personnel searching for potential hires.

employment and salaries in 26 industries in all OECD countries over 23 years. We begin by estimating models that relate privately funded R&D in a given country, industry and year to government funded R&D in the same country, industry and year, conditioning on a full set of country-industry and industry-year fixed effects, and using defense R&D as an instrumental variable.

Military R&D provides arguably exogenous variation because changes in defense spending reflect political and military priorities that are largely independent of productivity shocks in different domestic industries (Mowery, 2010). Wars, changes of government and terrorist attacks have had major influences on defense spending. In the US, for example, military R&D spending was ramped up under 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 the fraction of publicly funded R&D is much higher in some industries (e.g. aerospace) than others (e.g. motor vehicles).[7]

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 in 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 make some marginal private sector projects profitable;[8] (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. Increases in government funded R&D generated by increases in defense R&D translate into significant increases in privately funded R&D expenditures, with the most reliable estimates of the long run elasticity between 0.2 and 0.5. On

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[7] The idea of using military spending as an exogenous component of government spending has been used in other contexts. In the analysis of fiscal multipliers Ramey (2011) and Barro and Redlick (2011) have argued for the importance of using defense spending to mitigate endogeneity concerns. See also Perotti (2014).

[8] Examples of fixed costs include labs that can be used both for government financed R&D and for private R&D, or human capital investment in the form of learning by scientists on topics that have both military and civilian applications.

average, \$1 of additional public funds for R&D translates into \$2.4 to \$5.9 of extra R&D funded by the private sector. Defense related R&D is responsible for an important part of private R&D investment in some industries. For example, in the US "aerospace and other transport equipment" industry, defense related R&D amounted to \$36.9bn in 2003 (2016 prices). Our estimates suggest that this public investment translates in \$7.1bn-\$7.8bn additional investment in private R&D. 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 Germany increased its defense R&D as a fraction of GDP to the level of the US, privately funded R&D would increase by 44%.

The increases in private R&D expenditures appear to reflect actual increases in R&D activity, not just higher wages and input prices. We uncover significant positive effects on employment of R&D personnel, with positive but small wage increases. This is consistent with a fairly elastic local supply of specialized R&D workers within an industry across countries.

In principle, some of the gains in one country may come at the expense of other countries. For example, an increase in government funded R&D in the US chemical industry may raise the industry's private R&D in the US, but it may also reduce private R&D in the German chemical industry. This type of cross-border displacement may occur for a number of reasons: (i) the German firms may free-ride on US innovation; (ii) German firms may give up in the R&D race if one country gets too far ahead (strategic substitutability); (iii) the total number of chemical engineers in the world may be fixed in the short run; (iv) there are local agglomeration economies. Our estimates indicate that this is indeed the case. Increases in government funded R&D in one country significantly *reduce* private R&D spending in the same industry in other countries, although the magnitude is small.

In the second part of the paper we turn to the effect of private investment in R&D on productivity. We first estimate models where TFP growth in an industry-country pair is regressed on lagged R&D intensity, using defense R&D as an instrumental variable. We find estimates of the return to R&D that are economically meaningful and confirm the key role played by innovation in driving economic growth. We also find that an increase in the defense R&D to value added ratio of one percentage point is associated with a 5% increase in the yearly growth rate of TFP. We view this as an important, but not overwhelming effect - it suggests that a non-trivial fraction of US economic growth is accounted for by investment in defense R&D. For example, defense R&D in the US increased by

52% between 2001 and 2004 following the 9/11 attack. We estimate that this translated into 0.005 percentage point increase of the annual TFP growth rate in the US in the affected years – a 2% increase (holding taxes constant). Cross-country differences in defense R&D play a role in explaining cross-country differences in productivity of private sector firms.

Finally, consistent with the existence of international technology spillovers, we uncover a positive effect of investment in R&D in an industry and country on productivity of firms in the same industry but in different countries. Thus, government funded R&D by one country appears to have two opposite effects on the productivity of other countries. On the one hand, it displaces private investment in R&D in other countries in the same industry. On the other hand, it raises foreign TFP through technology spillovers. The net effect appears to be positive. An increase in total R&D/GDP ratio in country *i* by one percentage point results in a 0.07 percentage point (8.4%) increase in the TFP growth rate in country *j* if *i* and *j* are “technologically close” and in a 0.008 percentage point (0.9%) increase at the mean level of technological distance. We estimate that TFP growth rates are 0.01% higher in France and Germany due to the increase in Pentagon funded R&D following the 9/11 attacks.

Our findings have several policy implications. First, our models point to a concrete 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 significantly exceeds its dollar value because government funded R&D stimulates additional R&D investment on the part of the private sector. Second, the positive effect of government funded R&D on private R&D in the country is important not just in itself, but because it generates higher productivity.

We caution that this does not necessarily imply that it is desirable for all countries to raise defense R&D or government funded R&D across the board. Our finding that government funded R&D results in an increase in TFP is by no means evidence that public monies were used *efficiently*. 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.

A third policy implication arises at the international level, as our findings point to the fact that these spillovers do not stop at a country’s borders: government funded R&D by one country benefits not only private firms in that country, but also private firms in 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 (Keller, 2004).

The structure of the paper is as follows. Section 2 presents a simple framework and the empirical models. Section 3 describes the data. Sections 4 and 5 present the empirical results. Section 6 concludes.

2 Conceptual Framework and Econometric Models

In this section we present a simple framework that is useful in deriving the empirical models that we take to the data and in clarifying how to identify and interpret our empirical estimates. Using this framework, we seek to study two related sets of questions:

a) What are the direct and indirect effects of government funded R&D on private R&D activity? Specifically, we seek to estimate the effect of government funded R&D in a particular industry and country on private R&D investment, wages and employment in the same industry and country. We also look for evidence of international displacement effects and estimate the effect of changes in government funded R&D in a particular industry and country on private R&D activity in the same industry in other countries.

b) What are the direct and indirect effects of R&D investment on productivity? In particular, we seek to estimate the effect of R&D investment in an industry and country on total factor productivity in that industry and country. In addition, we look for evidence of international technological spillovers and estimate the effect of R&D investment in a specific industry and country on TFP in the same industry in other countries.

2.1 The Effect of Government Financed R&D on Private R&D Activity

We assume that output of industry *i* in country *k* at time *t* is a function of capital, *K*, labor, *L*, and intermediate inputs, *M*, and has the form:

$$Y_{ikt} = A_{ikt} F(K_{ikt}, L_{ikt}, M_{ikt}) \tag{1}$$

where *A* is a Hicks neutral efficiency term. Following the R&D literature (e.g. Griliches, 1979) we assume that the evolution of *A* is governed by the R&D knowledge stock:

$$\ln A_{ikt} = \eta \ln G_{ikt-1} + \gamma X_{ikt} + u_{ikt} \quad (2)$$

where $\eta = \frac{\partial Y}{\partial G}\frac{G}{Y}$ is the elasticity of output with respect to the total R&D stock, X are other factors influencing TFP and u_{ikt} is a stochastic error term. We assume that the R&D stock is an increasing function of current and lagged values of privately funded R&D expenditures (*R)* and government funded R&D expenditures (*S*).

The demand for private R&D depends on the technology embodied in equations (1) and (2), as well as on the cost of R&D. Let *U* be the Hall-Jorgenson tax-adjusted user cost of R&D capital. We assume that we can write the (static) demand for private R&D as:

$$\ln R = \beta \ln Y + \sigma \ln U + v \quad (3)$$

This equation can be rationalized as the steady state demand for R&D from the first order conditions from specializing equation (1) to a CES production function (see Bloom, Griffith and Van Reenen, 2002). Under this interpretation σ is the elasticity of substitution and β is the returns to scale parameter (β =1 indicates constant returns). The user cost will be a complex function of current and expected interest rates, depreciation, the tax system as a whole (including R&D tax credits) and public subsidies (see Criscuolo et al, 2012). We assume that we can take a first order approximation of this function as:

$$\ln R_{ikt} = \alpha \ln S_{ikt} + \beta \ln Y_{ikt} + \lambda X_{kt} + d_{ik} + d_{it} + \upsilon_{ikt} \quad (4)$$

where the other determinants of R&D can be captured by a set of industry by country fixed effects (d_{ik}), industry by year dummies (d_{it}, e.g. industry specific product demand or technological shocks), country by year observables X_{kt} and an idiosyncratic error (υ_{ikt}).[9] In our baseline models, X_{kt} includes current and past GDP levels, thus controlling for country specific business cycles. We also present even more demanding specifications where we control for the X_{kt} with a set of country by year dummies (d_{kt}) and allow for lagged dependent variables.

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[9] We include dummy variables to control for the country-industry fixed effects which formally require strict exogeneity (the within-group estimator). Since our panel is long (up to 26 years) we do not think there is likely to be too much bias from this issue, but to check we also estimated in first differences which requires weaker exogeneity assumptions and obtained similar results.

In practice, the impact of *S* and *Y* on R&D does not need to be immediate. Therefore in our empirical models we allow for a distributed lag in these variables. Our baseline empirical model has a private R&D equation as a generalization of equation (4) where we allow for two lags:[10]

$$\ln R_{ikt} = \sum_{l=0}^{l=2} \alpha_l \ \ln S_{ikt-l} + \sum_{l=0}^{l=2} \beta_l \ \ln Y_{ikt-l} + \sum_{l=0}^{l=2} \lambda_l \ X_{kt-l} + d_{ik} + d_{it} + u_{ikt} \tag{5}$$

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 throughout the paper are multi-way clustered by country by industry pair and country by year pair (Miller, Cameron and Galbech, 2009).

Equation (5) indicates that private investment in R&D depends on the expected economic environment and on R&D investment by the government. The focus of our analysis is on estimating the parameters α_l, that relate changes in government funded R&D to changes in private R&D. The sum of the three α's provides an estimate of the long run effect of public funds for R&D on private R&D, holding constant industry-specific and country-specific shocks.

The sign of this sum is *a priori* unknown. If increases in government funded R&D crowd out private R&D, the sum of the α's should be negative. (Recall that the dependent variable is only the privately funded part of business R&D, so there is no mechanical association between *R* and *S*.) 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, for example, if the supply of inputs in the R&D process in any given industry was perfectly inelastic in the short run. With inelastic supply, 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 crowds in private R&D, the sum of the α's should be positive. In this case, more public R&D stimulates even more private R&D. There are three possible reasons for why this might be the case.

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[10] We also show specifications with lags of the dependent variable and consider even longer lag structures than two years. The two year distributed lag seemed an adequate representation of the data generating process.

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 intellectual understanding of a specific literature or her mastering of a scientific technique acquired while working on a specific project can in some cases be helpful in other projects as well. 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, government financed R&D investment by a firm may make other firms in the same industry more productive because of technology spillovers (see for example, Griliches, 1992; Moretti, 2004a,b). 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. There is a growing body of evidence that suggests that production is characterized by strong forces of agglomeration at the industry level in the form of localized increasing returns to scale (Greenstone, Hornbeck and Moretti, 2010; Kline and Moretti, 2013).

Third, if firms are credit constrained, the public provision of R&D might relax these financial constraints. Although capital markets are generally well developed for the OECD countries we study, the special nature of R&D investments highlighted by Arrow (1962) such as riskiness and asymmetric information may make it especially vulnerable to financial frictions.[11]

Employment and Wages. We also 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*. We distinguish between the effect on labor market outcomes of R&D workers and labor market outcomes of non-R&D workers. If the supply of R&D workers is completely inelastic in the short run, increased R&D spending could simply result into

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[11] See Bond, Harhoff and Van Reenen (2005) and Garicano and Steinwender (forthcoming) for some empirical evidence on financial frictions for R&D.

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 are also ambiguous, and depend on whether R&D generates technologies that are substitute or complement such labor. On the one hand, more R&D in an industry may result in product innovation, higher sales and therefore more labor demand. On the other hand, process innovation can easily reduce employment by making it easier to produce the same output with less labor inputs.

To empirically assess these questions, we estimate models similar to the one in equation (5) where the dependent variable is the employment of R&D workers, the average wage of R&D workers, total industry employment and average industry wages.

International Displacement. It is in principle possible that increases in the government funded R&D in an industry in a given country may result in lower R&D in similar industries abroad. For example, an increase in government funded R&D the German chemical industry may reduce private R&D in the French chemical industry. This may be because of strategic reasons as French firms decide it is not worth competing to catch up with their German rivals (e.g. between country R&D is a strategic substitute) or the cost of internationally used industry-specific R&D inputs (e.g. chemical engineers) may be driven up. To assess how large the displacement effect may be, we estimate models of the form:

$$\ln R_{ikt} = \alpha \ln S_{ikt} + \beta \ln Y_{ikt} + \gamma \ln SP_{ikt} + \lambda X_{kt} + d_{it} + d_{ik} + \upsilon_{ikt} \qquad (6)$$

where SP_{ikt} is a weighted average of government funded R&D in other countries in the same industry and year, with weights measuring the economic or geographic distance between country *i* and each other country. Empirically $SP_{ikt} = \sum_j d_{ij} S_{jkt}$ where d_{ij} is the "distance" between country *i* and country *j* (normalized to sum to 1 for each country *i*) and S_{jkt} is government funded R&D in industry *i* in country *j* (we also examine using total R&D spillovers instead of just S_{jkt} in some specifications). Equation (6) estimates displacement across countries within industries. Of course, in principle $\gamma > 0$

could also be possible. If increased public R&D in Germany induces French firms to invest more to keep up in the race, R&D will be a strategic complement between countries.

2.2 The Effect of R&D on Productivity

Endogenous growth theory and empirical evidence have found that investment in R&D is correlated with productivity increases. However, existing estimates that do not account for the potential endogeneity of R&D may be spurious, if, for example, higher R&D reflects expectations of future productivity changes. After all, our framework makes clear that R&D is an input that is endogenously chosen by firms. To make progress, we first estimate TFP, and then quantify the effect of R&D on TFP using arguably exogenous variation in total R&D.

To estimate industry-country-year TFP, we approximate F(.) in equation (1) by a second order flexible form and can therefore estimate TFP as the superlative index:

$$\Delta \ln A_{ikt} = \ln\left(\frac{VA_{ikt}}{VA_{ikt-1}}\right) - \frac{1}{2}\left(\theta_{ikt} + \theta_{ikt-1}\right)\ln\left(\frac{L_{ikt}}{L_{ikt-1}}\right) - \left(1 - \frac{1}{2}\left(\theta_{ikt} + \theta_{ikt-1}\right)\right)\ln\left(\frac{K_{ikt}}{K_{ikt-1}}\right) \tag{7}$$

where VA_{ikt} is value added, L_{ikt} is total employment, and K_{ikt} is the capital stock. We measure θ using labor's share of value added in two ways. First, we simply used the industry-specific average of the share (across all countries and years).[12] Alternatively, we use Harrigan (1997) smoothing methods to construct the share of labor in value added θ_{ikt}. Both methods gave very similar results (see Data Appendix).

Once we have TFP, we can turn to the effect of R&D on TFP. We assume that the total R&D stock can be described by the perpetual inventory formula: $G_{ikt} = R_{ikt} + S_{ikt} + (1-\delta)G_{ikt-1}$ where and δ is the depreciation rate of knowledge. If δ is close to zero, the TFP growth equation can be approximated by:

$$\Delta \ln A_{ikt} = \rho\left(\frac{R+S}{VA}\right)_{ikt-1} + \gamma\Delta X_{ikt} + \Delta u_{ikt} \tag{8}$$

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[12] Since our TFP estimates are at the industry level, this method is more suited to estimate productivity than alternative methods such as Olley-Pakes (1996) or Levinsohn-Petrin (2003) which are designed for productivity estimation at the level of the firm.

where $\rho = \frac{\partial Y}{\partial G}$ is the gross rate of return to R&D capital. We estimate equation (8) using two alternative instrumental variables: (i) government funded R&D, *S*; and (ii) defense related government funded R&D, *DR.*[13]

Equation (8) provides an estimate of the effect of a country's public R&D investment on its own TFP. 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 R&D ends up benefitting the productivity of firms in different countries due to international knowledge spillovers. To test for this possibility, we estimate a more general version of equation (8) that allows for international spillover effects:

$$\Delta \ln A_{ikt} = \rho((R+S)/VA)_{ikt-1} + \kappa(RP/VA)_{ikt-1} + \gamma \Delta X_{ikt} + \Delta u_{ikt} \qquad (9)$$

where $(RP/VA)_{ikt-1}$ 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 these other countries (as in the spillover variable in equation (6)). In this model, the focus is on the parameter κ where a positive κ would indicate the existence of positive international technological spillovers. Note that this specification focuses on cross-country intra-industry spillovers. We cannot identify intra-industry spillovers within countries as our data is industry level but we do also investigate other types of spillovers, such as within country inter-industry spillovers.

2.3 Identification and Threats to Validity

Equation (5) allows us to control for a wide variety of shocks that affect private R&D and may also be correlated with government financed R&D. Specifically, the inclusion of industry-year dummies accounts for the fact that different industries have different propensities to invest in R&D and these differences can vary over time as a function of technology shocks and product demand shocks. The

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[13] Although conventional, assuming $G_{ikt} = R_{ikt} + S_{ikt} + (1-\delta)G_{ikt-1}$ is very restrictive. We considered an alternative specification $G_{ikt} = R_{ikt} + \mu S_{ikt} + (1-\delta)G_{ikt-1}$ which allows dollar of public R&D to have a different effect on the knowledge stock than a dollar of private R&D. This implies including two separate R&D terms on the right hand side of equation (8). The problem is that this requires an additional instrument for privately funded R&D as publicly funded R&D is instrumented by the defense share. We considered using R&D tax credits, but the first stage had insufficient power when both public and private R&D were taken as endogenous.

inclusion of industry-country fixed effects accounts for the fact that firms in different countries have different propensities to invest in R&D and that these international differences may be more pronounced in some industries than others.

Even after conditioning on this rich set of controls, our models yield inconsistent estimates if governments tend to allocate R&D funding to specific industries based on criteria that are correlated with unobserved determinants of private R&D investment. This may happen, for example, if governments tend to use public funds to help local industries that are struggling and are experiencing declines in private R&D over and above those experienced by the same industry in other countries. Note that what matters are *industry-country specific time-varying* shocks. Equation (5) is robust to industry specific time-varying shocks shared by all countries. For example, if the telecommunication industry is struggling in *all* countries, and governments decide to endogenously increase publicly funded R&D for the industry, equation (5) would yield consistent estimates.

A similar concern arises in the opposite scenario, if governments tend to use public funds to help industries that are thriving, and experiencing increases in R&D over and above those experienced by the same industry in other countries. In either case, S_{ikt} will be correlated with υ_{ikt} and standard OLS estimates of equation (5) will be biased. The sign of the bias is a priori undetermined. If governments help winners, the correlation between S_{ikt} and u_{ikt} is positive. If governments disproportionately help losers (compensatory policies), the correlation between S_{ikt} and u_{ikt} is negative.

To address this problem, we use an instrumental variable strategy based on variation in defense spending (DR_{ikt}). More precisely, out instrumental variable is the product of total country-level defense spending in each year times the industry share in the relevant year. Mowery (2010) explains that defense R&D is the most important example of “mission R&D”, i.e. R&D that is spent not in order to pursue economic goals, but any other, unrelated government objectives. In particular, defense R&D is usually motivated by geopolitical, and not economic considerations. Our identifying assumption is therefore that variation in defense related R&D is largely driven by events exogenous to industry-specific 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.

Defense R&D is by far the largest component of government R&D in many countries, e.g. United States, United Kingdom, or France. This ensures that our instrument has a strong first stage. Defense R&D also causes the biggest variations in public R&D over time, and there is also a large variation across countries, ranging from pacifist country like Japan or neutral countries like Austria to defense heavy countries like the United States or South Korea.

One practical issue is that although we have defense R&D spending data at the country-year level, data on the industry breakdown by year are available only in the US and UK.[14] To build our instrument for countries other than the UK, we use the share of defense R&D allocated by the US to each industry in each year. This imputation weakens the power of the instrument in the first stage, but it should not compromise 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.

Several points are worth nothing in regard to the validity and the interpretation of our instrumental variable estimates.

First, it is possible that while the *overall* level of defense spending in a country is orthogonal to the residual u_{ikt}, the industry composition of defense spending may still be correlated with u_{ikt}. This would be the case if, for example, France defense spending declined after the end of the Cold War for exogenous reasons, but the decline was smaller in, say, aerospace, because of endogenous reasons. Empirically, this is unlikely to be a major source of bias. Because we are using US industry share for all countries other than UK, this is a problem only to the extent that endogenous adjustments to the industry share reflect unobserved industry-specific time varying shocks that are shared by the U.S. and the relevant country. Empirically, models that exclude US or UK yield similar estimates.

More importantly, our estimates are insensitive to alternative definitions of the instrument that do not suffer from this problem. Specifically, we obtain similar estimates when we fix industry weights equal to the US industry share at the beginning of sample period. In these models, variation in the instrument does not reflect potentially endogenous changes in industry share. We also obtain similar estimates when we ignore variation across industries and only use the variation in defense R&D at the country by year level. Most of the variation that drives our estimate is at the country-year level, and therefore presumably reflects exogenous geopolitical events.

A second issue to consider is that, although shocks to military R&D are unlikely to be related to technology shocks, they could in principle signal shocks to current or future product demand. Under this view an event such as 9/11 generated a direct increase in military R&D, but also increased current

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[14] We have the defense breakdown per industry for years 1993-2009 for the UK, and for the years 1987-2003 for the US. In our analysis we hold the 2003 share constant for the years after 2003.

and future demand for military products. In turn, this second channel could stimulate additional private R&D through a demand/market size effect, thus invalidating our instrument. While this is certainly possible in theory, the likelihood that this type of demand effect are large is not very high, because historically large increases in government defense procurement have been for existing, rather than new, technologies.[15] Empirically, our baseline regression (equation (5)) includes current and past industry output, current and past GDP and a range of dummies to control for demand effects (e.g. industry by year dummies). In addition, we also show several robustness checks intended to assess more directly the sensitivity of our findings to demand effects. Specifically, in some models we explicitly control for present and future demand by including *future* output in the industry and for *non-R&D* total military spending (present and future). We find that our results are robust to the inclusion of these controls, confirming that demand effects are unlikely to be a major source of bias for of our estimates.

A related issue centers on the possibility of macro-economic shocks that could be correlated with overall defense spending. Two important examples are the fall of the Soviet Union and the rise of China. Macro shocks of this kind are likely to affect both how much countries spend on defense, as well as their economic situation. Thus, the concern is that part of the variation in our instrument is endogenous. To address this concern, in some models we focus on variation in our instrument that is less likely to suffer from this problem. Specifically, we isolate a case study where variation in overall defense spending can be traced to a specific – and arguably exogenous – cause: the 9/11 terrorist attack.

A fourth issue with the interpretation of equation (5) has to do with the possibility that government funded R&D by country i is set endogenously in response to government funded R&D by country i's competitors. For example, an increase in government funded R&D in, say, the German chemical sector may induce France to increase its own government funded R&D in the chemical sector. This does not invalidate our estimates, but it affects their interpretation. In this case, the parameters α's should be interpreted as the effect of S on R, after allowing for the endogenous reaction

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[15] This is why many historians like Milward (1977) have argued that wars tend to retard technological change by engendering a more conservative attitude to military procurement.

of other countries.[16] This is a meaningful concept, because it informs policymakers of what they can expect in the real world from a policy change.

A final issue has to do with equations (7) and (8) and the way TFP is measured in practice. Variation in value added reflects both variation in physical productivity (i.e. amount of physical output produced for a given set of inputs) as well as variation in the price of output. This is a common problem in the estimation of production functions. In our context, this problem is likely to be serious because shocks to the demand for defense products (examples 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. To deal with this problem, we follow a long tradition in the literature and use industry and year-specific price deflators.

3 Data

3.1 Data Sources

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[17], 26 industries[18] and 23 years, from 1987 to 2009. The Data Appendix and Appendix Table A1 describe in

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[16] Note that even in an ideal randomized setting where public subsidies are randomly assigned to countries this issue would persist.

[17] The countries are Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Japan, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, South Korea, Spain, Sweden, Switzerland, United Kingdom and the United States.

[18] The industries are: Agriculture, hunting and forestry; Basic metals; Construction; Chemicals and chemical products; Coke, refined petroleum products and nuclear fuel; Community, social and personal service activities; Electricity, gas and water supply; Electrical machinery and apparatus not elsewhere classified ("n.e.c"); Finance, insurance, real estate and business activities; Fabricated metal products, except machinery and equipment; Food, beverages and tobacco; Mining and quarrying; Machinery and equipment, n.e.c.; Manufacturing n.e.c. and recycling; Medical, precision and optical instruments, watches and clocks (instruments); Motor Vehicles, trailers and semi-trailers; Non-metallic mineral products; Office, accounting and computing machinery; Other Transport Equipment; Pulp, paper, paper products, printing and publishing; Radio, TV and communications equipment and apparatus; Rubber and plastic products; Textiles, fur and leather; Transport, storage and communications; Wholesale and retail trade; restaurants and hotels; Wood and cork (not furniture)

detail how we cleaned and merged the data and provide the exact definition of each variable with the corresponding source.

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 (5) and (6).[19]
- 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).

3.2 Descriptive Statistics

There is wide variation in private R&D, public R&D and defense R&D across countries, industries and over time. 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 in the vicinity of 0.2%. Although there appears to be a general upward trend in R&D over time, there is a lot of variation across countries in growth rates, with some countries experiencing steep increases (e.g. Denmark) while others experience declines (e.g. the UK).

R&D intensity also varies widely across industries. In Appendix Table A3 we present industry R&D as a percentage of value added averaged across the countries in our data. The most R&D intensive industries are generally IT (Office, accounting and computing machinery) and

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[19] We could have used all BERD as a dependent variable in equation (5) and (6) but this would cause a mechanical positive correlation with public R&D (*S*) as this is a right hand side variable.

telecommunications (Radio, TV and other communications equipment) with R&D intensities of over 20%. The next most R&D intensive sectors are chemicals (includes pharmaceuticals), medical/precision instruments and transport equipment with over 10% of value added devoted to R&D. By contrast there is very little formal R&D in the distributive trades (wholesale and retail), personal services and construction.

Public R&D varies widely across countries and over time. Table 1 shows that the US and Eastern European nations such as Poland 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). We explicitly add controls for tax incentives in robustness checks presented below.

The share of government funded R&D varies not only geographically but also across sectors (see Table 2). The industries which depend most on public R&D funding are IT, agriculture and community, social and personal services. The least subsidized industries are the chemicals, coke & petroleum and automotive sectors. One might be concerned about the quality of measurement in some parts of the service sector. For example, the definition of R&D in community/social services may be very imprecise. For this reason, in some specifications in the empirical analysis we have re-estimated our models focusing on manufacturing industries only to make sure our results are robust to dropping the "hard to measure" sectors.

Table 3 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 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.[20] Ideally we would have just the government funded and business conducted part of R&D, but this data does not exist over time across countries. It is likely that the two series track each other, however. Indeed, in the case of the UK, both series are available, and the correlation of the two series is 0.85.

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[20] Specifically, "Total government funded R&D" are all government budget appropriations or outlays of total R&D, i.e. not just the government funded part R&D conducted by businesses, but also the government funded part of R&D conducted outside of enterprises.

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 fixed effects. Figure 1 illustrates how the three largest economies experienced very different developments in their share of defense related and government funded R&D in GDP 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 military R&D spending ramped up again under the "War against Terrorism" 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 as the Cold War ended with the rise of President Gorbachev and the fall of the Berlin Wall. In 1996, however, Germany founded a military agency with France focusing on R&D activities in 1996 that later turned into a European agency causing a pick-up in defense R&D.[21] In contrast to the US, Germany did not ramp up defense spending after 9/11, instead it continued to downsize its military.[22] Our third country, 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 as a reaction to North Korea's missile tests in the late 1990s by starting a surveillance-satellite program that resulted in satellite launches in 2003, 2006, and 2007.[23]

Overall, the experience of these three major economies with highly varying levels of defense R&D illustrates how the timing of changes in defense R&D often reflects factors that are largely exogenous to economic and technological conditions, being driven by geo-political events that are heterogeneous across countries.[24]

Our instrumental variable strategy is predicated on the notion that defense R&D is an important driver of overall government funded R&D. Figure 2 presents the series of defense R&D and public

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[21] The agreement was titled "Gemeinsames deutsch-französisches Sicherheits- und Verteidigungskonzept", http://www.france-allemagne.fr/Deutsch-Franzosischer,367.html

[22] http://de.wikipedia.org/wiki/Bundeswehr#Ausr.C3.BCstung and European Parliament (2011).

[23] See Hagström and Williamsson (2009)

[24] These examples are not limited to large countries, but extends to small countries as well. For example, Spain saw a rise in military spending after 1996, when the conservative center-right party came to power and pursued a new defense policy and spending initiative. This initiative included a shift from conscripted to professional military service and a large increase in the military budget, much of this was captured in R&D related spending. The financial crisis in 2008 forced the Spanish government to significantly cut the military budget for the first time in over 10 years, and savings were realized particularly in procurement (including R&D contracts). See Miralles (2004), Barbé and Mestres (2007) or European Parliament (2011) for more details.

R&D by *country* (summed across industries). It is clear that in most cases the two series tend to move together: the weighted average correlation is 0.28 (standard error 0.06).

The importance of defense R&D is likely to vary across industries. For example, one would expect defense R&D to be more important in aerospace than construction or agriculture. To our knowledge, data on industry-specific defense related and business conducted R&D expenditure over long periods of time are available only for the US and the UK.[25] Figure 3 confirms that in both these countries aerospace is the single most important beneficiary of defense R&D. Other important industries are Mechanical Engineering and Electrical Machinery (in the UK) and Medical Precision and Optical Instruments in the US.

Figure 4 shows the relation between defense R&D and public R&D, by *industry* (averaged across countries). The figure confirms that in most industries the relationship is strong with a weighted average correlation of 0.32 (standard error: 0.07). In years when defense R&D is high (low), overall government funded R&D tends to be high (low). Below we quantify this relationship and test for statistical significance.

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

We begin our empirical analysis by examining an econometric case study of 9/11 (sub-section 4.1). We then estimate the effect of publicly financed R&D on privately financed R&D in the same industry and country (sub-sections 4.2 and 4.3) and on jobs and wages (sub-section 4.4). In sub-section 4.5 we estimate the effect of public R&D in an industry and country on private R&D investment in *other* countries. In the next section (section 5) we turn our attention to the effects of R&D on productivity.

4.1 A Case Study: The Effect of 9/11

Before turning to a systematic analysis of the effect the effect of public R&D and defense R&D in all countries and years, we begin with a case study that illustrates some of the forces at play. We focus

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[25] Most countries classify defense as one specific industry, and do not split R&D expenditure further by sub-industry. The defense sector comprises typically of aerospace products and parts (majority); navigational, measuring, electro-medical, and control instruments, as well as other transportation manufacturing industries. http://www.nsf.gov/statistics/seind12/c4/c4s2.htm#s4

on the effects of the 9/11 shock on R&D expenditures by private firms in the US. As shown in Figure 1, the 9/11 terrorist attacks induced the Bush administration to vastly increase military R&D spending.

Figure 5 shows the differential change in *private* R&D intensity experienced by two "defense sensitive" industries ---namely aerospace and ICT---compared to the change experienced by industries that are less dependent on defense R&D. We estimate difference in difference models using data from 1998 to 2005, with ln(private R&D/output) as the dependent variable and the defense sensitive dummy interacted with year dummies pre and post 2001 (as well as industry and time dummies). The figure shows that before 9/11 there is no obvious differential trend in private R&D intensity. But after 9/11, the data show a rapid increase in private R&D intensity in the defense sensitive sector compared to the other sectors. The effect of 9/11 appears both statistically significant and economically sizable.

In Figure 6 we plot the growth in industry-specific public defense R&D intensity in the post 9/11 period compared to the pre 9/11 period on the x-axis and the growth in private R&D intensity on the y-axis.[26] The figure shows a strong positive correlation (0.66, significant at the 1% level) between the industries that had the fastest increase in defense spending (like Aerospace) and those that had the fastest increase in private R&D spending.

This case study is consistent with a crowd-in effect, whereby an increase in public R&D results in additional increase in private R&D. We now turn to more systematic analysis.

4.2 Domestic Private R&D

(a) Baseline Estimates. Tables 4 and 5 present respectively OLS and IV estimates of variants of equation (5), in which the dependent variable is ln(private R&D) and the key independent variable is ln(public R&D). In the first column of Table 4 we control for a second order distributed lag of industry output, year dummies and country by industry fixed effects. In this first specification, rather than including country-year dummies, we control for a second order distributed lag of GDP. The coefficients on public R&D are all positive, with the largest coefficient on the current year: 0.242. The long-run effect is the sum of the three public R&D coefficients is shown at the bottom of the table. The long run effect is 0.339 and is significant, indicating that a 10% increase in government funded R&D is associated with a 3.4% increase in privately funded R&D. Taken at face value, this estimate suggests a

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[26] We use 1999-2000 as the pre-policy period and 2004-2005 as post policy period after the start of the Iraq War, but the exact choice of year makes little difference.

"crowding in" effect, whereby \$1 of additional public R&D generates more than \$1 of total R&D conducted in the private sector. Specifically, at average levels of public R&D and private R&D, the estimate implies that an extra \$1 of additional public R&D translates into \$4 of extra private R&D.[27]

Column (2) conditions on a full set of country by year interactions to control for all country-specific macro-economic factors that may affect private R&D (absorbing away the GDP coefficients). These controls reduce the long-run elasticity of private with respect to public R&D from 0.339 to 0.275, but the elasticity remains significant at conventional levels. Column (3) adds industry by time fixed effects to control for time-varying shocks to each industry. Our empirical estimates do not appear to be sensitive to the inclusion of all these dummy variables - if anything the estimated long run elasticity rises slightly to 0.319.

As an additional robustness check we add the one-year lagged and two-year lagged dependent variables in columns (4) and (5). The long-run elasticity remains highly significant at 0.329 and 0.325. In columns (6) to (8) we re-estimate models identical to the ones in columns (3) to (5) but drop industry output which could be endogenous. The long-run elasticity appears to be generally stable across columns.

As discussed in Section 2, an obvious concern with these results is the possibility that the provision of public R&D spending is correlated with unobserved determinants of private R&D. In Table 5 we use defense R&D as instrument for public R&D. All columns include a full set of country by industry fixed effects and a full set of industry by year dummies.[28] We begin in the first two columns with a parsimonious specification including only contemporaneous public R&D - the variable most likely to be endogenous. The OLS estimate in column (1) yields an elasticity of 0.162. When we instrument this with defense R&D in column (2), the coefficient on public R&D rises to 0.478 and remains statistically significant at conventional levels. In columns (3) and (4) we repeat the exercise for the variables lagged one period generating an OLS elasticity of 0.172 and an IV of 0.459.

The first stages of our instrumental variable estimates are generally well identified. The diagnostics over weak instruments is reported at the bottom and shows that the instruments have good power: the F-Test (Kleibergen-Paap) ranges from 12 to 15 and Anderson-Rubin Wald test rejects the null hypothesis of weak instruments at the 5% level. The full first stage regressions are reported in

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[27] In constant 2000 \$.The means of public and private R&D are given in Table A1.

[28] We omit country by year effects because the first stage is weak. This is to be expected, since much of the variation in the instrument is at this level. We do include GDP to account for at least some of the country and year macro-economic shocks.

Appendix Table A4. These are interesting in their own right. A priori it is unclear whether an increase in defense R&D in an industry will necessarily result in an increase in total government funded R&D in that industry. A crowding out effect is in principle possible, whereby increases in defense spending could result in an equivalent lowering of non-defense subsidies leading to no effect on total public R&D. The estimates in the table, however, suggest that this is not the case. A 10% increase in defense R&D is associated with a 1.5 to 1.7% increase in total government funded R&D, so there is not complete crowding out.[29]

Columns (5) and (6) of Table 5 use a more general dynamic specification with longer lags of output and GDP.[30] We see qualitatively similar results with IV estimates of 0.288, somewhat smaller than column (2). Columns (7) and (8) push our models even further, including the first and second lag of the dependent variable. This specification is the same as column (1) of Table 4, although it is estimated on a smaller sample because the instrument is missing in some cases. The estimates confirm the results of the simpler specifications. The OLS long-run effect in column (7) is 0.182, while its corresponding IV estimate in column 8 is 0.262. However, the diagnostic tests for weak instruments deteriorate significantly in these more demanding models as we are adding many more insignificant variables.

To probe the robustness of our findings, we estimate a number of alternative specifications. First, to account for the possible endogeneity of allocation of R&D funds across industries within a country, in Table A5 in the Appendix we also estimate IV models where the instrument is total defense spending in a country-year (as opposed to industry specific defense spending). While this weakens the first stage somewhat, the results are in line, and even somewhat larger, to what we found in Table 5. For example, in column (2) of Table A5 the coefficient on public R&D is 0.529, statistically significant at the 5% level.

We also estimated our baseline IV but dropped the US or the UK from the analysis (the ones we have time-varying industry level defense R&D information), to mitigate the potential endogeneity. The results were very similar. For example, Table A6 in the Appendix provides the results when dropping the US, a country which has a very large defense sector. In our main IV specification, column

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[29] Note that there are the sources of measurement error in the instrument discussed above that could attenuate the relationship between public R&D and defense R&D.

[30] There are two main differences between the model in column (7) in Table 5 and the model in column (1) in Table 4. First, the sample is different, as we have defense data only for a subset of observations. Second, the controls are slightly different. The reduction of the coefficient comes mainly from the reduction of the sample rather than the different controls.

(2), the coefficient (standard error) on public R&D was 0.488 (0.169) when the US was dropped. When the UK is dropped, the equivalent estimate is 0.516 (0.168).[31]

Second, in Appendix Table A7, we report estimates that only include the manufacturing sector. The motivation for this table is that R&D is a better defined concept and has less measurement error in manufacturing than in service industries. Our estimates are robust to this change in the sample, although somewhat smaller in magnitude.

Third, we investigated whether our finding may be driven by outliers. In Appendix Table A8, we trim the baseline sample by (i) winsorizing observations in the top and bottom 1% of the *level* of R&D/output distribution and (ii) winsorizing observations in the top and bottom 1% of the *changes* in R&D/output distribution. Our results remain robust to these experiments. In Appendix Table A9, we apply the winsorizing in growth rates to the instrument. The first stages remain strong, and the results are robust to these modifications as well.

Finally, we were concerned that the results could be driven by some countries with very low defense R&D levels (since we rely on changes over time in subsidies to identify effects). Hence, we re-estimated all the results dropping countries with below median defense R&D to GDP ratios. All results were robust to this experiment – indeed they were generally stronger as one would expect (see Table A10 for example). There is also the opposite concern: that all the results could be driven by the US as the world's largest R&D defense spender (e.g. Mowery, 2010). The results were actually very similar when we re-estimated all the results in Tables 4, 5, and 8 dropped the US.[32]

Taken together, the estimates in Tables 4 and 5 lead us to draw two conclusions. First, increases in public R&D translate into increases in private R&D expenditures, with the most reliable estimates of the long run elasticity between 0.2 and 0.5. This implies that $1 of additional public funds for R&D translates into $2.4 to $5.9 of extra R&D funded by the private sector at the mean values of public and private R&D. 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. It is also consistent with large fixed costs or credit constraints.

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[31] Results available on request.

[32] For example, the coefficient (standard error) on public R&D in IV specification is 0.488(0.169) without the US (column (2) in Table A6), slightly higher than the coefficient of 0.478(0.165) on the sample including the US (column (2) in Table 5). The coefficient on R&D in the TFP growth regression of column (3) Table 9 falls from 0.064(0.027) when the US is included to 0.055(0.026) when the US is dropped (details available on request).

In some industries, defense related R&D is responsible for a significant part of private R&D investment. For example, in the US "aerospace and other transport equipment" industry, defense related R&D amounted to \$34.5bn in 2003 (constant 2000 \$).[33] Our estimates suggest that this public investment translates in \$7.1bn-\$7.8bn additional investment in private R&D.[34] Defense related R&D is also very important in the medical/precision instruments sector, with spending of \$16.5bn in 2003.[35] According to our estimates, this translates into \$3.4-3.7bn additional investment in private R&D.

Interestingly, differences in defense related R&D can potentially account for some of the differences in private R&D across countries. Our estimates indicate that if Germany increased its defense R&D to the level of the US as a fraction of GDP (admittedly a very large increase), private R&D investment would increase respectively by 44.4%.[36]

Second, there is little evidence of upwards bias in the OLS estimates. OLS estimates are stable across specifications, and are consistently below IV estimates. In the context of our discussion in Section 2, this is consistent with compensatory government policies. In other words, our findings are consistent with a situation where governments tend to subsidize industries that are underperforming in terms on R&D investment, all else equal.[37]

(b) Robustness: Accounting for other public policies. Changes in defense R&D subsidies might be correlated with other public policies and therefore bias our estimates. One might worry especially about changes in defense R&D that are due to changes in the political orientation of a government, as this might also lead to changes in other policies (e.g. Republicans in the US favor both defense spending as well as other pro-business policies). In this section we account in different ways for other public policies (such as R&D tax credits, R&D subsidies to the academic sector, business

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[33] According to our US defense data, 58% of total government funded, defense related R&D expenditure of \$59bn pertains to the other transport equipment industry (excluding motor vehicles, including aerospace).

[34] 58% of total defense R&D translates into 58%*0.148*0.478=4% (elasticities from Tables A4 and 5) of total private R&D which was \$172bn in the United States in 2003. Upper estimates use the elasticities with a one year lag. Similar calculation for the precision/medical instruments sector.

[35] According to our US defense data, 28% of total government funded, defense related R&D expenditure of \$59bn pertains to the medical, precision and optical instruments industry.

[36] Defense R&D expenditure as share of GDP in our data (averaged over all years) is 0.61% for US and 0.08% for Germany. To reach the defense R&D share of the US, Germany would have to increase own defense R&D spending by a factor of 6.3 – a very large increase. Multiplying this with the coefficients of the first stage and the IV estimates yields the resulting percent increase in private R&D spending.

[37] See Criscuolo et al (2012), for a related finding on investment subsidies.

taxes), but it turns out that in our data defense R&D is sufficiently uncorrelated with other public policies and therefore does not bias our results.

We start by considering R&D tax credits, another form of government support for R&D which is used by a number of countries. In fact, over the past 20 years many governments have started to replace direct R&D subsidies with fiscal policies such as R&D tax credits. This trend is most pronounced in European countries such as Denmark, France and the Netherlands (Guellec and van Pottelsberghe de la Potterie, 1999), but is also visible in the US.[38] From the point of view of governments, publicly funded R&D and R&D tax credits are likely to be substitutes. In this case, it is possible that the two types of public support are negatively correlated and our estimates of equation (6) underestimate the true effect of government funded R&D. The magnitude of this bias is unlikely to be quantitatively large. First, while the importance of R&D tax credits is growing, they are still a small minority of public subsidies. The vast majority of government funded R&D spending in most countries is still direct rather than indirect (e.g. OECD 2010). Second, R&D tax credit regimes are part of the national tax code and unlike the direct R&D subsidies we focus on, R&D tax credits are only rarely industry-specific. While it is possible that the shift towards tax credits may have some differential impact across industries within each country, this is unlikely to be first-order.

To investigate this directly we used data from Thomson (2012) who has calculated a measure of the generosity of the R&D tax credit over time for a sub-sample of the countries and years. In columns (1) and (2) of Table 6 we re-estimate our model of Table 5 on the sub-sample for which R&D tax credit data and other policies are available and find that the results are robust. We then include a measure of R&D tax credits in columns (3) and (4). As in the extant literature more generous R&D tax credits are associated with significantly greater R&D, with an elasticity of around unity. Most importantly for our purposes, the coefficient on public R&D remains positive and significant in our main IV and OLS specifications with only a slightly smaller effect.[39]

Besides businesses, also other institutions like universities or government funded research labs receive subsidies for R&D, which might be correlated with business R&D subsidies. In order to make sure that our estimate does not capture spillover effects from correlated R&D subsidies to non-business

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[38] For example, over the past two decades, general R&D tax credits offered by US states have become increasingly important, with the average effective credit four times larger today than what it was 20 years ago (Moretti and Wilson, 2012).

[39] In Table A11 of the Appendix we experiment with different lags of R&D tax credits, but the results are unchanged.

institutions, we include the latter as a control in columns (5) and (6) of Table 6. Our results are robust to this inclusion.[40]

R&D subsidies might also be correlated with other business favoring policies, for example taxes to businesses, which might also affect private R&D directly. In fact, in our data defense R&D is positively correlated with business taxes. In columns (7) and (8) we therefore control for the average business tax rate (tax revenue data is from OECD) directly. Again, our results are unchanged.[41]

Finally, if R&D subsidies are correlated with other government policies, this is likely to be especially true for the case when defense R&D changes due to changes in the political orientation of the government after elections. In Table A14 of the Appendix we use only the variation in defense R&D that is *not* due to changes in government, by controlling for the orientation of a government. The political orientation data is from the Database of Political Institutions (DPI) by the World Bank and indicates whether the chief executive's party is right wing, center, or left wing. Again, our results are unchanged.

Overall, our results seem fairly robust to the inclusion of a variety of other public policies which might potentially be correlated with defense R&D. In reality, however, defense R&D is not highly correlated with other policies, which reassures us that defense R&D is driven by exogenous military, rather than economic considerations.

(c) Robustness: Accounting for Demand Effects. Our identification strategy of using military R&D as the exogenous component of public R&D is justified by the idea that defense spending is uncorrelated with the residual in the R&D equation being driven by geopolitical shocks rather than technology shocks. However, a concern is that increases in military R&D spending are correlated with increases in expected demand for output. For example, after 9/11 US firms producing aircraft may have anticipated increased demand for military planes and increased private R&D in expectation of this greater demand, even in the absence of public R&D. This would potentially violate the IV strategy as both public and private R&D respond to an exogenous event.

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[40] In Table A12 of the Appendix we experiment with different lags of non-business public R&D, but the results are again unchanged.

[41] In Table A13 of the Appendix we experiment with different lags of the average business tax rate, but the results are again unchanged.

We tackled this concern in a number of ways. In our baseline estimates above we conditioned on a large number of variables that should control for such demand expectations such as distributed lags in industry and aggregate output and industry by time dummies. Still, these may not fully account for expectations of future demand changes. Here we implement a very conservative test by controlling for *future* demand (industry output) in specifications as in Table 5. Since private R&D will increase future output (see next section) this is an endogenous variable and will absorb some of the variation we are interested in. Nevertheless, if we still observe an effect of defense R&D on private R&D this would be a strong test. Panel A of Table A15 shows that output next year is indeed a predictor of current R&D which could be because of expectations or a genuine causal effect of R&D on future output. The coefficient on public R&D in OLS and instrumented by defense R&D is robust to this test. Panel B includes future leads of output up to *t+3* and shows the results remain robust.[42]

An alternative approach to dealing with expected demand is to condition on non-R&D military spending and expectations thereof (as this is the omitted variable that could violate the exclusion assumption). We do not have data on total public military spending for all countries but Table A16 shows that the results are robust on the sub-sample where we do have this information. Including total military spending does not change the results (e.g. the coefficient on defense R&D is remarkably constant across columns (1) to (4)). The direct effect of total military spending, or procurement, on private R&D is positive, as expected, but not significant.

Table A17 implements an even tougher test by estimating the model solely on the US (where we have industry-specific R&D and non-R&D public military spending). Column (1) shows that military R&D is significantly and positively associated with private R&D even including a full set of industry and time dummies (as in Figure 5). And columns (2) through (4) show that this result is robust to including current and future values of total military R&D spending. While the effect of defense R&D on private R&D falls somewhat, consistent with some private R&D being spent in expectations of future sales to military, the effect remains positive and significant across specifications even including military procurement up to 2 years ahead.

We perform one final check to make sure that our instrument is using the right variation and our results are not driven by changes in defense procurement that stimulate demand rather than R&D,

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[42] We also constructed the expectation of demand by running VARs of industry output against third order distributed lags of all variables in Table 5. We entered these demand expectations terms into the Table 5 specifications using only information dates t and earlier. The IV results are smaller, but still large and significant.

by using the defense spending components unrelated to R&D subsidies paid to businesses as a placebo instrument. The placebo instruments should not be correlated with public R&D, in other words, should not give a strong first stage. If we found a strong correlation between the placebo instruments and public R&D, we would be concerned that our findings were spurious – our findings might be driven by expected demand effects coming from defense spending other than R&D, or by a correlation of defense spending with other policies that encourage economic growth and therefore R&D. We try four different versions of a placebo instrument. Reassuringly, all of them deliver a first stage F-statistics of basically 0: 1) Defense procurement excluding R&D has an insignificant effect of 0.080 (SE: 0.104) on public R&D (first stage F-statistics: 0.587) ; 2) Defense procurement excluding R&D, civil defense, and foreign military aid (coefficient: 0.079, SE: 0.103, first stage F-stat: 0.584); 3) Military wage bill excluding R&D (coefficient: -0.018, SE: 0.094, first stage F-stat: 0.037); and 4) Military wage bill excluding R&D, civil defense, and foreign military aid (coefficient: -0.012, SE: 0.091, first stage F-stat: 0.017).[43]

In summary, the effects of defense R&D (and public R&D in general) appear to reflect forces of supply rather than demand expectations in stimulating private R&D.[44]

4.3 Employment and Wages

Having found that increases in public R&D translate into increases in private R&D, we now turn to the effect of public R&D on employment and wages. We distinguish between R&D personnel and non-R&D personnel. The discussion in Section 2 suggests that the effects are governed by different economic forces. If the supply of R&D workers is inelastic in the short run, increased R&D spending could translate into significantly higher wages (Van Reenen, 1996) especially of R&D workers (Goolsbee, 1998). Thus, it is in principle possible that the finding of increases in private R&D expenditures following increases in government funded R&D may simply reflect an increase in the cost of inputs used in R&D, namely specialized labor.

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[43] The non-R&D components of defense were only available at the country*year level (source again from OECD), so we interacted all of them with defense R&D industry shares as described for our main instrument, defense R&D.

[44] One other concern that we tested is whether the positive effect of public R&D subsidies on private R&D subsidies in the same industry might be driven by R&D subsidies to industries which are connected by input output linkages. In order to test this, we control for domestic R&D in other industries, which we weigh by their input or output share to the respective industry. This concern does not seem to be relevant in the data, as our estimates remain unchanged (results available upon request).

Table 7 estimates models similar to the one in equation (6) where the dependent variable is employment or wages. Since data on employment and wages are not available for all countries and industries and years, column (1) reports the baseline estimates of the effect of public R&D on private R&D estimated on the sample for which employment and wage data are available. Panel A reports the results from an OLS regression (equivalent to column (1) in Table 5), and panel B reports results using defense R&D as IV for public R&D (equivalent to column (2) in Table 5).

When we focus on workers directly engaged in R&D activities, we uncover significant positive effects in column (2). The IV estimates are even larger than the OLS estimates. Scientists appear fairly mobile, presumably because it is easy for R&D workers to relocate to the affected industry from other industries and countries. Indeed, the estimated elasticities are high – between 0.2 and 0.3 – and similar to or slightly smaller than the one for R&D expenditures in column (1). The IV estimate in column (3) also uncovers positive, but smaller effects on personnel outside R&D.[45] This result is consistent with the notion that the effect of labor augmenting innovations is somewhat larger in magnitude than the labor saving innovations.[46] It is also consistent with shared fixed costs - whereby the marginal R&D activity induced by public R&D requires new scientists and non-scientific personnel but utilizes existing labs.

In columns (4) and (5) we turn to wages. The dependent variable in column (4) is the average salary of R&D workers.[47] The coefficient on public R&D is positive (0.062) and significant at the 10% level in the OLS, but gets insignificant (though larger) in the IV version. It is therefore unlikely that a Goolsbee (1998) type of mechanism is in place, or even that the composition or quality of researchers changes. Column (5) focuses on the average wages and finds virtually no effect. This would suggest that innovations in public R&D industries do not have a skill bias.

4.4 International R&D Displacement Effects

In sub-sections 4.1 to 4.3 we estimated the effect of government funded R&D in an industry and country on private R&D activity in the same industry and country. We now turn to the effect of

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[45] This is consistent with Berman, Bound and Griliches (1994) who found a positive association of defense R&D with the share of non-production workers in US industries.

[46] We dropped the output terms to examine this in Table A18 in the appendix, and the effects of public R&D is somewhat larger with an elasticity of 0.091 (standard error 0.038) in the IV estimation.

[47] We measure average salary of researchers by dividing the costs of R&D personnel by the number of R&D personnel. We measure average salary by dividing total wagebill by total employment

government funded R&D in an industry and country on private R&D investment in other countries.[48] It is possible that increases in the government funded R&D in an industry in a given country may result in lower R&D in similar industries abroad. To quantify this displacement effect we estimate equation (6) where we include both own public R&D and neighbors' public R&D.

Specifically, in Panel A of Table 8 we regress private R&D on domestic public R&D and lagged neighbors' public R&D (to allow time for reaction), measured as a weighted average of public R&D in other countries in the same industry and year, with weights reflecting "proximity". We use a variety of alternative measures of geographic and economic proximity. Column (1) uses the difference in GDP per capita as a distance measure, column (2) the geographic distance in kilometers between the capital cities, column (3) the difference in skill intensity as measured by the share of the population with tertiary education, column (4) the similarity of patent technology classes (out of 15 different technology classes), column (5) the FDI flows that a country receives from other countries, column (6) the difference in R&D intensity as measured by R&D/GDP, column (7) the imports that a country receives from other countries (as in Coe/Helpman 1995), and column (8) the exports that a country sends to other countries.

The effect of domestic public R&D on private R&D remains positive across all specifications. By contrast, the coefficients on neighbors' public R&D are negative in all columns and significantly so in columns (1), (3) and (4). The negative effect is consistent with significant displacement effects between close countries when proximity is defined as income proximity, skill proximity, and technological proximity. If one country increases its public R&D, business funded R&D in nearby countries in the same industry falls, controlling for public R&D received from its own government.

Panel B in Table 8 uses total R&D (not just government funded R&D) to compute the international spillover pool. Again, seven of the eight coefficients are negative (five of them significantly so), with elasticities that are somewhat larger than the ones in Panel A.

Panels A and B in Table 8 are estimated by OLS because our defense instrument does not have enough power to estimate models that include both direct effects and displacement effects by IV. However, the sharp difference between direct effect and indirect allays concerns about spurious correlation. Endogeneity could generate a spurious positive coefficient, but the coefficient on

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[48] We also investigated the possibility of displacement across industries within a country. Most of the estimates pointed to limited displacement (table available upon request).

international public R&D is robustly negative. An obvious explanation of these results is that there is some strategic interaction between countries. Faced with increased R&D spending by a rival country, a domestic firm may choose to cut back on its own spending either because (i) there is little chance of winning the technology race and/or (ii) the firm can free-ride off the benefits of neighbor's innovation (we will show some evidence for the latter effect below when looking at productivity spillovers).

In any case, the endogeneity is more likely to be a concern for own public R&D versus international R&D, so in Panel C of Table 8 we instrument domestic public R&D with defense R&D. Since most of the variation in defense R&D is at the country*year level, we omit country*year fixed effects and control for GDP instead.[49] The IV results are even more pronounced than the OLS results in Panel B, confirming the international displacement effect.

It is interesting that our data shows crowding out at the international level (Table 8), and crowding in at the domestic, intra-industry level (Tables 4 and 5). This suggests that the mechanism driving knowledge spillovers is in fact related to local agglomeration economies, which are not present at the international level.

5 Effect of R&D on Productivity Growth

Having documented the positive effect of government funded R&D on private R&D investment; we now turn our attention to quantifying the effect that private R&D investment has on productivity. We start by presenting estimates of the effect of R&D performed in an industry and country on productivity in the same industry and country. We then present the effect of R&D performed in an industry and country on productivity in the same industry but in different countries.

5.1 Domestic Productivity

In Table 9 we estimate equation (8) by regressing changes in TFP on lagged R&D intensity defined as R&D in an industry divided by value added. The first column presents the OLS estimate and indicates a strong and positive correlation between lagged R&D intensity and subsequent TFP growth. Column (2) adds country dummies and shows that the relationship is robust to this addition. Column (3) presents IV estimates using defense R&D as an IV for total R&D. As the first stage F-statistics at

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[49] The OLS version of Panel C (i.e. no country*year fixed effects, but country GDP) is shown in Appendix Table A19. The effects are qualitatively similar to Panel B, but somewhat smaller in magnitude.

the bottom of the table indicates, the instrument has power. The coefficient on R&D is 0.06, smaller but not statistically different from the OLS estimate of about 0.10. Column (4) reports the reduced form estimate. In this model the independent variable is defense R&D divided by value added. As expected, defense R&D is both positive and statistically significant.

In columns (5) to (8) of Table 9 we re-estimate our models using changes over time computed over a two year time horizon. The coefficients increase as we move from the one year to the two year differences which suggest attenuation bias due to transitory measurement error. This is a common finding in the R&D and productivity literature (e.g. Griliches and Mairesse, 1995). The instrument shows a comparably strong first stage in the two year time horizon.

We probed the robustness of our finding using several alternative specifications, and found that our estimates are generally stable. For example, estimates of the impact of R&D on TFP using Harrigan (1997) smoothing techniques are very similar: the equivalent coefficient (standard error) on R&D intensity in column (3) of Table 9 was 0.060 (0.026).[50]

The magnitude of the effect we find is significant not just statistically, but also economically. Using the estimates in Table 9, column (4), a permanent increase in the defense R&D to value ratio of one percentage point is associated with an increase in the annual growth rate of TFP of 0.05 percentage points. Since average annual TFP growth in our sample is around 1.01%, this represents an increase from 1.01% to 1.06% a year.

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 9% and 3%, respectively.

Defense R&D/GDP in the US increased following the 9/11 attacks from 0.45% to 0.60% between 2001 and 2004. Thus, our estimates suggest that defense related R&D translated into a 2% increase of the annual TFP growth rate and therefore GDP growth rate by 2009. (Of course, this calculation ignores the deadweight loss caused by the additional tax revenues needed to finance R&D).

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[50] We have also tested for heterogeneity of the effect. The effect of R&D on TFP seems slightly more pronounced in low R&D intensive countries. It also varies across industries, but this variation is not systematically associated with industry R&D intensity.

Finally, given that we find positive effects on productivity, the positive spillover effects we find on private R&D are very unlikely to be driven by a relabeling of other expenditure as R&D expenses in order to obtain subsidies. A pure relabeling would not result in productivity increases.

5.2 International Spillovers

Finally, we turn to the question of international productivity spillovers. We re-estimated the specifications of Table 9 but include a measure of international spillovers defined in the same way as Table 8. Table A20 uncovers statistically significant positive international spillovers. The magnitude of the coefficient varies from 0.07 to 0.25. In order to interpret the magnitudes of the coefficient note that the average values of own R&D/value added and the international spillover pool are different, so the coefficients cannot directly be compared. For example, in column (1) an increase by 1 standard deviation of own R&D/value added (equivalent to 14.4 percentage points) is associated with future TFP growth by 0.8%. Similarly, an increase by one standard deviation of the spillover pool (equivalent to 9.7 percentage points) increases TFP growth by 1.4%. The effect of the spillover pool is larger because it requires all the other countries to increase their public R&D.[51]

Overall, public R&D in an industry and country has two offsetting effects on productivity in other countries. On the one hand, it lowers R&D in other countries, and therefore it indirectly lowers TFP there (Table 8). On the other hand, it generates positive TFP spillovers (Table A20). According to our estimates of displacement in Table 8 and of spillovers in Table A20 the net effect is positive, but the magnitude depends on the closeness between two countries.[52] For example, the net effect of an exogenous increase in total R&D in country *i* by one percentage point on the TFP growth rate in country *j* is 0.007 percentage points (0.8%) at mean geographic distance (ranging from 0.0003 percentage points or 0.03% to 0.0839 percentage points or 10.2%) and 0.008 percentage points (0.9%) at mean technological distance (ranging from 0.0007 percentage points or 0.1% to 0.0689 percentage

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[51] The coefficient on domestic R&D falls and becomes insignificant when spillovers are included which is due to the fact that domestic and international R&D is highly correlated, so it is difficult to estimate both effects simultaneously.

[52] The spillover effect is the coefficient on international R&D/value added in Table A20 multiplied by the distance weight. The displacement effect is the product of the coefficient on international Total R&D in Panel B of Table 8, the share of private R&D in total R&D (on average around 90%), the coefficient on own R&D/value added in Table A20, and the distance weight. Note that Table A20 measures the effect of a percentage point change, while Table 8 measures the effect of a percentage change; so appropriate conversions have to be made before the spillover effect and the displacement effect can be added up. The net effect is positive for all our distance measures, but the magnitude depends on the actual distance between two countries.

points or 8.4%). Countries that have large government funded R&D budgets (like the US) indirectly benefit the productivity of countries that have low government funded R&D budgets.

5.3 Magnitude of the Effects

We end with a summary of the magnitudes of various effects arising from our analysis. To make matters concrete we consider an increase in US military R&D on the scale that occurred after the 9/11 attacks. As mentioned above, US defense R&D rose by 52% from 0.45% to 0.60% of GDP between 2001 and 2004 (see Figure 1). We use all the linkages in the results above (see Appendix B). We calculate that the 9/11 shock induced a 2% increase in US TFP growth. This comes from using the TFP results in Table 9 (column (4)) combined with an increase in total US R&D/GDP of 0.08 percentage points (or 4.3%; which is composed of public R&D rising by 7.7% according to Table A4, and private R&D rising by 3.7% according to the IV results of Table 5 due to crowding in). By contrast, TFP growth in other OECD countries rose by 0.04% on average. This comes primarily from the international spillover arising from the increase in US R&D (Table A20). But there is also a small TFP offset because US R&D displaces some foreign R&D (down -0.03% on average, Table 8, panel B).

Note, however, that in this study we looked only at effects occurring at a relatively short horizon. It is likely that the effects are larger when looking at a longer time horizon, e.g. over decades, therefore our estimates are likely to be a lower bound of the true effect of public R&D subsidies on private R&D and productivity growth.

5 Conclusions

A large body of empirical research has argued that R&D is a key source of firm productivity growth (e.g. Griliches, 1979) and this notion has long been at the heart of modern growth theory. But there are at least two limitations with the existing empirical evidence. First, it is unclear how much of the association between productivity and R&D is causal and how much reflects unobserved factors which are correlated with both. Improving institutions and technology, for example, could cause countries or industries that experience faster R&D investment do tend to also have higher productivity growth. Despite the importance of this issue, few empirical studies make use of plausibly exogenous sources of variation in R&D.[53] Second, even if the association of productivity with R&D is entirely causal, the question remains as to what policies can successfully raise R&D, and whether these policies are socially efficient.[54]

In this paper, we study the impact of public R&D spending on private R&D spending and productivity. We address the potential endogeneity of public R&D by using the defense component as an instrument exploiting natural experiments such as the start of hot wars and the ending of cold wars. We uncover some unexpected intellectual spoils of war. First, our results suggest that government R&D "crowds in" rather than "crowds out" private R&D with a long-run elasticity of around 0.3 (i.e. a 10% increase in government funded R&D increases private R&D by 3%). This affects seems causal – when we instrument public R&D with the arguably more exogenous defense related component, this relationship strengthens, suggesting that (if anything) public R&D is often used to compensate industries facing negative shocks.

Second, we find that R&D investment plays an important role in raising TFP and therefore economic output. We uncover estimates of the rate of return to R&D that range between from 0.6 to 0.10. This effect is economically meaningful. Public R&D in general, and defense R&D in particular, account for some of the differences across countries in TFP.

Finally, we uncover an interesting pattern of international spillovers. An increase in public R&D benefits other countries through a positive productivity spillover, but we also find that on average these other countries respond by cutting back on their R&D investments (which by itself will reduce their productivity growth). Simple simulations suggest that the first effect dominates, however, and that government-funded R&D by one's neighbors is to be welcomed rather than feared.

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[53] Some papers have sought to use standard panel data techniques using assumptions over the serial correlation properties of the errors (e.g. Hall and Hayashi, 1989). The only paper using policy instruments for R&D that we know of is Bloom, Schankerman and Van Reenen (2013) who use state and federal R&D tax credits in the US. There are a few recent papers that focus on causality, but not private R&D as outcome, and focus mostly on small scale experiments in single countries: Bronzini and Iachini (2014); Howell (2015); Azoulay et al (2015); and Jacob and Lefgren (2011).

[54] The existing literature on the evaluation of R&D policies includes two types of studies. First, there are studies that focus on fiscal policies towards R&D such as Hall (1993), Hall and Van Reenen (2000), Bloom, Griffith and Van Reenen (2002), Wilson (2009), Moretti and Wilson (2013) and Rao (2013). Second, there are studies that focus on direct R&D subsidies, a more common form of R&D support. Examples include Azoulay et al (2015); González et al (2005); Gorg and Strobl (2007); Lach (2002); Jacob and Lefgren (2011) and Wallsten (2000). In most cases, existing studies focus on a single country. Guellec and van Pottelsberghe de la Potterie (2001) is a rare example of a paper looking at both types of R&D policies simultaneously and finds that they both increase R&D. For surveys see David, Hall and Toole (2000) or Klette, Møen and Griliches (2000).

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APPENDIX A: DATA

Main Variables. R&D data was obtained from the OECD database Main Science and Technology Indicators (MSTI). This dataset contains industry level R&D conducted by businesses (“Business Enterprise R&D” or “BERD”) for 26 countries between 1987 and 2009. This is our main R&D variable, but note that BERD is the main component of general R&D (“GERD”) which also includes R&D conducted by non-businesses such as universities and government R&D labs (it is not possible to break this down by industry).

The panel is unbalanced as some data is not available for some countries especially in the early years. Note that BERD is R&D conducted by business but can be financed from several sources. The OECD breaks BERD into three sources of funding: government, business and abroad. Our main variable is BERD that we generally refer to simply as “R&D”. The variable “Public R&D” is the government funded part of BERD (S). We used the OECD’s PPP US$ values to deflate all nominal variable such as GDP, output and R&D. From the same dataset we also obtained the total number of R&D personnel by industry and country (all measured in full-time equivalent on R&D activities) which is broken down into scientists (“# researchers”) and other R&D personnel such as lab technicians. We also have the total wage bill of these R&D personnel which enables a crude construction of the “R&D wage” of R&D labor cost divided by total R&D personnel.

For the main regressions where we use R&D as the dependent variable, we use the industry-funded part of BERD as the dependent variable. We refer to this as "private R&D" (*R*). For the regressions where we use TFP growth as the dependent variable we use R&D as the key right hand side variable - i.e. total BERD from all sources of funds. We take output, employment, wage bill, capital and value added data from the OECD STAN database. We use the level of industry aggregation that maximized the matches between the databases STAN and MSTI, ending up with 26 industries (see below).

Data for missing years was linearly interpolated for all variables (between the first and the last year available per country), but no data was extrapolated forward or backwards. These imputations accounted for between zero and 35% of the final sample, depending on the variable. The results are robust to dropping interpolated values.

The industry level breakdown of BERD by source of funding was missing for the United States after 2001 in the MSTI because a change in industry classification of the OECD (to ISIC Rev. 3) required a new crosswalk from the industry classification used in the US, NAICS. However, we obtained the original R&D data from the National Science Foundation, Survey of Industrial Research and Development (SIRD), and implemented the crosswalk to our data set, verifying that the totals (all source of funds) by industry matched the totals published by the MSTI. The crosswalk is available on request.

Defense R&D. Our instrument, DR_{ikt}, is the defense related part of R&D spending. The OECD's MSTI reports the value of Government Budget Appropriations or Outlays for defense related R&D ("$DefGBAORD_{kt}$") by country and year. Ideally we would like to know the part of business enterprise R&D that was solely related to defense spending and then to break this down into the government and privately financed components, but this is unavailable. In the time series, however, it is likely that increases in $DefGBAORD_{kt}$ are strongly associated with increases the part of public R&D that goes to defense. Our first stages regressions confirm that this relationship is strong in the data. Further, in the UK we have a more detailed breakdown and we confirm that the correlation is 0.85.

A second limitation of this measure is that public defense R&D is not separately identified by industry in MSTI. However, it is possible to make such a breakdown in the US and UK, the two countries with the highest shares of public R&D devoted to defense (Table 3). In the UK this is given by the Office for National Statistics (dataset “Expenditure on civil and defense R&D performed in UK businesses by broad product groups”, ONS/GSS reference number: rdbd5, downloaded from http://statistics.gov.uk/statbase/Product.asp?vlnk=2714&More=Y in December 2010; now available in the National Archives under http://webarchive.nationalarchives.gov.uk/20100406130654/http://statistics.gov.uk/statbase/Product.asp?vlnk=2714&More=Y).

In the US we can estimate the breakdown by using data on individual defense contracts which are made publicly available because of procurement transparency rules. Draca (2012) analyses the millions of defense contracts from the early 1960s onwards and generously shared his data with us. His dataset combines historical military procurement data from the National Archives and Records Administration (NARA) with company accounts information from COMPUSTAT. NARA procurement data contains all prime military contracts awarded by the Department of Defense (DoD) between 1966 and 2003. Each year comprises around 250,000 different contracts awarded for the procurement of goods and services, with a minimum reporting threshold of 25,000 USD between 1984 and 2003 (the part of the dataset that we use). The data includes a 4-digit product code known as the Federal Supply Code (FSC); we use only expenses with product code “R&D” as our measure of defense related R&D spending. Draca matched the name of the awardee with the COMPUSTAT database. The COMPUSTAT data include a four digit industry classification (SIC4) for each company. We aggregated the defense R&D expenses by industry and match the SIC4 industry codes to the (more aggregate) industry classification used in the OECD datasets in order to get a distribution of R&D defense spending across industries in the US.

Consequently we constructed an estimate of industry specific defense R&D using the industry weights from the US and the UK. In the absence of any other information we assumed that the share of defense R&D allocated to an industry *k* in year *t* in country *i* (w_{ikt}) was the same as it was in the US for every country except for the UK where we used the UK specific weight. Specifically, for all countries but the UK, defense R&D is:

$$DR_{ikt} = w_{kt}^{US} * DefBAORD_{\mathrm{it}}$$

where the weight w_{jt}^{US} is sector j's share on the US's defense R&D performed in businesses. The US defense contracts data ends in 2003, so we assume the US weights remain the same for the last few years of the data. Similarly, there is no UK breakdown prior to 1993 so we assume the weights for the UK were the same in pre-1993 as they were in 1993. In the IV regressions we tested variants of the instrument such as dropping the weights (so setting $w_{kt} = 1$), using time invariant weights, using the UK weights for other EU countries instead of the US weights, and so on. The results were robust showing that the main source of variation comes from the country by year variation.

Total Factor Productivity, TFP. TFP growth can be measured by a superlative index derived from the translog production function (as in Caves et al, 1982). This results in the following expression for industry-country-year TFP:

$$\Delta \ln A_{ikt} = \ln\left(\frac{VA_{ikt}}{VA_{ikt-1}}\right) - \frac{1}{2}\left(\theta_{ikt} + \theta_{ikt-1}\right)\ln\left(\frac{L_{ikt}}{L_{ikt-1}}\right) - \left(1 - \frac{1}{2}\left(\theta_{ikt} + \theta_{ikt-1}\right)\right)\ln\left(\frac{K_{ikt}}{K_{ikt-1}}\right)$$

where VA_{ikt} is value added, L_{ikt} is total employment, K_{ikt} is the capital stock, and θ_{ikt} is the share of labor in value added.

Value added is from the STAN database, we use the variable VALK which gives value added in volumes. STAN uses volume indices provided by national statistical agencies that are typically derived by applying detailed deflators based on Producer Price indices (PPIs) or Consumer price indices (CPIs) coming from detailed surveys. Volumes for activity groups are either fixed-weight Laspeyres aggregates or annually re-weighted chained aggregates of the volumes of detailed sectors.

Employment is given in STAN by the total number of persons engaged (total employment) reported in variable EMPN.

Capital stock is given in STAN in variable CPGK, "gross capital stock (volumes)". For some countries (e.g. US, Japan, Australia, Norway, Sweden) the capital stock was not available in the STAN database, but investment data was (variable "GFCK", gross fixed capital formation in volumes). For these countries we follow Scarpetta and Tressel (2002) and OECD (1999) and construct capital stock using a perpetual inventory model which simulates the process of capital accumulation using past investment data that is adjusted for scrapping. Gross capital stock GCS_t at time t is:

$$GCS_t = \sum_j INV_{t-j} * (1 - \delta_j)$$

where INV_{t-j} is investment undertaken in period t-j, i.e. with vintage j at time t, and 1-δ_j is the survival coefficient which represents the fraction an investment of vintage j that is still in use in year t contributes to gross capital stock in year t. The survival coefficient is between 0 and 1, and falls with vintage. We follow the literature and assume that depreciation follows a delayed linear retirement pattern, where scrapping starts only 5 years after the investment has been undertaken.

Average services lives (ASL) are usually used to measure the depreciation process of an investment. If depreciation starts after 5 year and is linear, ASL is given by

$$ASL = 5 + \frac{n}{2}$$

where n is the time period during which an investment has positive depreciation (and $n+5$ is the total life time of an investment). Thus, with linear depreciation, in each year depreciation equals a constant fraction δ of past investment (starting after 5 years):

$$\delta = \frac{1}{n} = \frac{1}{2 * (ASL - 5)}$$

Gross capital stock can therefore be constructed using the recursive relationship:

$$GCS_t = GCS_{t-1} + INV_t - \frac{1}{2 * (ASL - 5)} \sum_{j \geq 5} INV_{t-j}$$

Since our investment data starts only at the beginning of the sample period and we need past investment for the construction of gross capital stock, we assume that past, unobserved annual investment is equal to average investment across the sample years (separately for each industry within each country). Our results are robust to assuming past investment to be equal to initial observed investment, or average investment across the first observed years. This assumption about past investment can then also be used to calculate the gross capital stock at the beginning of the sample period. Average services lives (ASL) by country and industry are given in OECD (1999), p. 48. For countries without ASL data we use the US industry-specific ASL.

The share of labor in value added α is measured in two ways. First, we simply used the industry-specific unweighted average of the wage bill over value added (across all countries and years). Alternatively, we use the Harrigan (1997) smoothing method to construct the share of labor in value added α_{ikt}, by industry, country and year. For this we ran a pooled OLS regression of the form

$$\theta_{ikt} = \theta_{ik} + \phi_j \ln\left(\frac{K_{ikt}}{L_{ikt}}\right)$$

where θ_{ikt} is the observed labor share in value added, α_{ik} are a full set of industry-country pair fixed effects and K and L are capital stock and employment as described above. We then used the predicted values from this regression for the industry-country-year specific share of labor in value added θ_{ikt}. As robustness checks we also used the overall average labor share in our data, or a constant labour share of 0.65 to construct TFP, but our results were not sensitive to the specification of the share of labor in value added.

APPENDIX B: CACULATION OF MAGNITUDES

Figure A1 describes pictorially the linkages between an R&D shock in the US (calibrated to the 9/11 events) and the way this reverberates throughout the domestic US economy in terms of changes to public and private sector R&D as well as the international economy. We estimated that such a shock increases US TFP growth by 2% and the following calculations explain how this was calculated.

9/11 shock in the US. Between 2001 and 2004 US defense R&D spending (*DefGBAORD*) increased by 52%, from $46b to $70b. This represents an increase of US defense R&D spending as a proportion of GDP from 0.45% to 0.60%: by 0.15 percentage points.

Effect on US public R&D. Using the elasticity of public R&D with respect to defense R&D estimated in Table A4, column (1), the first stage of Table 5 column (2), the 9/11 shock generates a 7.7% increase in US public R&D.

Effect on US private R&D ("crowding in"). The increase in public R&D leads to an increase of US private R&D by 3.7%, using the elasticity of public R&D on private R&D as estimated in Table 5, column (2).

Effect on US total R&D. From Table 1 we can see that in the United States the share of public R&D in total R&D is on average 15.5%. The growth of US public R&D and US private R&D therefore translates into a growth of US total R&D of 4.3%. Since total business conducted R&D (BERD) as a proportion of GDP was 1.95% in the United States in 1997-2001, this increase is equivalent to an increase of BERD/GDP by 0.08 percentage points.

Effect on US TFP growth. Using Table 9, column (3), the increase of R&D/GDP translates into an increase of the TFP growth rate by 0.005 percentage points. Since the US TFP growth rate in 2000 was 0.3%, this represents an increase of around 1.8%.

As a cross check, a simpler method is to take the number can be directly from the reduced form estimates of Table 9, column (4) which has the effect of defense R&D on TFP growth. This produces an estimate of 2.3%.

Hence, both methods suggest that the increased in military R&D on the scale of the 9/11 shock increased TFP growth by about 2%.

So far we have considered only the effect of the 9/11 defense expenditure shock on the US. However, our regressions show that this shock impacts also foreign country. On one hand, there is a displacement effects, lowering private R&D in foreign countries (Table 8). On the other hand, there are direct spillover effects, increasing TFP growth in foreign countries (Table A20). The spillover effects dominate in all our estimations, leading to a net positive increase of TFP growth in the foreign country.

Effect on foreign private R&D (displacement effect). The increase in US total R&D reduces foreign private R&D by the elasticity on the international spillover pool (given in Table 8, panel B column (2)) multiplied by the distance weight of the US to the foreign country. For example, the average geographic distance weight of the US to other countries is 0.02; which translates into reduced private R&D on average of around -0.03% (=4.3%*(-0.325)*0.02).

Effect on foreign total R&D. Assuming that public R&D is unchanged in the foreign country, this reduction in private R&D is multiplied by the share of private R&D in total R&D (= 1 minus the share of public R&D in total R&D as given by Table 1) for the foreign country to yield the effect on foreign total R&D. Table A2 helps again to translate this percentage increase into an increase of total R&D/GDP. For the average country, the share of public R&D in total R&D is 10%, so total R&D falls by 0.026%, or 0.0003 percentage points in terms of total R&D/VA.

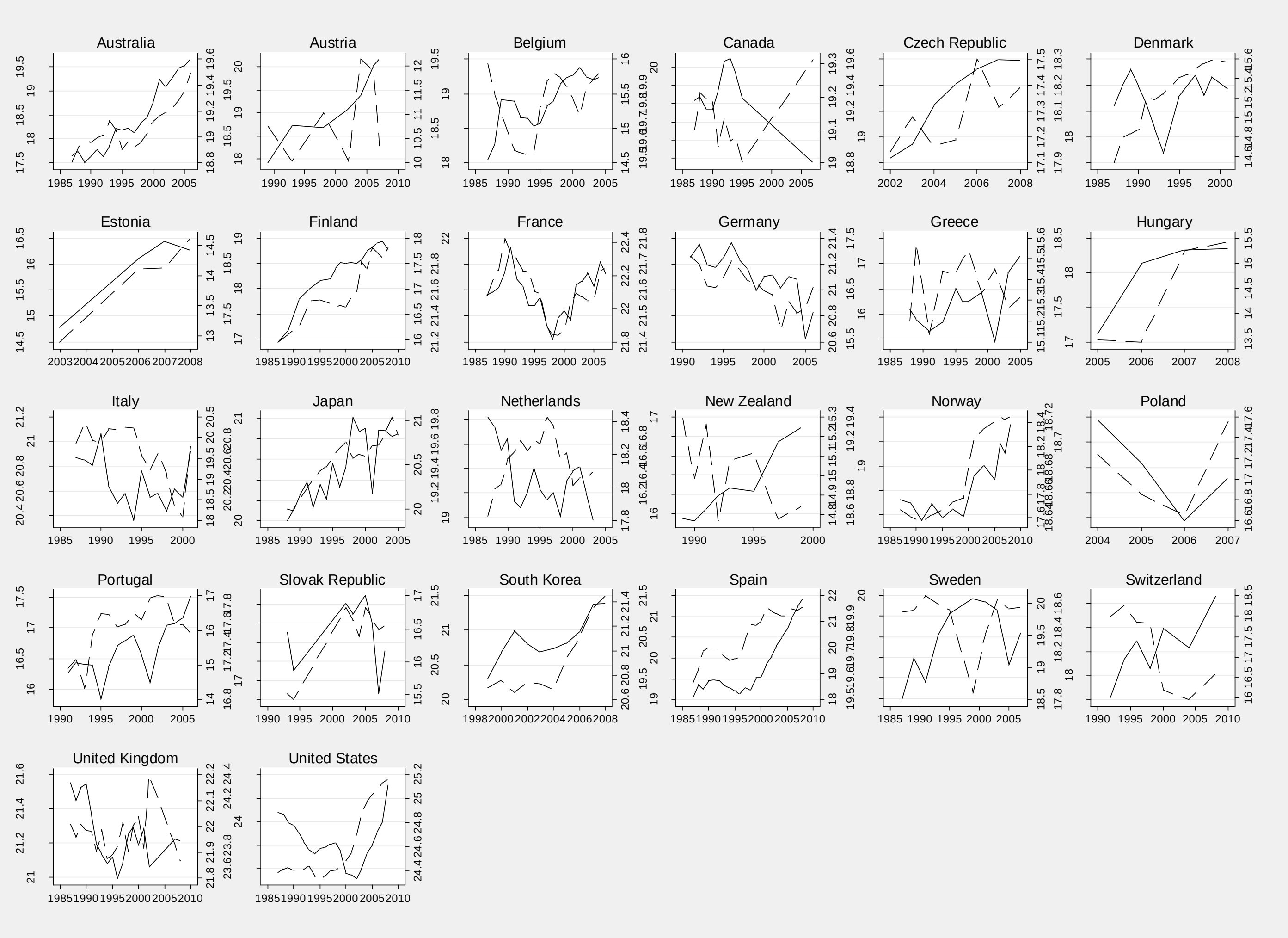
Effect on foreign TFP growth. As discussed, there is both a displacement effect as well as a positive spillover effect. The displacement effect reduces foreign total R&D as shown above. Using Table A20 reduced foreign R&D/value added leads to reduced foreign TFP growth (given by the estimated coefficient on R&D/value added). For example, in the case of the average country, the TFP growth rate falls by 0.00001 percentage points. However, the increase of US total R&D/VA by 0.08 percentage points (as shown above) has positive spillover effects as given by the coefficient on the international spillover pool estimated in Table A20, again multiplied by the distance weight of the US with respect to the foreign country. In the case of the average country, this leads to an increase in the TFP growth rate by 0.0004 percentage points. Since the positive spillover effect dominates the displacement effect, this is also roughly the same as the net increase in the TFP growth rate; and equivalent to the TFP growth rate increasing by 0.04%.

So in conclusion, a 9/11 type shock raises TFP growth by 2% in the US and an average of 0.04% in the rest of the OECD. In 2013 dollar terms the increase in US GDP defense R&D was $37bn. This leads to an additional $1.2bn p.a. in additional GDP per annum in the US and $0.2bn in the rest of the OECD. An additional $1.4bn is non-trivial, but is obviously not enormous.

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

Notes: This figure shows the defense related, government funded total R&D (GBAORD) as a share of GDP for the three largest economies in our data set: the United States, Germany and Japan.

FIGURE 2: PUBLIC R&D AND DEFENSE R&D – BY COUNTRY

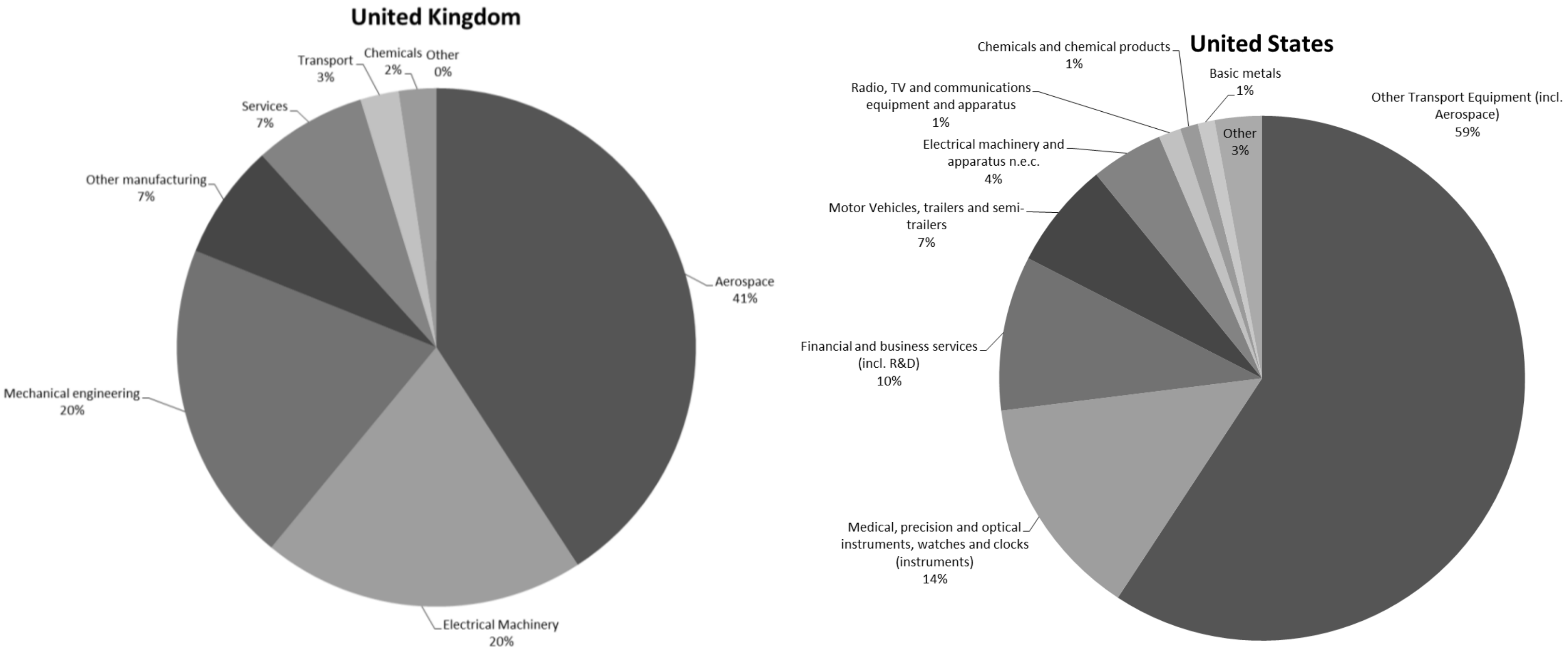


——— ln(government funded and business conducted R&D)

— — ln(defense related government funded R&D)

Notes: Solid line is ln(Public R&D), the log of the government funded and business conducted BERD which is scaled on the left axis. The dashed line is ln(Defense R&D), the log of government funded total defense R&D (GBAORD), which is scaled on the right axis.

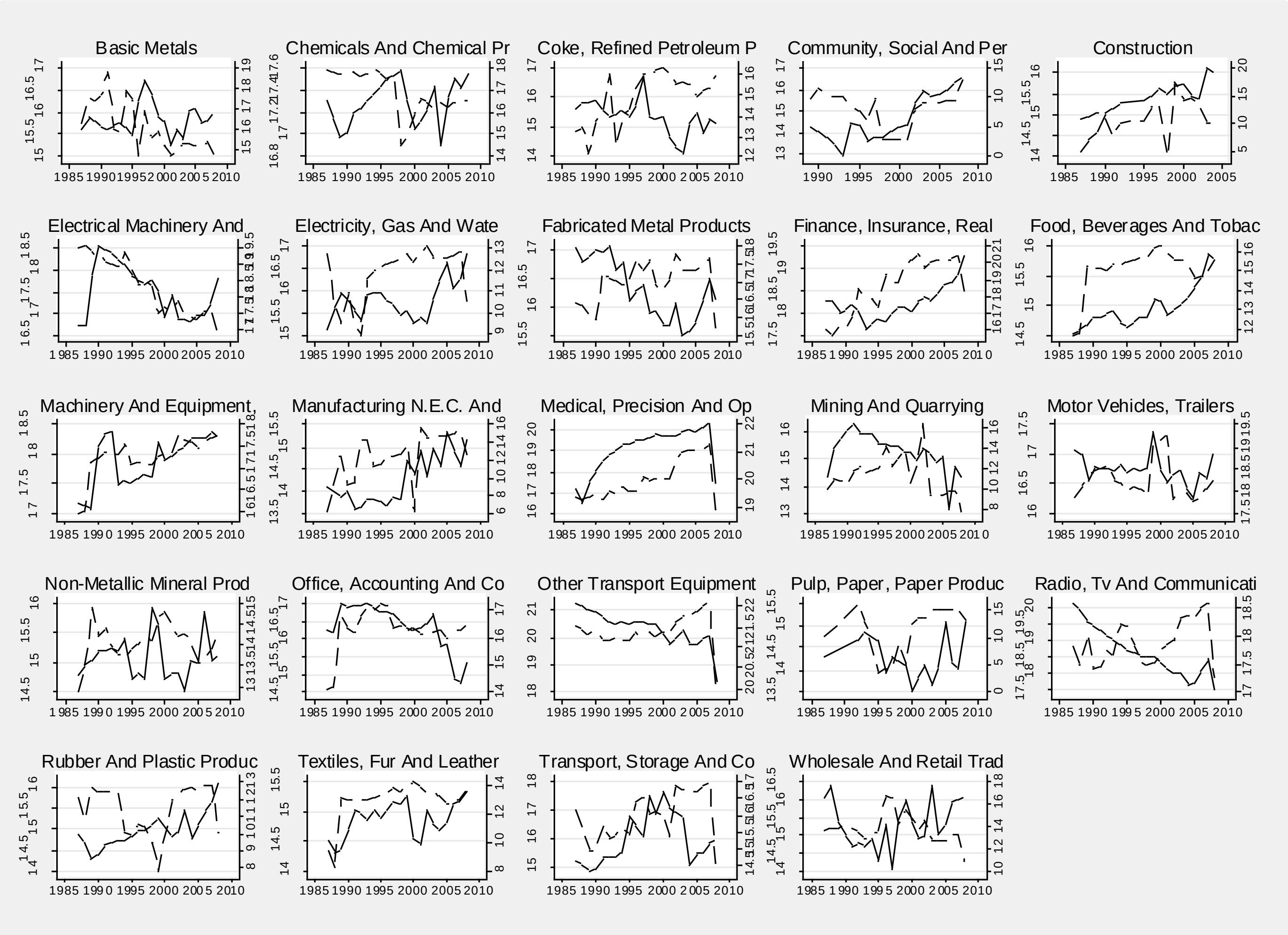
FIGURE 3: INDUSTRY SHARES OF DEFENSE R&D – EXAMPLES OF UK AND US



Notes: This figure shows each industry's share of defense R&D. Data for UK is averaged over 1993-2009 and data for US is averaged over 1987-2003.

Source: UK data from Office for National Statistics, dataset "Expenditure on civil and defense R&D performed in UK businesses by broad product groups", ONS/GSS reference number: rdbd5, downloaded from http://statistics.gov.uk/statbase/Product.asp?vlnk=2714&More=Y in December 2010 (now available in The National Archives under http://webarchive.nationalarchives.gov.uk/20100406130654/http://statistics.gov.uk/statbase/Product.asp?vlnk=2714&More=Y). US from DoD prime procurement contracts, generously provided by Mirko Draca (see Draca, 2012 for exact construction).

FIGURE 4: PUBLIC R&D AND DEFENSE R&D – BY INDUSTRY

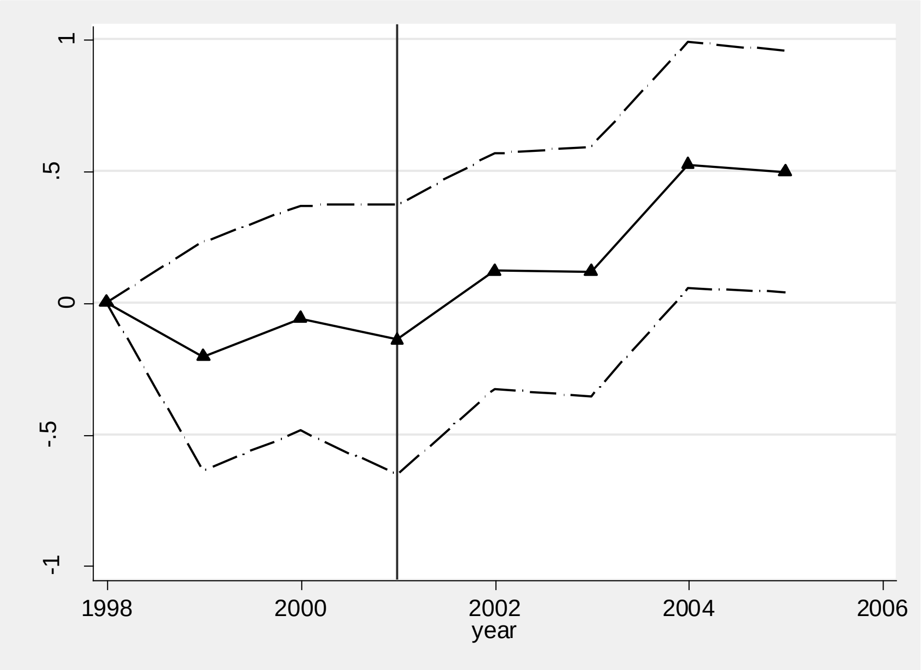


——— ln(government funded and business conducted R&D)

— — ln(defense related government funded R&D)

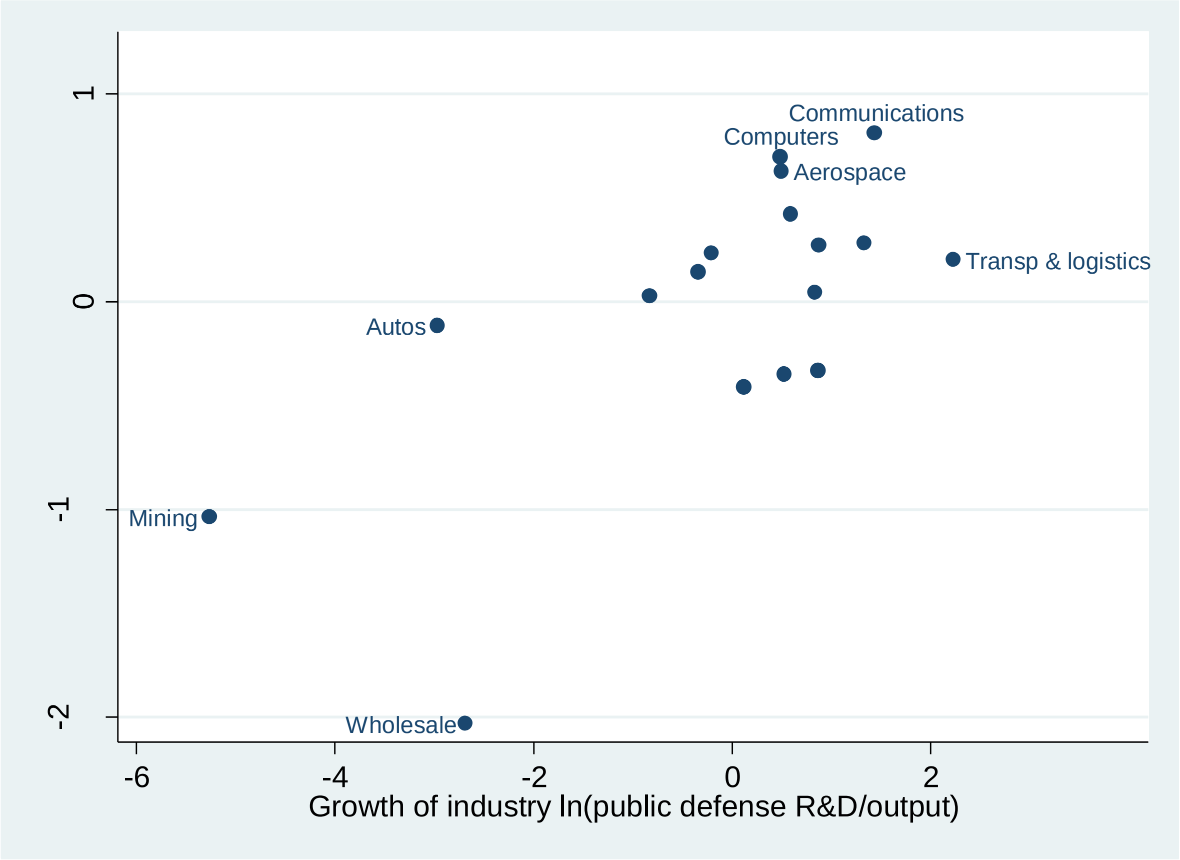
Notes: Solid line is ln(Public R&D), the log of the government funded and business conducted BERD which is scaled on the left axis. The dashed line is ln(Defense R&D), the log of government funded total defense R&D (GBAORD), which is scaled on the right axis. These are averages across all countries in our data set.

FIGURE 5: THE GROWTH IN US PRIVATE R&D INTENSITY IN DEFENSE SENSITIVE SECTORS BEFORE AND AFTER 9/11 2001



Notes: These are based on difference in difference regressions 1998-2005. "Defense sensitive sectors" are aerospace and other transport; information technology and Communication Technologies (Radio, TV and Communications Equipment). We run OLS regressions with industry dummies and time dummies and an interaction between the defense sensitive sectors and different year dummies pre and post 2001. Solid line is the OLS coefficient (base period is 1998) and 90% confidence intervals based on the robust standard errors.

FIGURE 6: THE GROWTH IN US PRIVATE R&D INTENSITY AND PUBLIC DEFENSE R&D INTENSITY BEFORE AND AFTER 9/11 2001



Notes: The horizontal axis is the change in industry-level ln(defense R&D/output) pre and post 9/11; the vertical axis is the same for ln(privately funded R&D /output). Pre-policy is 1999 and post-policy is 2005. The correlation is 0.66 and significant at the 1% level.

TABLE 1: PUBLIC R&D AS A PROPORTION OF TOTAL BUSINESS CONDUCTED R&D (BERD) - BY COUNTRY

Country	Mean	All years Standard deviation	Maximum-Minimum	1987-1991 Mean	1992-1996 Mean	1997-2001 Mean	2002-2006 Mean	2007-2009 Mean
Australia	3.32	0.78	2.76	3.29	2.52	3.43	4.03	
Austria	7.56	2.22	4.75	5.63	9.81	5.53	7.22	10.28
Belgium	5.52	1.16	5.05	6.00	4.89	5.86	5.52	
Canada	8.84	2.85	9.38	10.42	8.54			2.18
Czech Rep.	10.81	4.10	11.92		4.72	11.43	13.28	13.78
Denmark	7.21	3.07	8.76	10.54	6.09	4.16		
Estonia	8.86	4.12	13.76			10.06	7.67	8.23
Finland	3.92	0.97	3.58	3.91	5.85	3.92	3.53	3.00
France	13.64	4.60	13.9	20.88	14.09	9.53	10.86	9.78
Germany	7.96	2.24	6.25	10.06	10.39	7.65	5.42	
Greece	5.91	2.60	10.03	8.44	6.15	3.72	5.02	
Hungary	9.54	4.79	19.01	8.17	14.70	8.37	6.01	9.11
Italy	14.36	3.25	10.42	17.83	13.12	12.57	12.16	
Japan	1.39	0.28	1.24	1.40	1.28	1.53	1.32	
Netherlands	7.44	3.34	11.62	11.60	7.13	5.05	3.84	
New Zealand	7.85	1.35	3.82	6.62	7.14	9.08	9.98	
Norway	12.52	3.98	11.43	18.52	13.93	10.32	9.96	9.24
Poland	23.11	8.77	22.25		32.00	29.01	14.15	11.68
Portugal	5.94	2.46	7.26	5.00	7.97	6.47	4.30	
Slovakia	17.59	6.20	19.93		11.90	20.91	23.30	10.11
South Korea	5.53	1.18	4.51		3.96	6.31	5.17	6.06
Spain	11.34	2.96	11.33	12.78	9.93	8.12	12.24	17.12
Sweden	8.25	2.80	8.09	11.38	10.13	7.10	5.20	4.68
Switzerland	1.91	0.40	0.91		2.07	2.28	1.50	1.65
UK	11.54	3.96	13.42	17.10	10.68	9.67	7.07	6.69
United States	15.53	7.00	23.53	26.61	17.16	11.08	9.31	12.13

Notes: Our database comprises of an unbalanced panel of yearly values between the years 1987 and 2009. “Maximum-minimum” is the difference between the highest and the lowest value within a country across all years.

TABLE 2: PUBLICLY FUNDED BUSINESS R&D AS A PROPORTION OF ALL BUSINESS R&D - BY INDUSTRY

	All years	All years	1987-1991	1992-1996	1997-2001	2002-2006	2007-2009
Industry	**Mean**	**Standard deviation**	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**
Agriculture, hunting and forestry	35.27	93.25	29.45	27.21	62.46	20.82	27.38
Basic metals	7.63	9.59	8.83	8.38	6.88	6.59	8.28
Construction	17.62	43.96	19.22	28.91	13.67	10.52	12.03
Chemicals and chemical products	3.60	4.28	3.28	3.83	4.16	2.92	3.97
Coke, refined petroleum products and nuclear fuel	3.68	5.62	4.53	3.20	3.88	3.21	3.74
Community, social and personal service activities, etc.	23.48	22.57	21.34	19.62	21.34	26.36	27.82
Electricity, gas and water supply	8.39	12.78	9.94	5.71	8.51	9.28	10.12
Electrical machinery and apparatus n.e.c	9.77	22.98	19.57	8.64	8.46	5.26	8.79
Finance, insurance, real estate and business activities	15.89	13.28	27.74	15.95	14.36	15.27	15.32
Fabricated metal products (not machinery & equipment)	8.98	8.82	12.21	9.08	8.47	6.51	9.64
Food, beverages and tobacco	4.16	5.76	3.65	4.83	4.56	3.22	5.03
Mining and quarrying	9.76	14.49	12.71	10.82	9.80	7.96	4.43
Machinery and equipment, n.e.c.	11.57	10.63	9.89	11.45	13.11	11.05	12.73
Manufacturing n.e.c. and recycling	6.86	10.05	8.30	7.19	5.34	7.39	6.53
Medical, precision and optical instruments (instruments)	13.02	15.54	13.01	14.56	13.28	11.53	11.54
Motor Vehicles, trailers and semi-trailers	3.27	5.05	4.25	3.91	2.96	2.36	3.64
Non-metallic mineral products	5.54	7.85	5.53	6.88	6.23	3.92	3.85
Office, accounting and computing machinery	23.01	110.30	64.46	23.28	14.74	6.26	7.83
Other Transport Equipment	20.24	16.15	25.32	22.10	19.20	16.84	16.40
Pulp, paper, paper products, printing and publishing	7.33	13.23	4.13	6.86	7.08	6.95	14.85
Radio, TV and communications equipment and apparatus	7.79	10.93	13.81	9.38	6.12	3.94	5.13
Rubber and plastic products	3.96	3.95	3.29	4.27	4.09	3.63	5.73
Textiles, fur and leather	8.51	11.81	7.76	8.51	10.25	7.71	6.92
Transport, storage and communications	6.52	13.49	14.87	6.83	5.27	3.25	4.19
Wholesale and retail trade; restaurants and hotels	6.65	10.18	8.04	9.21	7.10	4.58	6.28
Wood and cork (not furniture)	16.51	71.21	22.80	12.69	10.39	24.47	8.63

Note: Our database comprises of an unbalanced panel of yearly values between the years 1987 and 2009. "n.e.c." – not elsewhere classified. These are averages across all countries in the dataset

TABLE 3: DEFENSE SHARE OF PUBLIC R&D

Country	All years Mean	All years Standard deviation	1987-1991 Mean	1992-1996 Mean	1997-2001 Mean	2002-2006 Mean	2007-2009 Mean
Australia	8.09	1.87	11.18	8.40	6.70	6.86	7.34
Austria	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Belgium	0.38	0.20	0.57	0.31	0.40	0.31	0.24
Canada	5.08	1.32	6.86	4.88	5.08	3.86	3.24
Czech Rep.	2.70	0.44				3.02	2.33
Denmark	0.60	0.21	0.44	0.61	0.53	0.88	0.55
Estonia	0.96	0.55				0.92	1.04
Finland	1.97	0.58	1.54	1.97	1.43	2.56	2.32
France	28.98	6.19	37.26	32.36	23.10	23.37	28.56
Germany	8.47	2.58	12.46	9.22	8.36	6.01	5.92
Greece	1.21	0.60	1.91	1.54	0.92	0.58	0.55
Hungary	0.38	0.25				0.10	0.56
Italy	4.47	2.83	7.65	6.45	2.62	3.29	2.16
Japan	5.03	0.74	5.27	6.01	4.74	4.57	4.44
Netherlands	2.43	0.61	2.81	3.20	2.33	1.90	1.86
New Zealand	0.91	0.41	1.50	1.07	0.73	0.95	0.00
Norway	6.15	1.30	7.77	5.64	5.77	6.55	4.82
Poland	1.91	0.85				1.42	2.64
Portugal	0.93	0.81	0.14	1.45	1.52	1.18	0.27
Slovakia	5.65	2.06		3.58	6.65	7.40	4.96
South Korea	16.59	2.69			19.59	14.52	17.22
Spain	17.63	7.83	15.19	11.79	27.63	20.41	10.11
Sweden	18.08	6.28	25.11	21.69	10.27	18.65	12.41
Switzerland	4.10	3.92	10.17	4.84	2.29	0.50	0.59
UK	35.00	8.16	44.27	39.08	36.10	28.97	20.93
United States	57.20	4.98	64.84	56.34	52.94	55.50	55.83

Note: Our database comprises of an unbalanced panel of yearly values between the years 1987 and 2009. The defense share of public R&D in this table refers to “all public R&D” which includes all government budget appropriations or outlays of total R&D (GBAORD), 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; while public defense R&D is the defense related part of “all public R&D”.

TABLE 4: EFFECT OF PUBLIC R&D ON PRIVATE R&D – OLS ESTIMATES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: ln(Privately funded business R&D)								
ln(Public R&D)$_t$	0.242**	0.172**	0.175**	0.130**	0.130**	0.190**	0.134**	0.134**
	(0.077)	(0.054)	(0.045)	(0.054)	(0.053)	(0.043)	(0.049)	(0.050)
ln(Public R&D)$_{t-1}$	0.040	0.063	0.073**	0.022	0.019	0.070**	0.009	0.009
	(0.049)	(0.040)	(0.030)	(0.041)	(0.040)	(0.030)	(0.040)	(0.039)
ln(Public R&D)$_{t-2}$	0.058	0.040	0.072**	-0.002	0.002	0.047	-0.015	-0.016
	(0.042)	(0.043)	(0.031)	(0.024)	(0.022)	(0.033)	(0.024)	(0.021)
ln(Output)$_t$	0.168	-0.053	-0.021	0.161	0.165			
	(0.240)	(0.231)	(0.261)	(0.243)	(0.243)			
ln(Output)$_{t-1}$	0.557**	0.607**	0.701**	0.486	0.477			
	(0.264)	(0.309)	(0.284)	(0.331)	(0.328)			
ln(Output)$_{t-2}$	-0.334	-0.058	0.173	-0.091	-0.079			
	(0.393)	(0.338)	(0.278)	(0.236)	(0.230)			
ln(GDP)$_t$	0.358							
	(0.361)							
ln(GDP)$_{t-1}$	-0.157							
	(0.302)							
ln(GDP)$_{t-2}$	0.440							
	(0.429)							
ln(Private R&D)$_{t-1}$				0.546**	0.561**		0.600**	0.599**
				(0.042)	(0.055)		(0.039)	(0.053)
ln(Private R&D)$_{t-2}$					-0.027			0.002
					(0.047)			(0.047)
Long-Run Effect of	0.339**	0.275**	0.319**	0.329**	0.325**	0.308**	0.317**	0.317**
Public R&D	(0.080)	(0.072)	(0.049)	(0.067)	(0.069)	(0.049)	(0.069)	(0.072)
Observations	5,499	5,499	5,499	5,499	5,499	5,499	5,499	5,499
Year (21)	YES	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Country*Year (637)	NO	YES	YES	YES	YES	YES	YES	YES
Industry*Year (815)	NO	NO	YES	YES	YES	YES	YES	YES

Notes: ** significant at 5% level, * significant at 10% level. Estimation by OLS with 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. All columns include a full set of country by industry fixed effects.

TABLE 5: EFFECT OF PUBLIC R&D ON PRIVATE R&D – IV ESTIMATES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Dependent variable: ln(Privately funded business R&D)								
ln(Public R&D)$_t$	0.162**	0.478**			0.146**	0.288*	0.090**	0.316
	(0.039)	(0.165)			(0.035)	(0.160)	(0.026)	(0.516)
ln(Public R&D)$_{t-1}$			0.172**	0.459**			0.080**	-0.076
			(0.039)	(0.171)			(0.023)	(0.362)
ln(Public R&D)$_{t-2}$							0.013	0.022
							(0.028)	(0.036)
ln(Output)$_t$	0.790**	0.508**			0.930**	0.886**	0.805**	0.825**
	(0.179)	(0.241)			(0.244)	(0.256)	(0.235)	(0.226)
ln(Output)$_{t-1}$			0.830**	0.617**	0.071	0.126	0.229	0.288
			(0.159)	(0.209)	(0.245)	(0.250)	(0.265)	(0.298)
ln(Output)$_{t-2}$					-0.266	-0.444	-0.232	-0.434
					(0.242)	(0.324)	(0.235)	(0.520)
Long-Run Effect of Public R&D	0.162**	0.478**	0.172**	0.459**	0.146**	0.288*	0.182**	0.262
	(0.039)	(0.165)	(0.039)	(0.171)	(0.035)	(0.160)	(0.048)	(0.183)
Observations	4,922	4,922	4,597	4,597	4,851	4,851	4,191	4,191
1st Stage F (excluded IV)		12.02		14.79		9.210		2.337
Anderson-Rubin Wald F-test		5.353		4.996		2.285		0.299
p-value		0.021		0.026		0.132		0.585
Endogeneity test-statistics		3.009		3.199		0.673		0.172
p-value		0.083		0.074		0.412		0.678

Notes: ** significant at 5% level, * significant at 10% level. 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. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output.

TABLE 6: CONTROLLING FOR OTHER PUBLIC POLICIES

	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV	(7) OLS	(8) IV
ln(Public R&D)$_t$	0.130**	0.443**	0.129**	0.430**	0.128**	0.364**	0.128**	0.377**
	(0.037)	(0.165)	(0.037)	(0.174)	(0.033)	(0.175)	(0.032)	(0.175)
R&D tax credit $_t$			0.378	0.220	0.246	0.126	0.281	0.164
			(0.430)	(0.469)	(0.423)	(0.444)	(0.434)	(0.459)
ln(Non-business public R&D)$_t$					1.029**	1.004**	0.945**	0.897**
					(0.307)	(0.382)	(0.311)	(0.355)
ln(Average Business Tax Rate) $_t$							0.066	0.083
							(0.084)	(0.113)
ln(Output)$_t$	0.769**	0.530*	0.771**	0.541*	0.596**	0.420	0.591**	0.404
	(0.225)	(0.291)	(0.225)	(0.298)	(0.214)	(0.287)	(0.217)	(0.294)
ln(GDP)$_t$	0.676*	0.948*	0.615	0.901*	0.188	0.423	0.119	0.348
	(0.403)	(0.514)	(0.410)	(0.542)	(0.384)	(0.509)	(0.406)	(0.550)
Observations	3,782	3,782	3,782	3,782	3,782	3,782	3,782	3,782
1st Stage F (excluded IV)		15.43		14.91		14.10		14.36
Anderson-Rubin Wald F-test		6.147		5.303		4.043		4.219
p-value		0.014		0.022		0.046		0.041

Notes: ** significant at 5% level, * significant at 10% level. 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. "Non-business public R&D" is government financed R&D performed not by the private sector, e.g. by universities or other institutions. "Business tax revenue" is tax revenue from taxes on income, profits and capital gains of corporates. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments.

TABLE 7: EFFECT OF PUBLIC R&D ON EMPLOYMENT AND WAGES

Dependent Variable:	(1) **ln(Private R&D)**	(2) **ln(R&D personnel)**	(3) **ln(empl excl. R&D)**	(4) **ln(avg R&D wage)**	(5) **ln(avg wage)**
Panel A. OLS					
ln(Public R&D) $_t$	0.162**	0.179**	0.006	0.062*	-0.004
	(0.039)	(0.043)	(0.005)	(0.035)	(0.003)
ln(industry output) $_t$	0.790**	0.537**	0.515**	0.275	0.115**
	(0.179)	(0.272)	(0.046)	(0.180)	(0.018)
ln(GDP) $_t$	0.213	0.865**	-0.128*	-0.339	0.724**
	(0.310)	(0.419)	(0.069)	(0.246)	(0.035)
Observations	4,922	3,980	3,932	3,837	3,162
Panel B. IV					
ln(Public R&D) $_t$	0.477**	0.331**	0.062**	0.137	0.001
	(0.165)	(0.142)	(0.027)	(0.085)	(0.018)
ln(industry output) $_t$	0.509**	0.416	0.471**	0.219	0.111**
	(0.241)	(0.286)	(0.053)	(0.193)	(0.022)
ln(GDP) $_t$	0.483	0.911**	-0.112	-0.316	0.729**
	(0.376)	(0.441)	(0.072)	(0.248)	(0.037)
Observations	4,922	3,980	3,932	3,837	3,162
F-stat first stage	12.02	14.96	15.45	15.76	6.87

Notes: ** significant at 5% level, * significant at 10% 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. All columns include industry*country FEs, industry*year FEs. Two way clustered SEs at country-industry and country-year level.

TABLE 8: INTERNATIONAL DISPLACEMENT EFFECTS OF PUBLIC R&D

Measure of neighbor for spillover	Baseline	Per-capita GDP (1)	Geo-graphy (2)	Skill Intensity (3)	Tech-nology (4)	FDI Flows (5)	R&D Intensity (6)	Trade (imports) (7)	Trade (imports) (8)
Dependent variable: ln(Privately funded business R&D)									
PANEL A. EFFECT OF PUBLIC R&D									
ln(Domestic Public R&D)$_t$	0.235**	0.241**	0.235**	0.242**	0.218**	0.245**	0.242**	0.242**	0.241**
	(0.038)	(0.038)	(0.036)	(0.040)	(0.034)	(0.040)	(0.038)	(0.038)	(0.038)
ln(Int. Public R&D)$_{t-1}$		-0.069*	-0.125	-0.068*	-0.549**	-0.106	-0.023	-0.071	-0.040
		(0.039)	(0.089)	(0.038)	(0.168)	(0.068)	(0.063)	(0.051)	(0.060)
ln(output)$_t$	0.674**	0.617**	0.602**	0.625**	0.609**	0.684**	0.632**	0.616**	0.627**
	(0.172)	(0.179)	(0.179)	(0.183)	(0.179)	(0.163)	(0.178)	(0.178)	(0.177)
Observations	6,671	6,474	6,474	5,669	6,474	6,022	6,474	6,455	6,473
PANEL B. EFFECT OF TOTAL R&D									
ln(Domestic Public R&D)$_t$	0.235**	0.243**	0.242**	0.247**	0.239**	0.251**	0.244**	0.246**	0.244**
	(0.038)	(0.038)	(0.038)	(0.040)	(0.037)	(0.037)	(0.037)	(0.037)	(0.038)
ln(Int. Total R&D)$_{t-1}$		0.001	-0.325**	-0.086	-0.850**	-0.086	-0.278**	-0.219**	-0.181**
		(0.064)	(0.102)	(0.086)	(0.277)	(0.077)	(0.086)	(0.070)	(0.077)
ln(output)$_t$	0.674**	0.637**	0.574**	0.628**	0.557**	0.637**	0.636**	0.610**	0.613**
	(0.172)	(0.179)	(0.180)	(0.183)	(0.175)	(0.180)	(0.180)	(0.181)	(0.178)
Observations	6,671	6,479	6,479	5,674	6,479	6,443	6,479	6,460	6,479
PANEL C. EFFECT OF TOTAL R&D - IV									
ln(Domestic Public R&D)$_t$	0.477**	0.476**	0.474**	0.468**	0.466**	0.533**	0.442**	0.450**	0.464**
	(0.165)	(0.167)	(0.169)	(0.167)	(0.166)	(0.181)	(0.159)	(0.168)	(0.169)
ln(Int. Total R&D)$_{t-1}$		-0.008	-0.048	-0.090	-0.328**	-0.155**	-0.237**	-0.168	-0.111
		(0.029)	(0.114)	(0.087)	(0.166)	(0.076)	(0.075)	(0.104)	(0.103)
ln(output)$_t$	0.509**	0.525**	0.514**	0.541**	0.486**	0.471	0.619**	0.539**	0.527**
	(0.241)	(0.243)	(0.236)	(0.237)	(0.242)	(0.287)	(0.239)	(0.237)	(0.240)
ln(GDP)$_t$	0.483	0.458	0.471	0.525	0.526	0.446	0.306	0.397	0.436
	(0.376)	(0.378)	(0.367)	(0.389)	(0.383)	(0.427)	(0.372)	(0.375)	(0.380)
Observations	4,922	4,776	4,776	4,194	4,776	4,614	4,776	4,759	4,776
First stage F	12.02	11.68	11.69	13.33	12.74	10.27	11.72	12.06	11.93

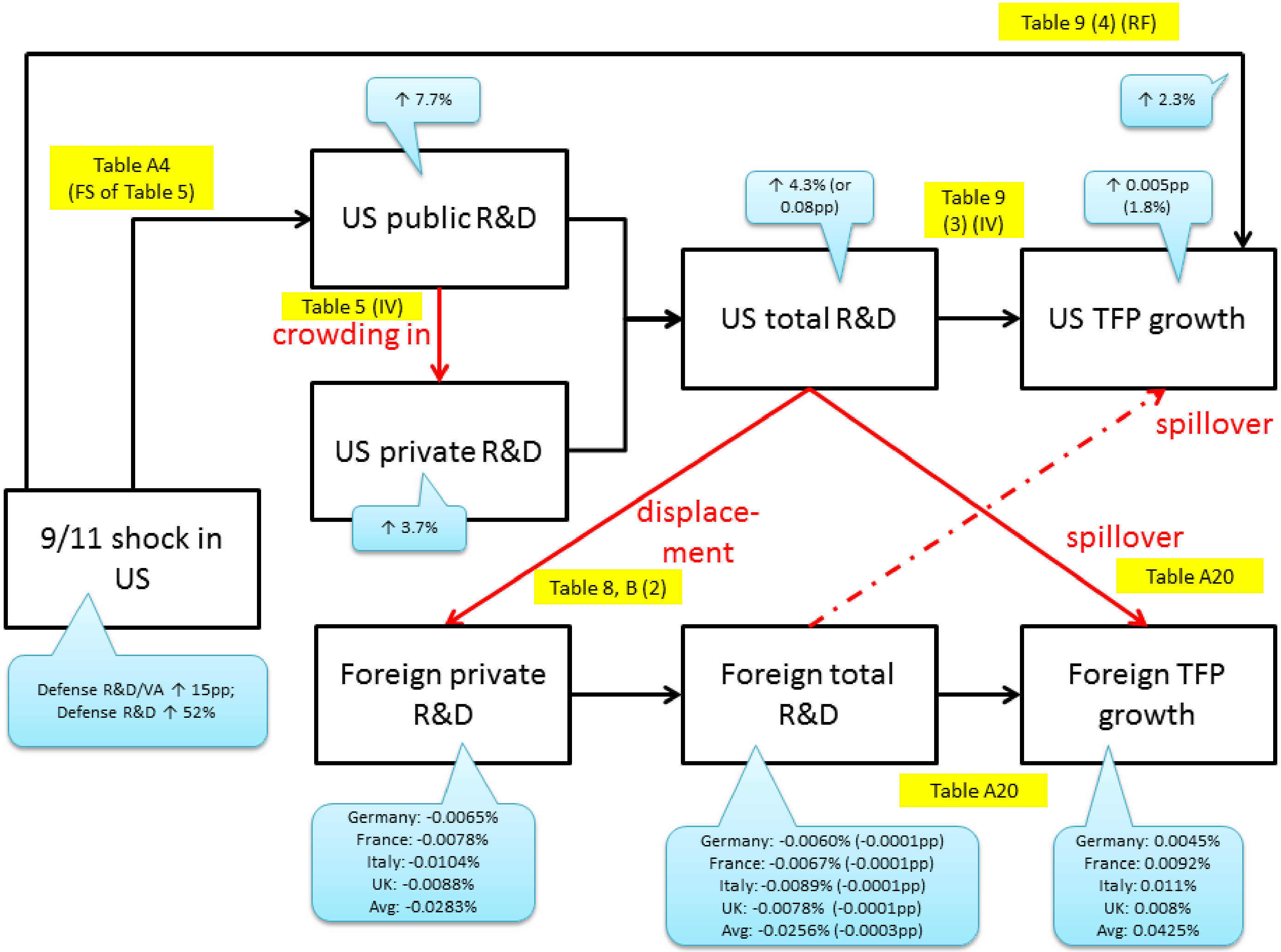
Notes: ** significant at 5% level, * significant at 10% level. Each column in each panel constitutes a separate regression. Two-way clustered standard errors at the industry*country and country*year level. All columns include full sets of country by industry fixed effects, and industry by year fixed effects. Panel A and B also include country by year fixed effects. 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. "Int. Pub R&D" is the weighted average of other countries' public R&D in the same industry and year, where each column uses different weights. "Int. Total R&D" is the weighted average of other countries' public and private R&D in the same industry and year, where each column uses different weights. Weights ω_{kl} are a "distance" measure between country k and country l and measured by: (1) GDP per capita. $\omega_{kl} = 1/abs(GDPcap_k - GDPcap_l)$; (2) Geographic distance. $\omega_{kl} = 1/dist_{kl}$ where geographical distance is measured in kms between capital cities; (3) Skill intensity. $\omega_{kl} = 1/abs(tert_k - tert_l)$ with $tert_l$ being the share of population with tertiary education in country *l;* (4) Patent similarity. $\omega_{kl} = \sqrt{\sum_i \left(pat_{ik} - pat_{il}\right)^2}$, pat_{ik} and pat_{il} are patent share of a specific technology class *i* (out of 15 patent technology classes) in country k or l (of total patents in that country); (5) Inward FDI flows. $\omega_{kl} = \frac{FDI_{kl}}{\sum_{j=1}^{J} FDI_{kj}}$ where FDI_{kl} is the amount of FDI that country *k* receives from country *l;* (6) R&D intensity. $\omega_{kl} = 1/abs\left(\frac{Total\ R\&D_k}{GDP_k} - \frac{Total\ R\&D_l}{GDP_l}\right)$; (7) Import share. $\omega_{kl} = \frac{IMP_{kl}}{\sum_{j=1}^{J} IMP_{kj}}$ where IMP_{kl} are imports from country *l* to country *k*; (8) Export share. $\omega_{kl} = \frac{EXP_{kl}}{\sum_{j=1}^{J} EXP_{kj}}$ where EXP_{kl} are exports from country *l* to country *k*.

TABLE 9: THE EFFECT OF R&D ON TFP GROWTH

Method	(1) OLS	(2) OLS	(3) IV	(4) OLS	(5) OLS	(6) OLS	(7) IV	(8) OLS
Dependent variable: TFP growth over	1 year	1 year	1 year	1 year	2 years	2 years	2 years	2 years
(R&D/value added)$_{t-1}$	0.097** (0.042)	0.099** (0.043)	0.064** (0.027)					
(Defense R&D/ value added)$_{t-1}$				0.049** (0.017)				
(R&D/value added)$_{t-2}$					0.183** (0.090)	0.181** (0.092)	0.085* (0.049)	
(Defense R&D/ value added)$_{t-2}$								0.064** (0.032)
Observations	4,779	4,779	4,779	4,779	4,543	4,543	4,543	4,543
Country FE	NO	YES	YES	YES	NO	YES	YES	YES
IV	NO	NO	Defense	Reduced Form	NO	NO	Defense	Reduced Form
First-Stage F (excluded IV)			18.72				18.40	

Notes: ** significant at 5% level, * significant at 10% level. Standard errors are two-way clustered at the industry*country and country*year level. All regressions include a full set of year fixed effects. Column (3) uses 1 year lagged defense R&D as instrument for 1 year lagged R&D. Columns (1)-(3) calculate TFP as a Solow residual using factor shares and use TFP growth over 1 year, while columns (5)-(7) use TFP growth over 2 years as dependent variable. Columns (4) and (8) show the reduced forms of columns (3) and (7), respectively.

FIGURE A1:
THE EFFECTS OF A 9/11 SHOCK OF US MILITARY R&D ON US AND FOREIGN TFP GROWTH AND PUBLIC AND PRIVATE R&D



Note: This describes the links from an exogenous increase in US defense R&D (calibrated to the increase after 9/11) to TFP growth in the US and overseas. Details are in Appendix B.

TABLE A1: VARIABLE DEFINITION AND SOURCES

Variable	Code	Construction	Source	Mean	Median	SD
Total R&D	R	Business enterprise R&D (BERD): Total R&D conducted by businesses from any funding source (government, business, overseas)	MSTI	\$733m	\$65m	\$2,471m
Public R&D	S	Government funded part of R&D (BERD)	MSTI, SIRD	\$57m	\$2.8m	\$369m
Defense R&D	DR	Defense share of industry in government budget appropriations or outlays on R&D (see Appendix A for details)	MSTI,ONS Draca (2012)	\$132m	\$0.07m	\$1,513m
# Scientists		Number of R&D scientists (FTE)	MSTI	4,729	427	15,295
R&D personnel	N^R	Total R&D workers (FTE)	MSTI	4,388	668	13,135
R&D wage bill	$(WN)^R$	Labor costs of all R&D personnel	MSTI	\$233m	\$29m	\$729m
R&D wage	W^R	BERD labour cost/ number of R&D personnel	MSTI	\$55,324	\$48,722	\$451,986
Output	Y	Total production (gross output), volumes	STAN	7,288bn	45bn	26,400bn
GDP	GDP	Total production (gross output) of a country	STAN	\$1,041bn	\$249bn	\$1,788bn
Wage bill	WN	Total cost of all employees	STAN	\$7,928m	\$1,591m	\$34,156m
Employment	N	Number of persons engaged (total employment), FTE	STAN	437,183	115,012	1,246,680
Value Added	VA	Value added, volumes	STAN	2,192bn	13bn	11,298bn
Capital	K	Gross capital stock, volumes; if missing in STAN own estimation based on investment	STAN	4,505m	43m	47,488m

Note: Summary statistics are based on the sample used in Table 4. All values in constant 2000 US dollars unless otherwise stated.

TABLE A2: BUSINESS CONDUCTED R&D (BERD) AS A PROPORTION OF GDP - BY COUNTRY

Country	Mean	All years Standard deviation	Maximum-Minimum	1987-1991 Mean	1992-1996 Mean	1997-2001 Mean	2002-2006 Mean	2007-2009 Mean
Australia	0.78	0.24	0.74	0.48	0.73	0.88	1.04	
Austria	1.27	0.39	0.96	0.81	0.73	1.11	1.57	1.50
Belgium	1.26	0.27	0.95	1.13	1.04	1.52	1.31	
Canada	0.85	0.16	0.43	0.74	0.99			0.92
Czech Republic	1.64	0.35	1.50		1.84	1.81	1.54	1.27
Denmark	0.89	0.36	1.06	0.63	0.72	1.19	1.65	
Estonia	0.51	0.18	0.53			0.36	0.58	0.69
Finland	1.58	0.64	1.87	0.77	1.15	2.10	2.14	2.00
France	1.25	0.18	0.62	1.17	1.16	1.41	1.28	1.07
Germany	1.52	0.29	0.95	1.50	1.19	1.66	1.70	
Greece	0.19	0.06	0.20	0.12	0.14	0.23	0.23	
Hungary	0.72	0.14	0.50	1.07	0.67	0.74	0.69	0.69
Italy	0.63	0.07	0.23	0.67	0.57	0.63	0.68	
Japan	1.53	0.34	1.14	1.42	1.17	1.61	2.03	
Netherlands	1.02	0.16	0.50	1.09	0.85	1.16	0.98	
New Zealand	0.38	0.13	0.41	0.30	0.33	0.46	0.55	
Norway	0.69	0.10	0.36	0.66	0.68	0.81	0.69	0.58
Poland	0.44	0.16	0.45		0.58	0.56	0.30	0.25
Portugal	0.23	0.11	0.43	0.17	0.14	0.25	0.37	
Slovakia	1.01	0.67	2.49		1.58	1.39	0.61	0.27
South Korea	2.71	0.47	1.71		1.87	2.67	2.88	3.26
Spain	0.56	0.13	0.38	0.46	0.42	0.61	0.68	0.71
Sweden	2.03	0.60	2.33	1.37	1.84	2.68	2.21	1.88
Switzerland	1.44	0.21	0.51		1.22	1.71	1.52	1.54
UK	1.24	0.19	0.77	1.43	1.26	1.18	1.23	0.90
United States	1.87	0.09	0.34	1.89	1.78	1.95	1.81	1.97

Note: Our database comprises of an unbalanced panel of yearly values between the years 1987 and 2009.

TABLE A3: BUSINESS CONDUCTED R&D AS A PROPORTION OF VALUE ADDED - BY INDUSTRY

Industry	All years Mean	All years SD	1987-1991 Mean	1992-1996 Mean	1997-2001 Mean	2002-2006 Mean	2007-2009 Mean
Agriculture, hunting and forestry	0.30	0.36	0.23	0.26	0.34	0.35	0.29
Basic metals	3.81	14.25	2.19	1.98	7.36	3.17	1.35
Construction	0.18	0.27	0.10	0.14	0.22	0.25	0.21
Chemicals and chemical products	10.84	6.63	8.92	9.38	11.65	12.29	13.67
Coke, refined petroleum products and nuclear fuel	5.60	18.74	3.73	4.23	4.35	4.73	29.73
Community, social & personal services, etc.	0.04	0.08	0.04	0.03	0.05	0.04	0.06
Electricity, gas and water supply	0.54	0.89	0.61	0.48	0.52	0.39	1.22
Electrical machinery and apparatus n.e.c	8.68	17.02	5.98	6.92	12.26	8.70	5.22
Finance, insurance, real estate and business activities	1.17	2.69	0.42	0.87	1.10	1.38	3.21
Fabricated metal products, except machinery and equipment	0.99	0.79	0.89	0.94	1.01	1.01	1.40
Food, beverages and tobacco	1.23	1.63	0.92	0.90	1.27	1.41	2.88
Mining and quarrying	0.98	1.25	0.88	1.01	1.09	0.96	0.59
Machinery and equipment, n.e.c.	4.91	4.08	3.66	4.31	5.21	5.56	7.42
Manufacturing n.e.c. and recycling	1.17	1.28	1.15	0.90	1.22	1.31	1.54
Medical, precision and optical instruments, watches and clocks (instruments)	11.85	11.98	8.32	10.64	12.37	13.15	17.98
Motor Vehicles, trailers and semi-trailers	10.16	10.01	11.15	8.99	9.85	10.15	14.55
Non-metallic mineral products	1.31	0.94	1.24	1.14	1.43	1.44	1.19
Office, accounting and computing machinery	25.12	56.00	32.57	19.76	15.91	36.31	24.35
Other Transport Equipment	11.36	11.27	11.01	11.50	12.80	10.47	8.78
Pulp, paper, paper products, printing and publishing	0.59	0.51	0.48	0.58	0.61	0.63	0.60
Radio, TV, communications equipment & apparatus	23.67	15.96	24.49	21.85	24.80	24.34	20.20
Rubber and plastic products	2.65	2.26	1.69	2.69	3.00	2.74	3.52
Textiles, fur and leather	1.00	0.86	0.58	0.74	1.06	1.32	1.93
Transport, storage and communications	0.47	0.95	0.24	0.31	0.57	0.44	1.33
Wholesale and retail trade; restaurants and hotels	0.24	0.34	0.11	0.16	0.26	0.29	0.42
Wood and cork (not furniture)	0.47	0.71	0.45	0.36	0.49	0.47	0.93

Note: Our database comprises of an unbalanced panel of yearly values between the years 1987 and 2009. These are averages across all countries in our dataset. SD is for standard deviation.

TABLE A4: FIRST STAGE

Dependent Variable:	(1) $\ln(\text{Public R\&D})_t$	(2) $\ln(\text{Public R\&D})_{t-1}$	(3) $\ln(\text{Public R\&D})_t$	(4) $\ln(\text{Public R\&D})_{t-1}$
$\ln(\text{Defense R\&D})_t$	0.148**		0.119**	0.039
	(0.043)		(0.039)	(0.026)
$\ln(\text{Defense R\&D})_{t-1}$		0.170**		
		(0.044)		
$\ln(\text{Public R\&D})_{t-1}$				0.684**
				(0.039)
$\ln(\text{Public R\&D})_{t-2}$				-0.038
				(0.043)
$\ln(\text{Output})_t$	0.895**		0.253	-0.100
	(0.309)		(0.416)	(0.274)
$\ln(\text{Output})_{t-1}$		0.747**	-0.318	-0.247
		(0.320)	(0.474)	(0.438)
$\ln(\text{Output})_{t-2}$			1.251**	0.903**
			(0.469)	(0.313)
Observations	4,922	4,597	4,851	4,191

Notes: ** significant at 5% level, * significant at 10% level. Estimation by OLS with two-way clustered standard errors at the industry*country and country*year level. All columns include a full set of country by industry fixed effects and a full set of industry by year fixed effects. Ln(GDP)_t included in all columns, $\ln(\text{GDP})_{t-1}$ and $\ln(\text{GDP})_{t-2}$ included in columns (3) and (4).

TABLE A5: EFFECT OF PUBLIC R&D ON PRIVATE R&D – USE ONLY COUNTRY*YEAR VARIATION IN DEFENSE INSTRUMENT

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Dependent variable: ln(Privately funded business R&D)								
ln(Public R&D)$_t$	0.218**	0.529**			0.210**	0.365**	0.135**	0.883
	(0.038)	(0.178)			(0.037)	(0.182)	(0.027)	(1.003)
ln(Public R&D)$_{t-1}$			0.227**	0.570**			0.102**	-0.426
			(0.035)	(0.146)			(0.022)	(0.712)
ln(Public R&D)$_{t-2}$							0.073**	0.101**
							(0.032)	(0.051)
ln(output)$_t$	0.504**	0.199			0.260	0.225	0.180	0.099
	(0.202)	(0.247)			(0.337)	(0.336)	(0.353)	(0.478)
ln(output)$_{t-1}$			0.656**	0.301	0.546**	0.542**	0.663**	0.892
			(0.179)	(0.234)	(0.243)	(0.255)	(0.260)	(0.551)
ln(output)$_{t-2}$					-0.286	-0.441	-0.365	-0.859
					(0.327)	(0.398)	(0.301)	(0.830)
Long-Run Effect of Public R&D	0.218**	0.529**	0.227**	0.570**	0.210**	0.365**	0.310**	0.558*
	(0.038)	(0.178)	(0.035)	(0.146)	(0.037)	(0.182)	(0.051)	(0.326)
Observations	5,919	5,919	5,534	5,534	5,836	5,836	5,078	5,078
Number of indctry	461	461	456	456	459	459	435	435
IV		Defense		Defense		Defense		Defense
1st Stage F		7.922		9.827		6.139		0.892
Anderson-Rubin Wald F-test		4.641		6.573		2.089		0.881
p-value		0.0319		0.0108		0.149		0.349
Endog test stat		2.655		4.799		0.653		0.769
Endog pval		0.103		0.0285		0.419		0.381

Notes: ** significant at 5% level, * significant at 10% level. Same specification at Table 5. Ln(GDP) included dated at same time as output.

TABLE A6: EFFECT OF PUBLIC R&D ON PRIVATE R&D – WITHOUT US

	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV	(7) OLS	(8) IV
Dependent variable: ln(Privately funded business R&D)								
ln(Public R&D)$_t$	0.152**	0.488**			0.135**	0.300*	0.090**	0.301
	(0.038)	(0.169)			(0.034)	(0.165)	(0.027)	(0.538)
ln(Public R&D)$_{t-1}$			0.181**	0.489**			0.082**	-0.067
			(0.041)	(0.185)			(0.024)	(0.388)
ln(Public R&D)$_{t-2}$							0.014	0.025
							(0.029)	(0.041)
ln(output)$_t$	0.763**	0.490**			0.877**	0.841**	0.833**	0.860**
	(0.188)	(0.241)			(0.249)	(0.258)	(0.242)	(0.233)
ln(output)$_{t-1}$			0.793**	0.580**	0.076	0.128	0.216	0.266
			(0.162)	(0.214)	(0.247)	(0.251)	(0.271)	(0.301)
ln(output)$_{t-2}$					-0.238	-0.433	-0.245	-0.431
					(0.243)	(0.320)	(0.239)	(0.531)
Long-Run Effect of	0.152**	0.488**	0.181**	0.489**	0.135**	0.300*	0.186**	0.259
Public R&D	(0.038)	(0.169)	(0.041)	(0.185)	(0.034)	(0.165)	(0.050)	(0.185)
Observations	4,667	4,667	4,354	4,354	4,596	4,596	3,999	3,999
Number of indctry	396	396	390	390	394	394	376	376
IV		Defense		Defense		Defense		Defense
1st Stage F		11.48		13.64		8.73		2.11
Anderson-Rubin Wald F-test		5.453		4.975		2.344		0.250
p-value		0.0202		0.0265		0.127		0.617
Endog test stat		3.203		3.131		0.860		0.142
Endog pval		0.0735		0.0768		0.354		0.706

Notes: Same specification at Table 5 but without the observations for the United States. Ln(GDP) included dated at same time as output.

TABLE A7: EFFECT OF PUBLIC R&D ON PRIVATE R&D – MANUFACTURING INDUSTRIES ONLY

	(1)	(2)	(3)	(4)	(5)
Dependent variable: ln(Privately funded business R&D)					
ln(Public R&D)$_t$	0.100**	0.100**	0.087**	0.083**	0.083**
	(0.026)	(0.023)	(0.021)	(0.019)	(0.019)
ln(Public R&D)$_{t-1}$	0.025	0.042**	0.035*	0.000	-0.001
	(0.025)	(0.021)	(0.019)	(0.020)	(0.021)
ln(Public R&D)$_{t-2}$	-0.016	0.005	0.018	-0.005	-0.003
	(0.034)	(0.023)	(0.017)	(0.016)	(0.015)
ln(Output)$_t$	0.361**	0.249	0.483**	0.434**	0.438**
	(0.150)	(0.174)	(0.175)	(0.160)	(0.158)
ln(Output)$_{t-1}$	0.271	0.220	0.128	-0.133	-0.144
	(0.262)	(0.312)	(0.219)	(0.176)	(0.173)
ln(Output)$_{t-2}$	-0.463	-0.284	0.055	0.079	0.096
	(0.286)	(0.282)	(0.177)	(0.121)	(0.115)
ln(GDP)$_t$	0.019				
	(0.226)				
ln(GDP)$_{t-1}$	-0.174				
	(0.296)				
ln(GDP)$_{t-2}$	0.800**				
	(0.331)				
ln(R&D) $_{t-1}$				0.521**	0.535**
				(0.065)	(0.090)
ln(R&D) $_{t-2}$					-0.029
					(0.066)
Long-Run	0.109*	0.148**	0.140**	0.078**	0.080**
Public R&D effect	(0.054)	(0.038)	(0.027)	(0.020)	(0.019)
Observations	4,043	4,043	4,043	4,043	4,043
Year (21)	YES	n/a	n/a	n/a	n/a
Cty*Year (637)	NO	YES	YES	YES	YES
Industry*Year (815)	NO	NO	YES	YES	YES

Notes: ** significant at 5% level, * significant at 10% level. Estimation by OLS with two-way clustered standard errors at the industry*country and country*year level. All columns include a full set of country by industry fixed effects.

TABLE A8: WINSORIZING EXTREME LEVELS AND GROWTH RATES IN R&D

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Dependent variable: ln(Privately funded business R&D)														
ln(Pub R&D)$_t$	0.283**	0.217**	0.215**	0.286**	0.370**			0.083	0.131**	0.123**	0.193**	0.209**		
	(0.074)	(0.055)	(0.048)	(0.045)	(0.059)			(0.077)	(0.041)	(0.037)	(0.044)	(0.074)		
ln(Pub R&D)$_{t-1}$	0.054	0.070*	0.096**			0.226**	0.297**	0.081	0.070	0.090**			0.182**	0.222**
	(0.046)	(0.038)	(0.032)			(0.042)	(0.048)	(0.076)	(0.044)	(0.040)			(0.044)	(0.068)
ln(Pub R&D)$_{t-2}$	0.052	0.018	0.027					0.099	0.046	0.065				
	(0.045)	(0.055)	(0.045)					(0.065)	(0.059)	(0.051)				
ln(Output)$_t$	-0.091	-0.080	0.413	0.718**	0.561**			0.009	-0.084	0.419	0.702**	0.629*		
	(0.393)	(0.457)	(0.505)	(0.311)	(0.258)			(0.316)	(0.322)	(0.428)	(0.348)	(0.335)		
ln(Output)$_{t-1}$	0.915**	0.566	0.261			0.645**	0.600**	0.989**	0.887*	0.923**			0.576	0.625*
	(0.325)	(0.359)	(0.399)			(0.311)	(0.298)	(0.401)	(0.498)	(0.405)			(0.373)	(0.321)
ln(Output)$_{t-2}$	-0.319	0.063	0.206					-0.359	-0.504	-0.648				
	(0.621)	(0.592)	(0.514)					(0.488)	(0.476)	(0.494)				
ln(GDP)$_t$	0.346				0.229			0.310				0.205		
	(0.474)				(0.429)			(0.383)				(0.422)		
ln(GDP)$_{t-1}$	-0.233						0.260	-0.460						0.203
	(0.316)						(0.459)	(0.385)						(0.388)
ln(GDP)$_{t-2}$	0.429							0.388						
	(0.538)							(0.513)						
Long-Run	0.388**	0.306**	0.339**	0.286**	0.370**	0.226**	0.297**	0.263**	0.247**	0.278**	0.193**	0.209**	0.182**	0.222**
Pub R&D effect	(0.083)	(0.079)	(0.061)	(0.045)	(0.059)	(0.042)	(0.048)	(0.096)	(0.072)	(0.061)	(0.044)	(0.074)	(0.044)	(0.068)
Observations	5,628	5,628	5,628	6,193	6,193	6,193	6,193	5,587	5,587	5,587	6,130	6,130	6,130	6,130
Year (21)	YES	n/a	n/a	n/a	n/a	n/a	n/a	YES	n/a	n/a	n/a	n/a	n/a	n/a
Cty*Year (637)	NO	YES	YES	YES	NO	YES	NO	NO	YES	YES	YES	NO	YES	NO
Industry*Year (815)	NO	NO	YES	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES

Notes: ** significant at 5% level, * significant at 10% level. Estimation by OLS with two-way clustered standard errors at the industry*country and country*year level. All columns include a full set of fixed effects (country by industry pairs). Columns (1)-(7) use winsorized R&D levels (R&D larger/smaller than 1st/99th percentile of R&D). Columns (8)-(14) use winsorized R&D (R&D growth larger/smaller than 1st/99th percentile of R&D growth).

TABLE A9: WINSORIZING EXTREME GROWTH RATES IN DEFENSE R&D

Dependent variable: ln(Privately funded business R&D)	(1)	(2)	(3)	(4)
$\ln(\text{Pub R\&D})_t$	0.478**	0.540**		
	(0.165)	(0.167)		
$\ln(\text{Pub R\&D})_{t-1}$			0.459**	0.371**
			(0.171)	(0.126)
$\ln(\text{output})_t$	0.508**	0.440		
	(0.241)	(0.302)		
$\ln(\text{output})_{t-1}$			0.617**	0.680**
			(0.209)	(0.220)
Observations	4,922	5,314	4,597	4,959
Instrument	Defense IV	Winsorized IV growth rates	Lagged Defense IV	Winsorized IV growth rates, lagged
First-Stage F (excluded IV)	12.02	14.67	14.79	16.97
Anderson-Rubin Wald F-test	5.353	5.811	4.996	4.744
p-value	0.021	0.016	0.026	0.030

Notes: ** significant at 5% level, * significant at 10% level. Estimation by 2SLS with two-way clustered standard errors at the industry*country and country*year level. The dependent variable is the total R&D conducted in the business sector that is also financed by the private sector (i.e. excludes the government funded R&D). All columns include country*industry fixed effects as well as industry*year fixed effects. "Public R&D" is government financed R&D performed by private firms. Column (1) repeats the baseline IV result. Column (2) uses the winsorized instrument based on growth rates of the instrument (larger/smaller than 1st/99th percentiles, respectively). Columns (3) and (4) repeat the same exercise for 1 year lagged regressors and instruments. Country-year ln (GDP) included dated at same time as output.

TABLE A10: EFFECT OF PUBLIC R&D ON PRIVATE R&D – HIGH DEFENSE SHARE COUNTRIES ONLY

	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV	(7) OLS	(8) IV
Dependent variable: ln(Privately funded business R&D)								
ln(Public R&D)$_t$	0.248**	0.627**			0.223**	0.406**	0.093**	0.220
	(0.060)	(0.160)			(0.052)	(0.157)	(0.043)	(0.368)
ln(Public R&D)$_{t-1}$			0.209**	0.606**			0.103**	0.041
			(0.043)	(0.210)			(0.033)	(0.173)
ln(Public R&D)$_{t-2}$							0.011	-0.006
							(0.037)	(0.067)
ln(output)$_t$	1.237**	0.746**			1.674**	1.462**	1.276**	1.269**
	(0.209)	(0.324)			(0.304)	(0.380)	(0.256)	(0.266)
ln(output)$_{t-1}$			1.078**	0.670*	-0.492	-0.481	-0.021	-0.067
			(0.209)	(0.351)	(0.302)	(0.304)	(0.126)	(0.199)
ln(output)$_{t-2}$					-0.054	-0.113	-0.182	-0.217
					(0.250)	(0.247)	(0.200)	(0.228)
Long-Run Effect of Public R&D	0.248**	0.627**	0.209**	0.606**	0.223**	0.406**	0.206**	0.256*
	(0.060)	(0.160)	(0.043)	(0.210)	(0.052)	(0.157)	(0.0539)	(0.151)
Observations	2,188	2,188	1,904	1,904	2,135	2,135	1,839	1,839
1st Stage F (excluded IV)		13.45		8.507		9.431		7.274
Anderson-Rubin Wald F-test		9.219		5.562		3.411		0.265
p-value		0.00282		0.0197		0.0667		0.608

Notes: Same specification at Table 5 except we condition on countries which have more than the median defense/R&D share (US, France, UK, South Korea, Sweden, Spain, Germany, Slovakia, Italy). Ln(GDP) included dated at same time as output.

TABLE A11: INCLUDING A CONTROL FOR R&D TAX CREDITS FOR A SUB-SAMPLE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: ln(Privately funded business R&D)								
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
ln(Public R&D)$_t$	0.141**	0.418**	0.139**	0.380**			0.123**	0.198
	(0.038)	(0.152)	(0.038)	(0.160)			(0.033)	(0.169)
ln(Public R&D)$_{t-1}$					0.162**	0.387**		
					(0.037)	(0.176)		
R&D tax credit (1 - B index)$_t$			0.851**	0.708*			0.241	0.206
			(0.406)	(0.418)			(0.327)	(0.358)
(R&D tax credit)$_{t-1}$					0.957**	0.821**	0.436	0.434
					(0.353)	(0.383)	(0.374)	(0.399)
(R&D tax credit)$_{t-2}$							1.204*	1.207*
							(0.626)	(0.624)
ln(output)$_t$	0.783**	0.545**	0.792**	0.584**			0.723**	0.709**
	(0.197)	(0.248)	(0.201)	(0.259)			(0.269)	(0.275)
ln(output)$_{t-1}$					0.853**	0.684**	0.248	0.287
					(0.172)	(0.225)	(0.263)	(0.276)
ln(output)$_{t-2}$							-0.259	-0.374
							(0.279)	(0.405)
Observations	4,343	4,343	4,343	4,343	4,197	4,197	4,278	4,278
IV		Defense		Defense		Defense		Defense
1st Stage F (excluded IV)		14.74		14.40		15.00		11.06
Anderson-Rubin Wald F-test		4.981		3.944		3.625		1.083
p-value		0.0264		0.0480		0.0580		0.299

Notes: ** significant at 5% level, * significant at 10% level. Same specifications as in Table 5. 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. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output. The change in sample is because R&D tax credits are not available for several countries (Slovak Republic, Estonia, South Korea) and years (so 2007-2009 are missing for all countries).

TABLE A12: INCLUDING A CONTROL FOR NON-BUSINESS PUBLIC R&D SPENDING

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: ln(Privately funded business R&D)								
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
ln(Public R&D)$_t$	0.136**	0.462**	0.133**	0.394**			0.124**	0.197
	(0.037)	(0.167)	(0.033)	(0.170)			(0.032)	(0.160)
ln(Public R&D)$_{t-1}$					0.150**	0.437**		
					(0.034)	(0.203)		
Non-business public R&D$_t$			1.116**	1.033**			0.261	0.225
			(0.276)	(0.344)			(0.441)	(0.435)
Non-business public R&D$_{t-1}$					0.962**	0.887**	-0.005	0.064
					(0.265)	(0.307)	(0.438)	(0.456)
Non-business public R&D$_{t-2}$							0.998**	0.944**
							(0.329)	(0.357)
ln(output)$_t$	0.813**	0.580**	0.641**	0.467*			1.003**	0.984**
	(0.223)	(0.287)	(0.205)	(0.269)			(0.274)	(0.285)
ln(output)$_{t-1}$					0.664**	0.485*	-0.089	-0.063
					(0.183)	(0.262)	(0.251)	(0.255)
ln(output)$_{t-2}$							-0.373	-0.451
							(0.227)	(0.292)
Observations	4,011	4,011	4,011	4,011	3,925	3,925	3,940	3,940
IV		Defense		Defense		Defense		Defense
1st Stage F (excluded IV)		14.03		13.38		12.81		10.53
Anderson-Rubin Wald F-test		6.461		4.940		3.897		1.401
p-value		0.0116		0.0271		0.0494		0.238

Notes: ** significant at 5% level, * significant at 10% level. Same specifications as in Table 5. 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. “Public R&D” is government financed R&D performed by private firms. “Non-business public R&D“ is government financed R&D performed not by the private sector, e.g. by universities or other institutions. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output.

TABLE A13: INCLUDING A CONTROL FOR BUSINESS TAX REVENUE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: ln(Privately funded business R&D)								
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
ln(Public R&D)$_t$	0.162**	0.477**	0.163**	0.466**			0.144**	0.285*
	(0.039)	(0.165)	(0.038)	(0.166)			(0.034)	(0.167)
ln(Public R&D)$_{t-1}$					0.172**	0.458**		
					(0.038)	(0.172)		
ln(Business Tax Revenue)$_t$			0.169**	0.172			0.092	0.076
			(0.086)	(0.110)			(0.083)	(0.091)
ln(Business Tax Revenue)$_{t-1}$					0.063	0.065	0.044	0.077
					(0.091)	(0.114)	(0.082)	(0.093)
ln(Business Tax Revenue)$_{t-2}$							-0.006	-0.016
							(0.077)	(0.078)
ln(output)$_t$	0.790**	0.509**	0.764**	0.492**			0.857**	0.808**
	(0.179)	(0.241)	(0.183)	(0.244)			(0.241)	(0.256)
ln(output)$_{t-1}$					0.817**	0.605**	0.176	0.230
					(0.163)	(0.211)	(0.230)	(0.242)
ln(output)$_{t-2}$							-0.317	-0.491
							(0.233)	(0.327)
Observations	4,922	4,922	4,922	4,922	4,597	4,597	4,847	4,847
IV		Defense		Defense		Defense		Defense
1st Stage F (excluded IV)		12.02		11.94		14.74		8.641
Anderson-Rubin Wald F-test		5.330		5.283		5.004		2.119
p-value		0.0216		0.0222		0.0260		0.146

Notes: ** significant at 5% level, * significant at 10% level. Same specifications as in Table 5. 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. “Public R&D” is government financed R&D performed by private firms. “Business tax revenue” is tax revenue from taxes on income, profits and capital gains of corporates. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output.

TABLE A14: INCLUDING A CONTROL FOR GOVERNMENT COMPOSITION

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable: ln(Privately funded business R&D)								
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
ln(Public R&D)$_t$	0.160**	0.442**	0.157**	0.454**			0.149**	0.390**
	(0.040)	(0.159)	(0.039)	(0.156)			(0.038)	(0.159)
ln(Public R&D)$_{t-1}$					0.168**	0.422**		
					(0.039)	(0.162)		
Right wing government$_t$			0.186**	0.090			0.053	0.053
			(0.084)	(0.102)			(0.116)	(0.116)
Right wing government$_{t-1}$					0.238**	0.122	0.103	0.103
					(0.087)	(0.106)	(0.097)	(0.097)
Left wing government$_t$			0.227**	0.143			0.109	0.109
			(0.077)	(0.092)			(0.104)	(0.104)
Left wing government$_{t-1}$					0.218**	0.107	0.101	0.101
					(0.079)	(0.108)	(0.095)	(0.095)
ln(output)$_t$	0.800**	0.546**	0.807**	0.542**			1.005**	1.005**
	(0.182)	(0.239)	(0.181)	(0.234)			(0.290)	(0.290)
ln(output)$_{t-1}$					0.843**	0.652**	-0.459	-0.459
					(0.164)	(0.207)	(0.281)	(0.281)
Observations	4,756	4,756	4,756	4,756	4,472	4,472	4,715	4,715
IV		Defense		Defense		Defense		Defense
1st Stage F (excluded IV)		12.60		13.53		17.08		15.36
Anderson-Rubin Wald F-test		4.789		5.231		4.599		4.027
p-value		0.029		0.023		0.033		0.046

Notes: ** significant at 5% level, * significant at 10% level. Same specifications as in Table 5. 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. “Public R&D” is government financed R&D performed by private firms. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output. Right (left) wing government is an indicator variable indicating that the chief executive party has a right (left) wing orientation, central orientation is the omitted category.

TABLE A15: CONTROLING FOR FUTURE AND PAST OUTPUT IN R&D EQUATIONS

PANEL A: INCLUDE OUTPUT $_{t+1}$

Dependent variable: ln(Privately funded business R&D)	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV
ln(Public R&D)$_t$	0.157**	0.488**			0.144**	0.328**
	(0.037)	(0.163)			(0.034)	(0.159)
ln(Public R&D)$_{t-1}$			0.164**	0.466**		
			(0.035)	(0.165)		
ln(output)$_{t+1}$	0.773**	0.555**	0.830**	0.905**	0.670**	0.581**
	(0.245)	(0.268)	(0.204)	(0.245)	(0.237)	(0.249)
ln(output)$_t$	0.060	-0.031	0.190	-0.082	0.216	0.249
	(0.287)	(0.316)	(0.138)	(0.290)	(0.260)	(0.272)
ln(output)$_{t-1}$			0.019	-0.016	0.183	0.246
			(0.202)	(0.239)	(0.235)	(0.246)
ln(output)$_{t-2}$					-0.283	-0.513
					(0.234)	(0.318)
Long-Run Effect of	0.157**	0.488**	0.164**	0.466**	0.144**	0.328**
Public R&D	(0.037)	(0.163)	(0.035)	(0.165)	(0.034)	(0.159)
Observations	4,817	4,817	4,454	4,454	4,746	4,746
1st Stage F (excluded IV)		11.48		15.27		8.750
Anderson-Rubin Wald F-test		5.809		5.621		2.854
p-value		0.0165		0.0184		0.0921

Notes: Equivalent specifications to Table 5 except include future realizations of ln(industry output). Panel A includes output one year ahead. Panel B includes output in (t+1), (t+2) and (t+3). ** significant at 5% level, * significant at 10% level. 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. All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output.

TABLE A15: CONTROLING FOR FUTURE AND PAST OUTPUT IN R&D EQUATIONS – CONT.

PANEL B: INCLUDE OUTPUT $_{t+1}$, OUTPUT$_{t+2}$, OUTPUT$_{t+3}$

	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV
ln(Public R&D)$_t$	0.123**	0.513**			0.114**	0.391**
	(0.031)	(0.143)			(0.030)	(0.133)
ln(Public R&D)$_{t-1}$			0.154**	0.517**		
			(0.034)	(0.180)		
ln(output)$_{t+3}$	0.159	0.405	-0.158	-0.195	0.139	0.360
	(0.359)	(0.347)	(0.353)	(0.415)	(0.365)	(0.323)
ln(output)$_{t+2}$	0.074	-0.143	0.568*	0.787**	0.006	-0.106
	(0.224)	(0.230)	(0.291)	(0.358)	(0.234)	(0.233)
ln(output)$_{t+1}$	0.429	0.131	0.442	0.303	0.418	0.186
	(0.341)	(0.398)	(0.363)	(0.380)	(0.331)	(0.363)
ln(output)$_t$	0.153	0.135	0.227*	-0.125	0.253	0.363
	(0.312)	(0.358)	(0.132)	(0.328)	(0.270)	(0.309)
ln(output)$_{t-1}$			-0.028	0.053	0.155	0.244
			(0.237)	(0.296)	(0.237)	(0.244)
ln(output)$_{t-2}$					-0.221	-0.555*
					(0.239)	(0.304)
Long-Run Effect of	0.123**	0.513**	0.154**	0.517**	0.114**	0.391**
Public R&D	(0.031)	(0.143)	(0.034)	(0.180)	(0.030)	(0.133)
Observations	4,354	4,354	3,976	3,976	4,283	4,283
1st Stage F (excluded IV)		13.05		11.65		10.78
Anderson-Rubin Wald F-test		9.194		5.849		6.100
p-value		0.00265		0.0163		0.0141

Notes: Same as Panel A except we include output in (t+1), (t+2) and (t+3).

TABLE A16: CONTROLLING FOR GOVERNMENT NON-R&D DEFENSE SPENDING - ALL COUNTRIES, REDUCED FORM

Dependent variable: ln(Privately funded business R&D)	(1)	(2)	(3)	(4)
ln(Defense R&D)$_t$	0.068**	0.068**	0.075**	0.076**
	(0.029)	(0.032)	(0.033)	(0.032)
ln(output)$_t$	0.811**	0.923**	0.940**	0.965**
	(0.199)	(0.263)	(0.269)	(0.281)
ln(GDP)$_t$	0.125	0.112	0.134	0.246
	(0.312)	(0.415)	(0.411)	(0.451)
ln(Total Public				0.061
Defense Spending)$_{t+2}$				(0.313)
ln(Total Public			0.302	0.242
Defense Spending)$_{t+1}$			(0.223)	(0.203)
ln(Total Public		0.028	-0.184	-0.278
Defense Spending)$_t$		(0.323)	(0.327)	(0.447)
Observations	5,245	3,756	3,705	3,532
# ind*cty clusters	436	381	381	379
Long run effect of Total Public		0.028	0.119	0.025
Defense Spending		(0.323)	(0.349)	(0.468)

Notes: ** significant at 5% level, * significant at 10% level. 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). All columns include a full set of country by industry fixed effects and industry by year fixed effects. Even numbered columns use government funded R&D in defense as instrument for government financed R&D. The Anderson-Rubin Wald F-test tests the null hypothesis of weak instruments. Regressions include controls for country level ln(GDP) dated at the same time as output. “Total Public Defense Spending” is the total government expenditure on defense (including the non-R&D budget).

TABLE A17: CONTROLLING FOR GOVERNMENT NON-R&D DEFENSE SPENDING - US ONLY, REDUCED FORM

Dependent variable: ln(Privately funded business R&D)	(1)	(2)	(3)	(4)
ln(Defense R&D)$_t$	0.090**	0.085**	0.070**	0.051*
	(0.024)	(0.026)	(0.028)	(0.030)
ln(output)$_t$	0.997**	0.982**	1.048**	1.050**
	(0.267)	(0.269)	(0.286)	(0.317)
ln(Total public Defense spending)$_{t+2}$				0.040
				(0.046)
ln(Total public Defense spending)$_{t+1}$			0.012	0.020
			(0.045)	(0.050)
ln(Total public Defense spending)$_t$		0.020	0.032	0.028
		(0.042)	(0.048)	(0.047)
Observations	190	190	173	158
# ind clusters	17	17	16	16
Long run effect of Total Public Defense Spending		0.020	0.044	0.088
		(0.042)	(0.051)	(0.062)

Notes: ** significant at 5% level, * significant at 10% level. Standard errors clustered by industry. 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 a full set of industry and year fixed effects. “Total Public Defense Spending” is the total government expenditure on defense (including the non-R&D, excluding the R&D budgets).

TABLE A18: EFFECT OF SUBSIDIES ON EMPLOYMENT, NOT CONTROLLING FOR INDUSTRY OUTPUT

	(1)	(2)	(3)
Dependent Variable:	**ln(Private R&D)**	**ln(R&D personnel)**	**ln(empl excl. R&D)**
Panel A. OLS			
ln(Public R&D) $_t$	0.177**	0.175**	0.012**
	(0.043)	(0.039)	(0.005)
ln(GDP) $_t$	0.927**	1.416**	0.294**
	(0.314)	(0.375)	(0.059)
Observations	5,330	4,302	4,159
Panel A. IV			
ln(Public R&D) $_t$	0.715**	0.464*	0.091**
	(0.287)	(0.274)	(0.038)
ln(GDP) $_t$	0.973**	1.289**	0.254**
	(0.358)	(0.351)	(0.064)
Observations	5,330	4,302	4,159
F-stat first stage	9.46	10.36	10.51

Notes: ** significant at 5% level, * significant at 10% 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. All columns include industry*country FEs, industry*year FEs. Two way clustered SEs at country-industry and country-year level.

TABLE A19: INTERNATIONAL DISPLACEMENT EFFECTS OF PUBLIC R&D, PANEL C - OLS

Measure of neighbor for spillover	Baseline	Per-capita GDP (1)	Geography (2)	Skill Intensity (3)	Technology (4)	FDI Flows (5)	R&D Intensity (6)	Trade (imports) (7)	Trade (imports) (8)
Dependent variable: ln(Privately funded business R&D)									
EFFECT OF TOTAL R&D - OLS									
ln(Domestic Public R&D)$_t$	0.162**	0.169**	0.169**	0.167**	0.175**	0.176**	0.171**	0.174**	0.174**
	(0.039)	(0.041)	(0.041)	(0.041)	(0.039)	(0.043)	(0.040)	(0.040)	(0.039)
ln(Int. Total R&D)$_{t-1}$		-0.002	-0.059	-0.024	-0.198	-0.117*	-0.218**	0.017	-0.139
		(0.031)	(0.106)	(0.094)	(0.130)	(0.068)	(0.070)	(0.066)	(0.087)
ln(output)$_t$	0.790**	0.791**	0.774**	0.820**	0.757**	0.864**	0.848**	0.806**	0.778**
	(0.179)	(0.188)	(0.186)	(0.188)	(0.184)	(0.188)	(0.192)	(0.202)	(0.187)
ln(GDP)$_t$	0.213	0.203	0.221	0.245	0.254	0.129	0.091	0.128	0.182
	(0.310)	(0.314)	(0.305)	(0.317)	(0.305)	(0.347)	(0.311)	(0.359)	(0.312)
Observations	4,922	4,776	4,776	4,194	4,776	4,614	4,776	4,193	4,759

Notes: ** significant at 5% level, * significant at 10% level. Each column in each panel constitutes a separate regression. Two-way clustered standard errors at the industry*country and country*year level. All columns include full sets of country by industry fixed effects, and industry by year fixed effects. 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. "Int. Total R&D" is the weighted average of other countries' public and private R&D in the same industry and year, where each column uses different weights. Weights ω_{kl} are a "distance" measure between country k and country *l* and measured by: (1) GDP per capita. $\omega_{kl} = 1/abs(GDPcap_k - GDPcap_l)$; (2) Geographic distance. $\omega_{kl} = 1/dist_{kl}$ where geographical distance is measured in kms between capital cities; (3) Skill intensity. $\omega_{kl} = 1/abs(tert_k - tert_l)$ with $tert_l$ being the share of population with tertiary education in country *l;* (4) Patent similarity. $\omega_{kl} = \sqrt{\sum_i \left(pat_{ik} - pat_{il}\right)^2}$, pat_{ik} and pat_{il} are patent share of a specific technology class *i* (out of 15 patent technology classes) in country k or l (of total patents in that country); (5) Inward FDI flows. $\omega_{kl} = \frac{FDI_{kl}}{\sum_{j=1}^{J} FDI_{kj}}$ where FDI_{kl} is the amount of FDI that country *k* receives from country *l;* (6) R&D intensity. $\omega_{kl} = 1/abs\left(\frac{Total\ R\&D_k}{GDP_k} - \frac{Total\ R\&D_l}{GDP_l}\right)$; (7) Import share. $\omega_{kl} = \frac{IMP_{kl}}{\sum_{j=1}^{J} IMP_{kj}}$ where IMP_{kl} are imports from country l to country *k*; (8) Export share. $\omega_{kl} = \frac{EXP_{kl}}{\sum_{j=1}^{J} EXP_{kj}}$ where EXP_{kl} are exports from country *l* to country *k*.

TABLE A20: INTERNATIONAL SPILLOVER EFFECTS OF R&D SUBSIDIES ON TFP GROWTH

Measure of neighbor for spillover	Baseline	Per-capita GDP (1)	Geography (2)	Skill Intensity (3)	Technology (4)	FDI Flows (5)	R&D Intensity (6)	Trade (imports) (7)	Trade (exports) (8)
Dependent variable: TFP Growth									
Panel A. OLS									
(R&D/value added)$_{t-1}$	0.098**	0.054*	0.032	0.046	0.020	0.082**	0.038	0.031	0.030
	(0.040)	(0.032)	(0.024)	(0.033)	(0.022)	(0.037)	(0.029)	(0.025)	(0.026)
(International R&D/value added)$_{t-1}$		0.180**	0.212**	0.215**	0.254**	0.073**	0.184**	0.178**	0.181**
		(0.053)	(0.041)	(0.047)	(0.049)	(0.030)	(0.052)	(0.036)	(0.041)
Observations	6,608	6,602	6,602	5,748	6,602	6,602	6,602	6,388	6,388
Panel B. IV									
(R&D/value added)$_{t-1}$	0.098**	0.035	0.036	0.054	0.022	0.043	0.032	0.029	0.029
	(0.041)	(0.044)	(0.032)	(0.049)	(0.033)	(0.033)	(0.034)	(0.034)	(0.035)
(International R&D/value added)$_{t-1}$		0.188**	0.205**	0.183**	0.217**	0.140**	0.184**	0.176**	0.175**
		(0.086)	(0.055)	(0.070)	(0.062)	(0.040)	(0.068)	(0.054)	(0.058)
Observations	6,608	5,155	5,155	4,709	5,155	5,146	5,155	5,149	5,149
First stage F		5.793	7.614	6.274	6.961	7.546	6.741	6.477	6.391

Notes: ** significant at 5% level, * significant at 10% level. Standard errors are two-way clustered at the industry*country and country*year level. All regressions include a full set of country and year fixed effects. The dependent variable is TFP growth over 1 year. "International R&D/value added" is the weighted average of other countries' total R&D/value added in the same industry and year, where each column uses different weights. "R&D" is the total R&D conducted in the business sector (both financed by the private sector and by government).

Weights ω_{kl} are a "distance" measure between country k and country l and measured by: (1) GDP per capita. $\omega_{kl} = 1/abs(GDPcap_k - GDPcap_l)$; (2) Geographic distance. $\omega_{kl} = 1/dist_{kl}$ where geographical distance is measured in kms between capital cities; (3) Skill intensity. $\omega_{kl} = 1/abs(tert_k - tert_l)$ with $tert_l$ being the share of population with tertiary education in country l; (4) Patent similarity. $\omega_{kl} = \sqrt{\sum_i \left(pat_{ik} - pat_{il}\right)^2}$, pat_{ik} and pat_{il} are patent share of a specific technology class i (out of 15 patent technology classes) in country k or l (of total patents in that country); (5) Inward FDI flows. $\omega_{kl} = \frac{FDI_{kl}}{\sum_{j=1}^{J} FDI_{kj}}$ where FDI_{kl} is the amount of FDI that country k receives from country l; (6) R&D intensity. $\omega_{kl} = 1/abs\left(\frac{Total\ R\&D_k}{GDP_k} - \frac{Total\ R\&D_l}{GDP_l}\right)$