Macroeconomic Effects of Public R&D

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MACROECONOMIC EFFECTS OF PUBLIC R&D*

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Abstract

The direct public funding of R&D investment to stimulate technological innovation has a strong theoretical case and has gained renewed attention in the recent policy debate as a way to address the long-term challenges of modern society such as pandemics, climate change, and the transition to a low-carbon economy. We estimate the dynamic macroeconomic effects of government R&D investment and we find that it is very effective in fostering the total national innovation effort, crowding in private R&D investment, and in raising aggregate output in the long run. We also find that the public stimulus goes beyond private R&D activities and involves a very strong expansion of overall economic activity since the early periods. Finally, we uncover a strong positive impact of the private sector's anticipation of public R&D spending, which can be interpreted as a confirmation of the importance of managing expectations to reduce the uncertainty inherent to R&D activities.

Keywords: fiscal multipliers, structural vector autoregression, R&D investment, public R&D, government R&D, crowding-out, expectations, fiscal foresight.

JEL codes: C32, E62, O32.

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1. Introduction

In December 2022 the news of a breakthrough in the research on nuclear fusion by the US government scientists from the federal Lawrence Livermore National Laboratory in California made the headlines across the globe raising the hope for a clean energy alternative to fossil fuel. But what is the actual impact of publicly funded R&D investment on the economy in aggregate and across time?

The governments of all major world economies have recently shown renewed attention on the role that public investment in innovation can play in fostering technological progress, especially in response to the big societal challenges posed by climate change, the recent COVID pandemic, and the ongoing energy crisis. Since April 2021 President Biden proposed, and partially managed to pass through Congress, an initial $325 billion plan to boost the funding of most government science agencies. The vast program of public funding of R&D investment has been announced as a key instrument to stimulate the innovation process in a wide range of scientific areas, most notably in health, climate, energy, and digital technologies.

In Europe, a prominent example of a large publicly funded R&D program is the €100 billion EU fund for the 2021-27 Horizon Europe research grants scheme, which has been powered by the Next Generation EU plan, designed to make European economies and societies healthier, greener, and more digital (European Commission 2021). In the UK, in 2020 the government announced the Research and Development Roadmap, committing itself to an increase in the country's R&D investments to £22 billion by 2024. This plan includes the creation of a public agency along the lines of the US Advanced Research Projects Agency (ARPA), with the specific task of promoting high-risk research projects with the potential to make ground-breaking discoveries. At the global level, initiatives such as the Mission Innovation plan, announced in 2015, has led 20 countries to commit to a substantial increase in their governments' R&D budgets to stimulate the innovation necessary for the transition to a low-carbon economy.

Given the growing interest that governments have shown in using the direct funding of R&D investment, it becomes imperative to build a solid evidence base about its quantitative impact on the economy. In this paper we provide an empirical assessment of the dynamic macroeconomic effects of government R&D investment, looking at the historical experience of the US, which provides a rich and sufficiently long series of publicly funded innovation spending episodes. Our findings expand the existing knowledge within two different strands of literature. First, we contribute to the research thread on the magnitude of fiscal multipliers by focusing on the dynamic effects of public R&D spending. Second, we contribute to the research domain that analyses the influence that public R&D investment exerts on private R&D activities and its ultimate impact on aggregate productivity. We adopt a time series approach that is well-suited to capture the dynamic short-run macroeconomic effects of government R&D spending, but we also uncover the impact on aggregate output and aggregate innovation activities in the long run, and so we are able to say something about the implications for technological innovation and growth in the very long run.

The rationale for government-funded R&D investments relies mainly on the difference that exists between social and private returns from the knowledge creation typical of public goods (Mansfield et al. 1977), and on the high risk and asymmetric information between performer and investor that characterizes these types of activities (Arrow 1952), and which inevitably results in insufficient private R&D investments. Government funding helps also to overcome existing capital market imperfections that often hinder the transfer of an invention from the laboratory to the market (e.g. Mowery et al. 2010 and Howell 2017 on clean energy technologies), and to facilitate an investment process that is characterized by a long time interval before commercialization, highly uncertain payoffs, and huge initial fixed costs.

A rich empirical macroeconomic literature has sought to estimate the fiscal multipliers with respect to GDP using Structural Vector Autoregressive (SVAR) models. Most studies have considered total government spending in the US, like the seminal paper by Blanchard and Perotti (2002), who find a positive effect on output, or Mountford and Uhlig (2009), who highlight a crowding-out effect on private investments using an identification based on sign restrictions. Other papers have distinguished specific classes of government spending. Government investment is the focus of Perotti (2004), who shows that it crowds out private investment, although there is no consensus given that other studies uncover instead an expansionary effect that is above that of government consumption expenditure (Auerbach and Gorodnichenko 2012; Deleidi et al. 2021). A strand of research has explored the extent to which fiscal multipliers can be state-dependent. Auerbach and Gorodnichenko (2012) uncover that the impact of government consumption spending is higher during recessions that during economic booms, whereas Ramey and Zubairy (2018) find no compelling evidence that the amount of slack in the economy influences the size of the fiscal multiplier. Ilzetzki et al. (2013)

uses a panel SVAR on a set of countries to show that the impact of government consumption spending depends on key country characteristics, such as level of development and trade openness. Finally, some authors have tried to make sense of the existing wide variety of estimates for the size of the fiscal multipliers by uncovering that this is partially due to different model specifications (Caldara and Kamps 2008), or to a specific underlying and often implicit restriction on the systematic rule that links policy to output (Caldara and Kamps 2017).[1]

A correct estimation of the multiplier of government spendings and taxes may be undermined by the fact that the actual information set of the private agents is larger than that implied by a VAR. Ramey (2011a) offers strong evidence that VAR innovations can indeed be highly predictable using external forecasts or narrative-based exogenous variables. By contrast, Perotti (2014) shows that standard SVAR models that ignore expectations can still offer a sufficiently accurate estimation, and his analysis underlines that defense spending is contractionary while civilian spending is expansionary. This risk of *non-fundamentalness*, however, has spurred the development within this literature of alternative strategies to capture the policy anticipation by the private sector. One way to explicitly distinguish anticipated and unanticipated government spending shocks is to rely on the estimation procedure proposed by Mertens and Ravn (2010), which is based on a Blaschke matrix transformation to select a non-fundamental representation of the VAR. Many studies control for expectations by including external measures of private forecasts about future government spending. One notable example is Auerbach and Gorodnichenko (2012), who obtain that the fiscal multiplier of government consumption and defense spending are larger in recession than expansion, and that the multiplier increases once we take account of private sector forecasts on future spending. Within the narrative approach to fiscal multipliers, Mertens and Ravn (2012) use a timing convention to distinguish the impact of anticipated and unanticipated tax changes.

There is very little research on the fiscal multipliers of R&D spending, the only exception being Deleidi and Mazzucato (2021), who analyze the effects of mission-oriented policies in the US as proxied by defense-related R&D spending, and Antolin-Diaz and Surico (2022), who look at the effects of military spending news and find that public R&D spending in particular is able to match the observed long-run effects on productivity. Both studies use a SVAR model where identification is loosely reached via a triangular structure on the residual contemporaneous

[1] For an extensive overview of the existing empirical research on fiscal multipliers covering also other methodologies beyond SVAR, such as Narrative Approach, Local Projections, and DSGE, see Ramey (2011b, 2016b, 2019).

correlations, with the government spending of interest ordered as first, and without taking consideration of the potential problem posed by private sector anticipation.

The second research strand to which we contribute is the literature that studies the influence of public R&D on private R&D investments, and its ultimate impact on aggregate productivity, which typically employs a growth accounting framework. Despite earlier evidence suggesting a crowding-out effect, especially as a result of an inelastic supply of scientists and engineers (e.g. Goolsbee 1998, Wallsten 2000), the current evidence is mixed (e.g. David et al. 2000), but a growing share of studies finds an opposite crowding-in effect (Becker 2015). Recent work by Moretti et al. (2021), for instance, shows that in OECD countries private R&D rises in response to publicly funded defense R&D, both at industry and firm level.[2]

We adopt the same SVAR-based approach employed by the macroeconomic literature on fiscal multipliers, and we adapt it to the specific characteristics of our class of government spending. Since government R&D investments tend to be part of long-term plans addressing major societal goals, and are usually announced well in advance, the risk of non-fundamentalness of the policy shocks is particularly serious. To tackle this problem, we build on the contribution of Blanchard and Perotti (2002), and extend the standard SVAR framework into a *Rational Expectations SVAR* (RE-SVAR) model, which incorporates private agents' expectations about future government R&D spending decisions. Our analysis is performed in two stages. In the first stage, we make a robust case for an identification scheme that hinges on a set of mild restrictions for the contemporaneous correlation between variables, and we estimate the corresponding SVAR model. In the second stage, after discussing the risk of non-fundamentalness in the case of public R&D, we modify the SVAR model by including the forward-looking expected value of public R&D spending, and we estimate the new model under the assumption of perfect foresight of next-period spending and a slightly modified version of the same identification scheme.

Our findings can be summarized into four major points. First, there is strong evidence that public R&D investment crowds in private R&D investment, both at short and long horizons, with the consequence of accelerating the aggregate national scale of innovation activities. Second, this stimulus produced by public R&D goes beyond private R&D activities and involves an extraordinary expansion of overall economic activity since the first quarter. We

[2] For an extensive overview of the existing empirical research on the returns to R&D see Hall et al. (2010).

find that the fiscal multiplier of public R&D spending outperforms that of many other classes of government spending. Third, the increase that public R&D investment produces on aggregate output is permanent, while that of the other types of spending is not, which suggests that this type of innovation policy instrument is very effective in boosting the aggregate productivity level, and thus in accelerating the pace of economic growth in the very long run. Fourth, we find that the impact of private sector anticipation of public R&D spending is important, which represents a warning for empirical studies that ignore the role of expectations when estimating the corresponding multipliers. Such a result is far from surprising given the high uncertainty inherent to R&D activities, which typically hinders a sufficient private involvement, but it also highlights the importance of stabilizing expectations for a successful implementation of the public innovation policy.

The paper has the following structure. In section 2 we describe the main features of the public R&D investments in the US along with a brief historical account. In section 3 we set up our SVAR model, describe our dataset, and discuss our identification scheme. In section 4 we present the results from our SVAR model. In section 5 we set up our strategy to control for expectations and describe our RE-SVAR model. In section 6 we present the results from the RE-SVAR model. In section 7 we offer a final discussion and interpretation of the overall results.

2. Government R&D investments

The existing empirical research on fiscal multipliers has considered the macroeconomic impact of total government expenditure or has focused on some broad classes of public spending, such as consumption, investment, and sometimes distinguishing defense and non-defense spending. Given the relative novelty of an analysis that examines public R&D spending, it is useful to discuss some of its features that will be become relevant when setting up our empirical model.

2.1 Mission-oriented spending

There are three main peculiarities that distinguish R&D investments from other classes of government spending: (i) the motivation behind their funding, which is to pursue long-term strategic goals for the country; (ii) the public announcements that typically anticipate the beginning of their actual realization; (iii) the potential for producing long-lasting effects on economic growth by fostering technological innovation.

The public financing of defense and non-defense related R&D programs can be regarded as "allocation decisions […] based on assessments by policymakers of the research needs of specific agency missions" (Mowery 2010, p. 1223). These expenditures have been targeted at finding technical solutions to complex problems that represent long-term challenges for society. The R&D spending decisions have always reflected political priorities over strategic national goals, and so they have been largely independent of the short-term temporary fluctuations in the macroeconomic conditions.

Moreover, this class of government investment is typically anticipated by high-profile public announcements, and accompanied by detailed technical reports, defining the amount of funding and setting the stage for subsequent policy plans. This specific characteristic is fundamental to correctly solving the identification problem underlying the estimation of the causal impact of government spending on the economy, as it allows us to impose assumptions on the timing of the policy intervention, and on the information set available to the private economic agents at the time of the policy shock (Ramey 2011a).

By their very definition, the outcome of R&D investments is the production of new knowledge and technologies, with the possibility of boosting technological innovation in multiple sectors via knowledge spillovers. The motivation for government's involvement has been the recognition that private firms are unlikely to deliver socially optimal levels of R&D as a consequence of the numerous market failures. In the US, the government's innovation policy since the aftermath of World War II has been aimed at addressing grand societal challenges of strategic importance. These goals have been pursued through the launch of ambitious programs that have effectively succeeded in fostering and shaping the innovation process in many sectors, leading to major technological advances (Foray et al. 2012, Mowery et al. 2010, Mowery 2012, Mazzucato 2013, 2018).[3]

[3] Some prominent examples of both defense and non-defense research programs are: the Apollo project and the several space programs launched by the National Aeronautics and Space Administration (NASA); the Defense Advanced Research Projects Agency (DARPA) investment in ARPANET, which became the modern-day internet (Abbate 2000, Mowery and Simcoe 2002); the Advanced Research Projects Agency Energy (ARPA-E) investments in renewable energy technologies; the National Institutes of Health (NIH) investments in the biotechnology and biomedical sectors; and the investments in technologies for the agricultural sector (Block and Keller 2009, Foray et al. 2012). All these public initiatives have mainly consisted of large direct R&D investments

Total public R&D spending in the US has increased over time not gradually, but rather with sudden rises occurring approximately every 20 years, so in the early 1960s, 1980s, and 2000s – see Figure 1, where all values are in constant 2016 dollars. The largest of these rises occurred in the early 1960s, largely due to increases in the non-defense R&D components. Total R&D spending rose from $14 billion in 1953 to $91 billion in 1967, with about $50 billion spent in non-defense R&D. In terms of composition of the R&D budget – see Figure 2 – the defense share dropped from 80% in the 1950s to 50% in the 1960s, space increased from 2% to 25% in the same period and health rose from 2% in 1953 to 7% in 1969. After a moderate decline in non-defense R&D spending during the 1970s, we notice a substantial rise in defense R&D investments in the 1980s, reaching a peak share of 70% in 1987. From the mid-1980s health became the second most important area of R&D funding, while space occupied the third position. After a final rise during the 2000s, in 2017 total R&D investment reaches a level of $144 billion (from $14 billion in 1953), while the respective share of defense, health, and space is 54%, 23%, and 8%.

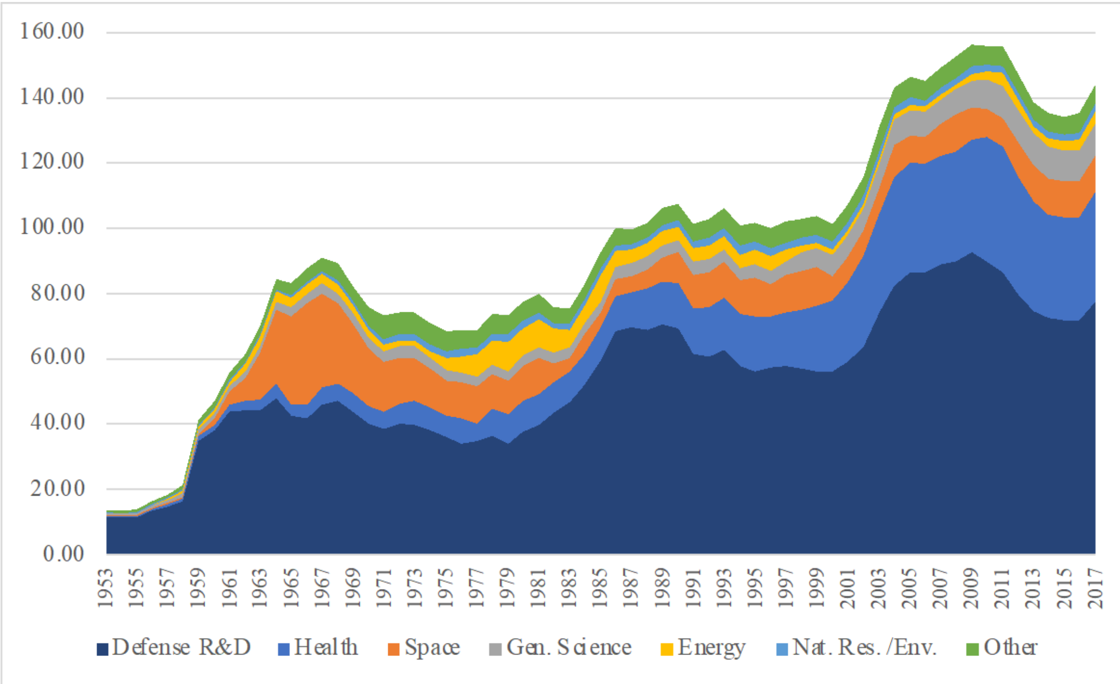

Figure 1. Federal R&D by function, in billions of constant 2016 US dollars, collected from American Association for the Advancement of Science, based on OMB Historical Tables in Budget of the United States Government.

at the federal level and have *de facto* operated as an industrial policy to achieve strategic national objectives (Foray et al. 2012, Moretti et al. 2021).

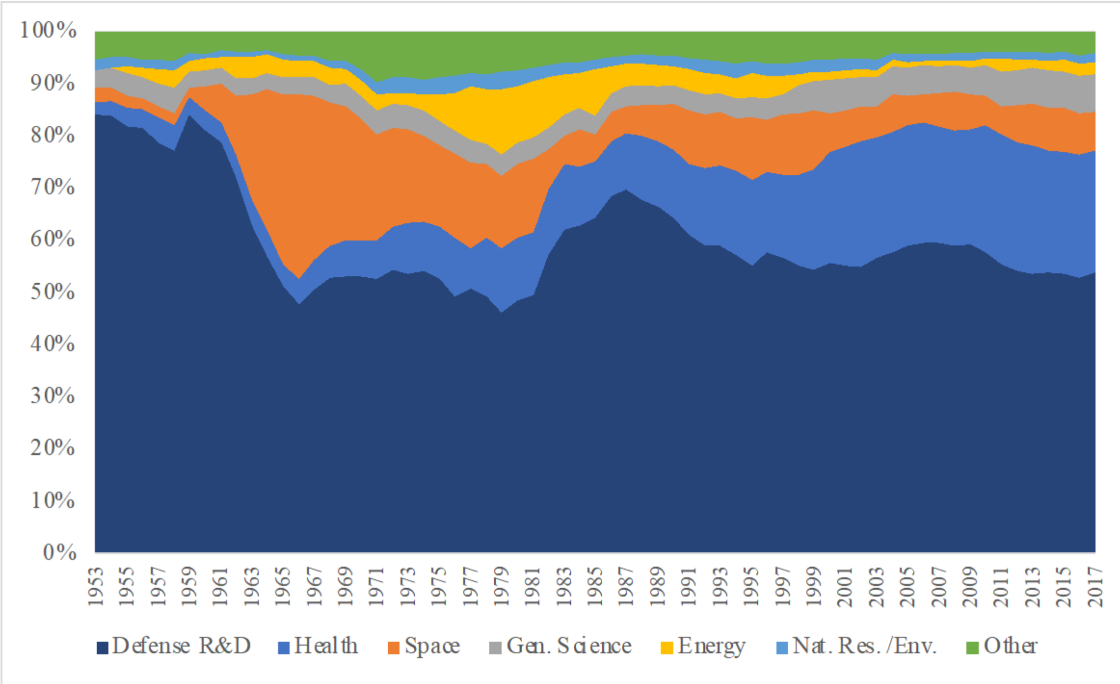

Figure 2. Share of each function in total federal R&D, collected from American Association for the Advancement of Science, based on OMB Historical Tables in Budget of the United States Government.

The historical pattern of these shares can be used to infer the evolution in the strategic importance assigned by the US government to different research domains. After a drop in the early 1960s, defense R&D share has remained stable at around 50% over 50 years, with the exception of the 1980s when tensions with the Soviet Union were high, but dropped immediately after the fall of the Berlin Wall in 1989; space was a strong priority during the space race in the 1960s and 1970s; energy appears to have been a major strategic area of research during the 1970s and 1980s, as a response to the Arab oil crisis; health has slowly drawn an increasing amount of attention from the US government starting from the 1970s.

For illustrative purposes we provide a brief account of some historical examples of federally funded R&D investment programs. This is useful not only to stress the long-term goals typically pursued by this type of government spending, but also to draw attention to the other peculiarity of public R&D spending: the role of early public announcements in influencing the anticipation by the private sector. We first consider some defense R&D programs, borrowing from the documentary evidence of fiscal policy episodes collected by Ramey (2016a), and based on *Business Week* (BW), the *New York Times* (NYT), and the *Washington Post* (WP). Then we collect published official documents and the press coverage for some non-defense R&D programs.

2.2 Historical examples of defense programs

The NASA mission in response to Sputnik started in October 1957, after which a Soviet intercontinental ballistic missile launched (October 4, 1957), the first artificial satellite in space. As reported by the October BW, the White House was not initially inclined to exceed the $38-billion military spending ceiling as a response to the Soviet launch. Only one month later, however, the Eisenhower administration announced new military expenditures to fill the technological and scientific gap with the Soviet Union. Specifically, the BW of December 1957 reported that the US administration planned to move the fiscal budget from the $38-billion ceiling, prearranged for the 1958-1961 period before the Soviet Sputnik launch, to $38.6 billion in 1958, $40 billion in 1959, $41.5 billion in 1960, and $43 billion in 1961. During 1958, the February BW reports the announcement of additional variations to the US military budget and the willingness of the US Congress to vote for a larger budget than the one requested by Eisenhower. Moreover, in February 1958 the Eisenhower administration inaugurated the opening of the Defense Advanced Research Projects Agency (DARPA), and in July of the same year the National Aeronautics and Space Administration (NASA). As reported by the Dwight Eisenhower Memorial Commission (2008), the original goals of these agencies were to fill the existing technological gaps with the Soviet Union and expand the frontiers of US science. For the fiscal year 1960, the Pentagon estimated an increase in defense expenditure to $50 billion, so 25% higher than the budget of $40 billion proposed in 1957.

During the 1970s, under the Nixon administration a shift in the US defense strategic nuclear policy occurred through the so-called Nixon's Nuclear Doctrine. When James Schlesinger was appointed as Secretary of Defense in May 1973, he aimed to modernize the army via an array of strategic military programs, stepping up R&D activities to create a large range of counterforce opportunities against a variety of potential enemy actions and improving the accuracy and striking power of the US nuclear arsenal. As announced by the NYT and BW of January and February 1974, there was an increase in the defense budget assigned to the nuclear program which reached a record level of $92.6 billion, with a sizable share devoted to the Pentagon’s R&D activities. Furthermore, in June 1975, the BW announced that Congress was extending its commitment for supporting Pentagon’s basic long-range research programs.

During the 1980s, under the Reagan administration, Congress launched the Strategic Defense Initiative (SDI), a long-term R&D plan aimed at creating a missile defense system to shield the US from nuclear weapons attacks. This program consisted of developing novel strategic technologies, largely based in space, for rendering nuclear weapons "impotent and obsolete". It was publicly announced by President Reagan on March 23, 1983 and work was begun by the Department of Defense in 1984. The Strategic Defense Initiative Office (SDIO), through the Innovative Science and Technology Programs directed by James Ionson (Ionson 1988), invested funds in research activities for technology such as computers, sensors, lasers, power, materials, directed energy propellants, and space science (*The Tech* 1985). The plan called "for devoting about $26 billion over the next six years to determining the applicability of technologies and systems concepts to the strategic defense mission" (CBO 1984, p. 1). On May 23, 1984, the Congressional Budget Office (CBO) announced the expected costs of the SDI research activities for the following fiscal years. The CBO estimated to spend $1 billion in 1984, $1.8 billion in 1985, $3.8 billion in 1986, $5 billion in 1987, $6.3 billion in 1988, and $7.4 billion in 1989.

After the 9/11 terroristic attack, under the Bush administration, a boost in military expenditures occurred. The October 2001 BW reported President Bush's intention to increase defense spending by $18.4 billion in 2002 fiscal year, and by $198 billion in the following 10 years. The actual US military R&D activities were increased by approximately 50% during the 2001-2004 fiscal period (Trajtenberg 2006, Mowery 2012, Moretti et al. 2021).

2.3 Historical examples of non-defense programs

In the late 1950s and early 1960s, under the Kennedy administration, the US launched the Moon Mission as a response to the Soviet Union's achievements in terms of physical exploration of the moon. In a special message about urgent national needs sent to Congress on May 25, 1961, President Kennedy announced the goal of sending a man to the moon as a plan of national interest. The day after, the NYT reported that the cost of these new space programs for the 1961 fiscal year would have exceeded the annual budget by $1.8 billion, including $679 million for space exploration projects, and that the budget for the space research program in the following five years would have reached $7-9 billion (Lawrence 1961). The expected cost of the space research program was reviewed several times during the 1960s. In July 1961 BW reported a cost of $35 billion in ten years, but this forecast was subsequently revised upwards during the 1962-1969 period (Ramey 2016a, pp. 75-90).

Another important initiative of the 1960s was the War on Poverty plan, announced on January 8, 1964 by President Johnson, who declared in front of Congress that poverty was a national problem requiring large improvements in the organization and support at state and local levels. The aim was to reduce poverty by expanding the federal government's education and health budget through the supply of preschool programs for children belonging to low-income families and an inclusive plan addressing a wide range of social needs. To this end there was an increase in federal expenditure on anti-poverty research projects, via national R&D centers and regional education laboratories (Simon-McWilliams 2007). Federal R&D expenditure on programs aimed at mitigating poverty increased from less than $3 million in 1965 to $100 million in 1967 and $200 million in 1980 (Vinovskis 2002). During the same 1964 speech to Congress, President Johnson announced a reallocation of public expenditure, cutting defense spending and boosting health and education spending. This news was covered a few months later by the NYT (Shanahan 1964).

During his State of the Union message of January 1971, President Nixon launched the War on Cancer, at the time the second cause of death in the US, later passed by Congress as the National Cancer Act. On December 4, 1970, the *National Program for the Conquest of Cancer* report was presented to the Senate Committee on Labor and Public Health. The report showed that the amount spent on cancer research was inadequate and suggested a substantial increase in government research activities. The committee estimated the need for an appropriation of $400 million in the 1972 fiscal year, with an increase in the cost of the program of $100-150 million per year, reaching a level of between $800 million and $1 billion in 1976. On May, 24 1971, President Nixon announced the appropriation of an additional $100 million, including funds for the National Cancer Institute (NCI) to establish 15 new cancer research centers and an international cancer research data bank. The Nixon administration converted the National Cancer Act to the public law 92-218 during the Congress meeting held on December 23, 1971. The law confirmed the costs for the NCI previously estimated by the 1970 report by authorizing a budget of $400 million for the 1972 fiscal year, $500 million for 1973, $600 million for 1974, and $700 million for 1975. In the fact books of 1975 and 1976, the NCI reported effective research costs of the project in line with predictions: $581 million for the 1974 fiscal year, $692 million for 1975, and approximately $1 billion for 1976 (National Cancer Program 1975, 1976).

During the 1980s, after a conference held in Santa Fe on March 3 and 4, 1986, the Department of Energy (DOE) announced the Human Genome (HG) initiative, which was defined as the 'most provocative biomedical research project in history' (NYT, December 13, 1987). The project aimed at producing long-term impacts on biotechnology and pharmaceutical industries, basic science, and medicine practices. The report written for the Santa Fe conference (DOE 1986) announced that the project would cost $3 billion over ten years.[4] In April 1987 the initiative was endorsed by the Department of Health, which announced a funding of $200 million annually and a total cost for the project of $3.5 billion (Barnhart 1989). The project lasted from 1990 to 2013, involving the DOE, the National Center for Human Genome Research, and the National Institute of Health (NIH), and ended up costing $2.7 billion in 1991 dollars.

The last R&D investment program we are considering is the Climate Action Plan, officially launched by the Obama administration in 2013, but anticipated by a climate change and energy plan that had been mooted since he took office in 2009. Before that, in 2007 President Bush launched in 2007 the "America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science" (COMPETES) Act, intended "to invest in innovation through research and development, and to improve the competitiveness of the United States". The act authorized the creation of the Advanced Research Projects Agency–Energy (ARPA-E) and the appropriation of $300 million annually for the 2008-2010 period. The goals of the ARPA-E were: (i) reductions of energy imports; (ii) reductions of emissions, including greenhouse gases; (iii) improvements of energy efficiency in all economic sectors. In November and December 2008, the NYT announced that President Obama would address the climate change challenge through the launch of an investment of $150 billion over ten years in new energy-saving technologies.[5] The plan was focused on R&D activities in the energy sector and was considered a national mission guided by DOE. In April 2009, the NYT reported Obama's public speech where he announced the first official funding for the ARPA-E and its 'high-risk and high-reward' research activities (Revkin 2009). The initial 2009 budget of $400 million was used to finance projects for $151 million in October 2009. The America COMPETES Reauthorization Acts of 2010 and 2014 authorized an amount of funding that grew each year, from $300 million in 2011 to $395 million in 2019, with ARPA-E receiving $180 million in 2011 up to $366 million in 2019.

[4] This news was also reported by the NYT on November 4, 1986 (Browne 1986).

[5] In November 2008 the NYT published an article on Obama's climate change goals (Broder 2008) and in December 2008 it reported Obama's energy and environment team announcement.

3. SVAR model

To study the dynamic macroeconomic effects of public R&D investment we build a small-scale SVAR model where we separate R&D spending from all the other types of government spending.

We start by defining a reduced-form VAR of order p as

$$X_t = \mu + \sum_{i=1}^{p} A_i X_{t-i} + u_t, \qquad (1)$$

where μ is vector of constants, X_t is the vector of endogenous variables measured at quarterly frequency, A_i is the matrix of reduced-form slope coefficients, and u_t is the vector of reduced-form errors. To preserve any existing cointegrating relationship that connects our variables in the long run we follow the standard practice of modelling the VAR in the log-levels of the variables, in addition to expressing them in constant prices and per capita. [6] In our case, $X_t = [GI_t; GR_t; RD_t;\ T_t;\ Y_t]$, where GI_t is the government R&D investments, GR_t is the government residual spending, RD_t is the private R&D investments, T_t is the tax revenues, and Y_t is the GDP.

The lag order of our VAR is chosen as a compromise between theoretical considerations and practical constraints. On theoretical grounds, we would ideally like to capture also the long-run effects that R&D investments ultimately produce in terms of productivity, in addition to the short-run aggregate demand-driven effects on economic activity. If we look at the literature that investigates the timing of the returns to R&D, we find that the largest share of studies suggests a lag between R&D expenditure and innovation in the range of one to three years, but there are also some work pointing at delays as long as 20 years.[7] If we employ the Hannan-Quinn Information Criterion we obtain a lag order of 6, which is between the two extreme values of 15 and 2 suggested by AIC and BIC respectively. While the timespan of the samples at hand probably prevents us from catching the effects of R&D on productivity in its entirety,

[6] See, for instance, Auerbach and Gorodnichenko (2012), and Kilian and Lutkepohl (2017).

[7] Pakes and Schankerman (1984) obtain that returns to R&D occur after 1.2 to 2.5 years; Geroski (1989) highlights that innovation can continue to influence productivity after three years; based on fit criteria, Adams (1990) concludes that it takes 20 years for academic research to yield the peak effect in terms of productivity; Adams and Jaffe (1996) find a time interval of five to six years between R&D and productivity; Kondo (1999) shows that patent application occurs 1.5 years after first R&D investment; de Rassenfosse and Guellec (2009) argue that the lag between R&D and patent application is one year on average; Danguy et al. (2013) argue for using a lag of one year to estimate the effect of R&D on patents; Argente et al. (2018) find a lag of 1 year between R&D expenditure and the introduction of a new product. Most empirical studies on the returns to R&D continue to employ a lag of one year. See for instance Moretti et al. (2021).

a lag of 1.5 years is not far from what is typically accepted in the empirical literature on the relation between R&D and aggregate productivity, suggesting that this is enough to pick up most of the impact produced by the R&D expenditure.[8]

The underlying SVAR model can be represented as

$$B_0 X_t = \nu + \sum_{i=1}^{p} B_i X_{t-i} + \varepsilon_t, \quad (2)$$

where B_0 is the matrix of structural contemporaneous parameters, B_i is the matrix of the structural parameters associated with the *i*-th lag of the variables, and ε_t is the vector of mutually and serially uncorrelated structural shocks.

The dataset we use covers the period 1947Q1-2017Q3 and includes the following variables, all collected from the US Bureau of Economic Analysis (BEA) and deflated by the 2009-based GDP deflator:

- Government R&D investment (GI_t) is defined as the total government gross investment in research and development, at federal, state, and local levels, including both purchases and grants for R&D activities from the government;
- Government Residual spending (GR_t) is defined as the sum of government consumption and gross investment expenditure net of GI_t;
- Net Taxes (T_t) is the current tax receipts after subtracting transfers, interest payments, and subsidies;
- Private R&D investment (RD_t) refers to private firm fixed investment in research and development;
- Gross domestic product (Y_t) is the usual measure of aggregate economic activity.

3.1 Identification scheme

To identify our SVAR model we impose three mild theoretical assumptions on the contemporaneous correlation structure: (i) government decisions on R&D investment are independent of the level of economic activity in the current quarter, and fiscal policy decisions in general (so including GI_t, GR_t, and T_t) are subject to a decision lag, which means they cannot be used to counteract unexpected economic shocks in the quarter in which they take place; (ii)

[8] Antolin-Diaz and Surico (2022) study the long-run effects of government spending and public R&D by estimating a VAR with 60 lags using Bayesian shrinkage techniques on a dataset covering 125 years.

government decisions on R&D investments are allowed to influence all other government expenditures (included in GR_t), but not vice versa; (iii) tax decisions affect contemporaneous government spending decisions (both GR_t and GI_t), but not vice versa. Past values of all variables from the previous quarter up to one year and half earlier are allowed to affect freely the current value of each variable.

The first assumption is the argument developed by Blanchard and Perotti (2002), according to which it takes more than a quarter for policymakers to learn about the GDP level, vote a fiscal program, and implement it. As we discussed in Section 2, the class of government R&D spending has the extra feature of being independent from the economic conditions of the current quarter as they reflect long-term policy decisions, making their use as a countercyclical policy instrument unlikely. Taxes are, however, allowed to respond to GDP levels in the same period through the automatic response underlying the changes in the tax base as a consequence of changes in the level of economic activity. The second assumption reflects the fact that government spending in R&D activities are typically the outcome of a long-term plan addressing national priorities with dedicated funding allocated in advance or ring-fenced. The third assumption, stating that tax decisions affect government spending decisions in the same quarter but not vice versa, is very plausible for government R&D spending (as it is relatively small), but less so for the sum of all other government expenditures, GR_t.[9] For this reason, in the robustness analysis we will relax such assumption and assess the impact of reversing the direction of causality between government spending and taxes. From a statistical point of view, we do not expect the last two theoretical assumptions to be very restrictive, considering the strength and statistical significance of the correlation between the relevant reduced-form VAR residuals.[10]

As a consequence of the assumptions above, the baseline SVAR model is identified by means of a set of short-run exclusion restrictions on B_0, indicated by the following system

[9] Over the sample used in this study, GI_t amounts to an average of 9% relative to tax revenues, which means that such expenditure decisions have only negligible consequences for the public budget balance. GR_t, on the other hand, amounts to an average of 155% relative to tax revenues, which implies that we cannot exclude a contemporaneous impact of spending decisions on tax decisions.

[10] Correlation amounts to 0.008 with a p-value of 0.89 for (GI_t, GR_t); -0.094 with a p-value of 0.12 for (GI_t, T_t), and 0.038 with a p-value of 0.53 for (GR_t, T_t).

$$\begin{bmatrix} 1 & 0 & 0 & b_{14} & 0 \\ b_{21} & 1 & 0 & b_{24} & 0 \\ b_{31} & 0 & 1 & 0 & b_{35} \\ 0 & 0 & 0 & 1 & b_{45} \\ b_{51} & b_{52} & b_{53} & b_{54} & 1 \end{bmatrix} \begin{bmatrix} u_t^{GI} \\ u_t^{GR} \\ u_t^{RD} \\ u_t^{T} \\ u_t^{Y} \end{bmatrix} = \begin{bmatrix} \varepsilon_t^{GI} \\ \varepsilon_t^{GR} \\ \varepsilon_t^{RD} \\ \varepsilon_t^{T} \\ \varepsilon_t^{Y} \end{bmatrix}. \quad (3)$$

The first equation defines government R&D investment (GI_t), which depends contemporaneously on T_t (assumption iii), but not on RD_t and Y_t (assumption i) or GR_t (assumption ii). The second equation defines government residual spending (GR_t), which is influenced by GI_t (assumption ii), in addition to T_t (assumption iii), but not by RD_t or Y_t (assumption i). The third equation describes private R&D investment (RD_t), as a function of GI_t and Y_t, but not of GR_t and T_t. Here, we select the variables that are most likely to be influential for private R&D investment decisions, so we include current public decisions on R&D but not government's generic residual spending, and the current level of economic activity. About the inclusion of taxes, we have no strong opinion, but its estimated small coefficient and a likelihood ratio test suggest an exclusion restriction on T_t.[11] The fourth equation represents taxes (T_t) as a function only of Y_t. Here we follow Blanchard and Perotti (2002) and set b_{45}, the tax elasticity to GDP, equal to their externally determined value of –2.08. The fifth equation is left completely unrestricted expressing GDP (Y_t) as a function of the current value of all the other variables.[12]

In Section 2 we described the peculiar features that characterize the class of government spending related to R&D investments. The main implication of such a discussion is that ε_t^{GI} is likely to be fully anticipated or at least highly predictable by the private sector. This predictability of ε_t^{GI} generates a serious risk of non-fundamentalness for model (3). In this first stage of the analysis we ignore this problem for the time being, and we address it instead later in Section 7, when we will extend the model to explicitly capture the influence of private sector's expectations.

To ascertain the robustness of the estimated parameters and dynamic fiscal multipliers for both the model with and without expectations, we perform three sets of robustness checks.

[11] We implemented a Likelihood Ratio test based on the models with and without T_t being included in the RD_t equation. The value of the test statistic is 0.571 with a p-value of 0.45, which confirms our over-identifying restriction.

[12] It is useful to remind the reader that while we impose a set of exclusion restrictions on the within-quarter relations between variables, their dynamic relations beyond the quarter are left completely unrestricted.

i. We consider the alternative identification scheme where government spending affects same-period taxes, but not vice versa.

ii. We change the data sample by excluding the period following the 2008 financial crisis.

iii. We increase the lag length of the VAR to 8.

The first robustness check implies reversing the same-period causal relation between government spending and taxes, which is achieved by adding coefficients b_{41} and b_{42} in the fourth equation after dropping b_{14} and b_{24} in the first two equations, leading to the following set of alternative restrictions on B_0

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ b_{21} & 1 & 0 & 0 & 0 \\ b_{31} & 0 & 1 & 0 & b_{35} \\ b_{41} & b_{42} & 0 & 1 & b_{45} \\ b_{51} & b_{52} & b_{53} & b_{54} & 1 \end{bmatrix} \begin{bmatrix} u_t^{GI} \\ u_t^{GR} \\ u_t^{RD} \\ u_t^{T} \\ u_t^{Y} \end{bmatrix} = \begin{bmatrix} \varepsilon_t^{GI} \\ \varepsilon_t^{GR} \\ \varepsilon_t^{RD} \\ \varepsilon_t^{T} \\ \varepsilon_t^{Y} \end{bmatrix}. \quad (4)$$

We denote by *SVAR model A* the model represented in equation (3) and by *SVAR model B* the model represented in equation (4). While the first set of robustness checks is discussed along with the main results in the next section of the paper, the remaining two are reported in the Appendix.

3.2 Pure fiscal multipliers

In the presentation and discussion of our results, we will focus on the impulse response functions associated with all identified shocks, and the dynamic fiscal multipliers of GI_t and GR_t. The impulse response functions (IRFs) measure the response of a variable in dollars to an exogenous one dollar increase in another specific variable.[13]

The dynamic fiscal multiplier at horizon *h*, when positive, is defined as the average increase in Y_t (or RD_t) obtained from each dollar spent over a period of *h* quarters in a specific class of government spending, GI_t or GR_t. The common way to calculate such multipliers is to divide

[13] Confidence bands for the IRFs are calculated standardly, using the normal quantiles and a residual-based recursive-design bootstrap procedure to obtain the standard deviations. In all IRF graphs we report the 68% confidence band (calculated running 500 replications). This choice is common in many studies, such as Blanchard and Perotti (2002); Perotti (2004); Caldara and Kamps (2017). While we obviously loose in statistical confidence, 68% confidence bands tend to have a substantially higher coverage accuracy than those based on 95% (Sims and Zha 1999).

the cumulative IRF of Y_t to a unit increase in, say, ε_t^{GI} by the cumulative IRF of total government spending $GI_t + GR_t$ to the same shock, up to period h. This practice can be highly misleading if the interest lies in comparing the value of the multipliers for different classes of government spending, because they are in general dynamically correlated. This means that, also in the simulation performed at the core for the IRF calculation, other classes of government spending, beyond the one of interest, will increase and exert their impact on GDP. In this way, it becomes impossible to distinguish the individual contribution of each class of spending from the others. For this reason, we calculate the dynamic fiscal multipliers using a method similar to the one discussed in Perotti (2004), which we label as *pure multipliers* to distinguish them from the standard calculation just described.

More in detail, we still take the ratio between the cumulative IRF of Y_t to a unit increase in, say, ε_t^{GI} and the cumulative IRF of total government spending to the same shock, but this time we obtain these two quantities from a modified structural model where we switch off the dynamics of GR_t. This modified structural model consists in the original estimated SVAR, but with the difference that we restrict to zero all coefficients of the contemporaneous variables in the second row of the B_0 matrix, apart its own unit coefficient, as well as the coefficients of all lagged variables inside the GR_t equation of the SVAR. While this solution is potentially exposed to the Lucas Critique, as discussed in Perotti (2004), how much this is an actual problem is not clear, but most importantly for us this method provides a more useful tool to compare the multiplying effect on GDP of one average dollar spent in different classes of government spending. The information about the actual co-movement of GI_t and GR_t in response to their own shocks is already well-captured by the graph of their standardly calculated IRFs.

4. Results from the SVAR model

We now present the results from estimating our leading identification, the *SVAR model A*, and we also show how results change if we estimate the alternative identification, *SVAR model B*, where the contemporaneous causal relationship between government spending and taxes is reversed. Finally, in the Appendix, the robustness of both models is studied with respect to the historical time interval and the lag length. The general conclusion from this robustness analysis is that the results we obtain remain very stable, with only minor quantitative differences and no qualitative variation.

The IRFs from the *SVAR model A* to a one-unit shock are displayed in Figure 3. Both GI_t and GR_t display some persistence after their initial increase, with GI_t increasing more strongly in size, but with less statistical significance than GR_t. After one unit shock, GI_t peaks at 6.57 after two years, while GR_t peaks at 1.79 after one year in response to its own shock. Compared to the other government spending classes GR_t, the public R&D component GI_t leads to the deployment of a larger total amount of public resources over time. Indeed, the lagged cross effect of these two spending components is very strong, although asymmetric: a GI_t shock stimulates a considerable increase in GR_t, which peaks at 18.23 after three years, whereas a GR_t shock causes an increase in GI_t, which builds up over time, although of much smaller size, reaching 1.38 after six years.

When we examine the effects on the economy of R&D investments, we find that both public and private R&D spending exert a considerable stimulus on the GDP level at all horizons, and much stronger than the other classes of government spending. At t = 0 the impact on Y_t is 13.54 for GI_t, and 0.73 for GR_t. In both cases the effect remains strongly significant for many years, and with a hump shape that peaks at 20.87 after three quarters for GI_t, and at 1.05 after two quarters for GR_t. An RD_t shock produces a dynamic impact on Y_t that is similar in shape to that of GI_t, but relatively stronger, reaching 19.44 at t = 0, and peaking at 29.84 after three quarters. The impact of a GI_t shock on RD_t is strongly significant, as is the impact of an RD_t shock itself, although of lower magnitude. The impact of GI_t on RD_t is 0.58 at t = 0 and increases over time up to a peak of 17.1 after nine quarters.

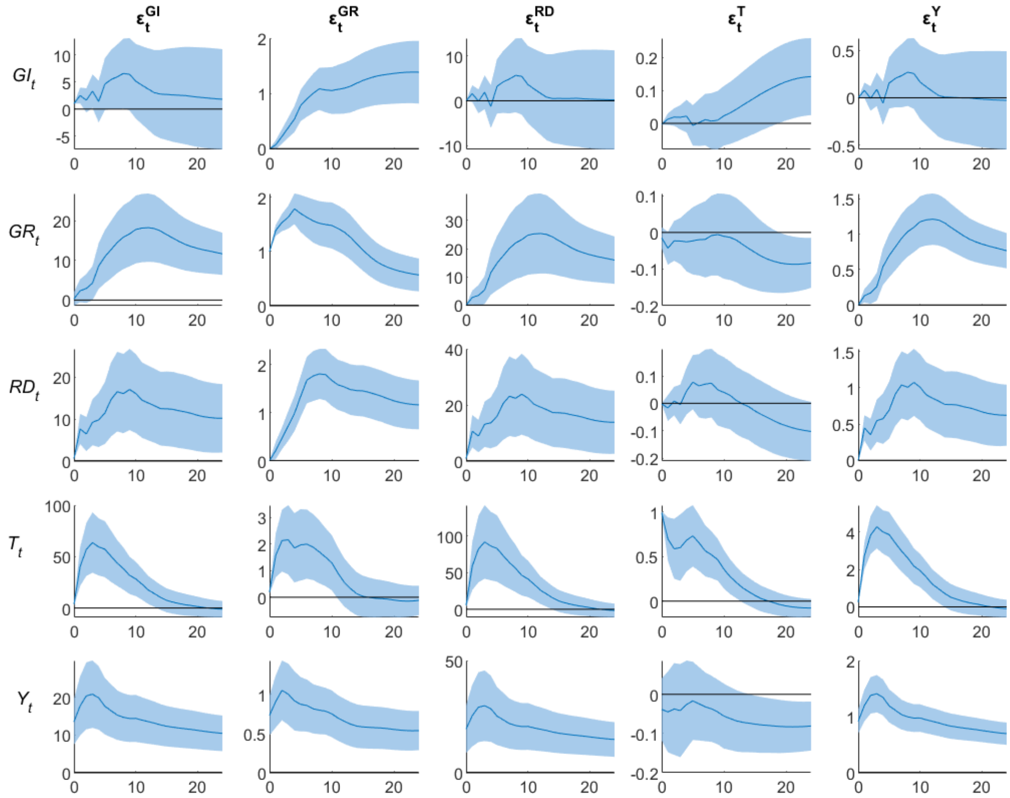

Figure 3. *IRFs to one unit shock from SVAR model A with 68% confidence band.*

When we estimate the *SVAR model B,* we obtain the IRFs displayed in Figure 4. From inspecting this set of graphs, we see that most responses remain virtually identical, and there is no noticeable difference with our main result (Figure 3), except for only minor changes in the magnitude of the effects of a GI_t shock.

Most notably, at t = 0 the impact of a GI_t shock on Y_t is now slightly lower, 10.02 (instead of 13.54), while that of a GR_t shock is also marginally lower, 0.70 (instead of 0.73). As before, for both spending classes, the effect on Y_t remains strongly significant for many years, and with a hump shape that peaks at 15.35 (instead of 20.87) after three quarters for GI_t and at 1.00 (instead of 1.05) after two quarters for GR_t. This outcome is clearly the result of a smaller overall increase in the size of the spending, given that in response to one unit shock GI_t peaks at 5.11 (instead of 6.57) after two years, with an accompanying GR_t that peaks at 13.23 (instead of 18.23) after three years.

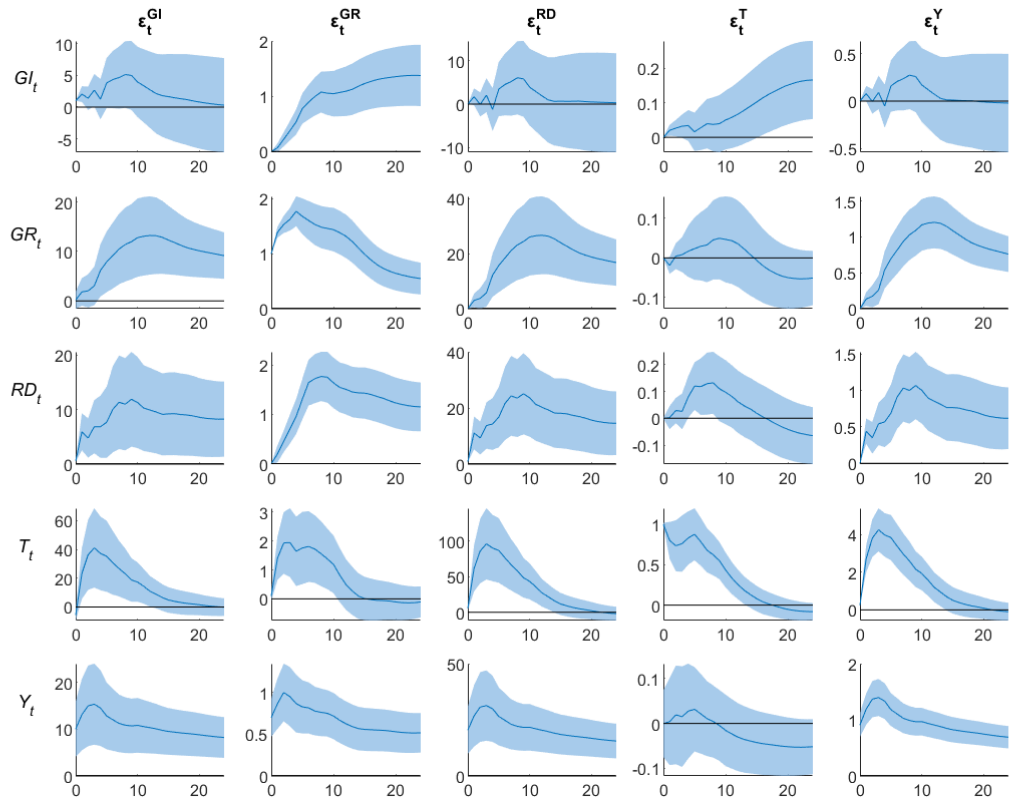

Figure 4. *IRFs to one unit shock from SVAR model B with 68% confidence band.*

The dynamic pure fiscal multipliers on GDP and private R&D investments are shown in Table 1 for intervals of one year and indicating the peak level. Considering our leading identification represented by *SVAR model A*, we see that both government spending classes have significant positive multipliers on GDP and private R&D investments across all time horizons. The striking difference, however, is the magnitude of such multipliers, with government R&D spending generating a rise in GDP that is considerably stronger than that produced by the other government spending classes.

SVAR model A		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y_t	**13.68**	**15.68**	**12.82**	**11.70**	**11.93**	**12.93**	**14.53**	**16.18 (3)**
	RD_t	**0.59**	**0.68**	**0.57**	**0.50**	**0.46**	**0.43**	**0.41**	**0.76 (2)**
GR_t	Y_t	**0.73**	**0.45**	**0.48**	**0.52**	**0.47**	**0.46**	**0.45**	**0.73 (1)**
	RD_t	0.00	**0.01**	**0.03**	**0.04**	**0.05**	**0.06**	**0.08**	**0.08 (24)**
SVAR model B		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y_t	**10.02**	**12.09**	**9.75**	**9.22**	**9.94**	**11.31**	**13.20**	**13.2 (24)**
	RD_t	**0.57**	**0.64**	**0.52**	**0.45**	**0.42**	**0.40**	**0.39**	**0.74 (2)**
GR_t	Y_t	**0.70**	**0.41**	**0.44**	**0.48**	**0.44**	**0.42**	**0.42**	**0.70 (1)**
	RD_t	0.00	**0.01**	**0.03**	**0.04**	**0.05**	**0.06**	**0.08**	**0.08 (24)**

Table 1. Dynamic pure fiscal multipliers from *SVAR model A* and *SVAR model B*. Significant values in bold, while peak indicates the maximum value with time horizon in parenthesis.

Within the quarter, one dollar spent in GI_t produces an increase in Y_t of 13.68 dollars, which goes up further, reaching a peak of 16.18 after three quarters and remaining at similar levels throughout a horizon of six years. The multiplier of GI_t on RD_t is 0.59 at t = 0, reaching the peak of 0.76 after two quarters and decreasing to 0.41 after six years. By contrast, one dollar spent in GR_t has a GDP multiplier of 0.73 at t = 0, also its peak value, and then stabilizes around 0.45, the value taken on after 6 years. The multiplier of GR_t on RD_t is equal to 0.01 after 1 year and reaches its peak of 0.08 after 6 years.

If we estimate the *SVAR model B*, the GDP and R&D multipliers retain similar values, only marginally smaller. Within the quarter, one dollar spent in GI_t produces an increase in Y_t of 10.02, which is maintained over time reaching a peak of 13.20 after six years. The multipliers of GI_t on RD_t are almost the same as those obtained from the *SVAR model A*. The multiplier of GR_t on Y_t is very close to one obtained from the *SVAR model A*, while the multiplier on RD_t is virtually identical.

5. Dealing with expectations: RE-SVAR model

The use of SVAR models to estimate fiscal multipliers has been criticized on the grounds that the information set implied by these models is likely to be smaller than the actual information set of private economic agents. This means that what appears to an econometrician as an unexpected change in a fiscal variable is, in fact, largely anticipated by the economy, with the consequence that estimated multipliers obtained from the fundamental representation of the VAR are biased (Forni and Gambetti 2014, Ramey 2011a, Mertens and Ravn 2012, Leeper et al. 2013). The main motivation for assuming this fiscal foresight is the presence of long legislative and operational lags, which means that it takes time for an announced fiscal decision of the government to be implemented. Nevertheless, it has also been noted that the potential distortions created by the problem of non-fundamentalness of the structural shocks might be small in practice, so a standard SVAR model may remain a satisfactory tool to obtain approximate impulse responses to the relevant structural shocks (Sims 2012, Beaudry and Portier 2014, Perotti 2011, 2014).

In our case, the very nature of the public R&D investment suggests that the anticipated component is likely to be important, because, as discussed in Section 2, this type of fiscal decision is often part of long-term government plans that are publicly announced well in advance. Moreover, there is a second reason that can potentially explain a flow of information towards the private sector about future government R&D actions, which is related to the existing established links between policy makers and private companies involved in R&D procurement contracts or co-investment projects.

Augmenting our SVAR model with an external measure of the private sector's expectations is not a feasible route, since a variable that measures expectations about future government R&D spending is difficult to find. Hence, we deal with the likely problem of non-fundamentalness by extending our original SVAR model into a *Rational Expectations SVAR* (RE-SVAR) model, which includes a forward-looking variable that explicitly captures private expectations about GI_{t+1}. We assume that these expectations are formed according to the Rational Expectations Hypothesis and that the information set of the private agents at time *t* includes the next period's shock in government innovation spending, ε_{t+1}^{GI}. Solving the non-fundamentalness problem by means of a non-causal VAR with Rational Expectations is a strategy also adopted by Blanchard and Perotti (2002), although they apply it to total government spending and taxes. In the case of government R&D investments, not only is it difficult to find external measures of private expectations, but the Rational Expectations Hypothesis with perfect foresight of the future shock also fits very well with the very characteristics of this type of government spending, as we have discussed in Section 2.

Since the anticipation argument is strong in the case of public R&D investments, but is less convincing in the case of the other classes of government spending, we assume that the perfect foresight involves GI_t but not GR_t, so shocks to residual government spending are considered unanticipated. By comparing the results from our RE-SVAR model with those from the standard SVAR model described in Section 3, we will also be able to say something about the ex-post empirical relevance of the role of fiscal foresight for government R&D spending.

Our RE-SVAR model can be represented as

$$B_0 X_t = \nu + F_1 E[X_{t+1}|\Omega_t] + \sum_{i=1}^{p} B_i X_{t-i} + \varepsilon_t, \qquad (5)$$

where B_0 is the matrix of structural contemporaneous parameters, B_i is the matrix of the structural parameters associated with the *i*-th lag of the variables, F_1 is the matrix of structural parameters associated with the forward-looking expectational variables at time $t+1$, $E[\cdot]$ is the expected value, Ω_t is the information set at time *t*, and ε_t is the vector of mutually and serially uncorrelated structural shocks. The lag length *p* is set to six as in the SVAR model.

For B_0 we use the same two alternative structures used in the SVAR model. The resulting model is labelled as *RE-SVAR model A* when we use the leading identification defined in equation (3), whereas it is labelled as *RE-SVAR model B* when we use the alternative identification of equation (4). The structure of the F_1 matrix is defined as

$$F_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ f_{31} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ f_{51} & 0 & 0 & 0 & 0 \end{bmatrix}, \qquad (6)$$

which reflects the fact that the expectation of the next period's government R&D investment $E[G_{t+1}|\Omega_t]$ enters the equation of the current private R&D investment (RD_t) and that of the current GDP (Y_t), while the current information set is defined as $\Omega_t = \{\varepsilon_{t+1}^{GI}, \varepsilon_t \;, \varepsilon_{t-1}, \ldots, X_t \;, X_{t-1}, \ldots\}$. The introduction of a forward-looking variable in our system implies that we need additional restrictions to ensure model identification. Indeed, now in the

GI_t equation, Y_{t-1} and RD_{t-1} are endogenous as a result of perfect foresight of ε_t^{GI}. At the same time, in the Y_t equation the component $E[GI_{t+1}|\Omega_t]$ is endogenous as a result of Y_t Granger-causing GI_t.

Identification is obtained by assuming that government R&D investments do not respond to the GDP (and private R&D) of the previous quarter in addition to not responding to GDP in the current quarter. The lack of response of GI_t to Y_{t-1} and RD_{t-1} is justified by the same argument that government R&D investment reflects highly autonomous policy decisions that are not related to short-run macroeconomic stabilization objectives, which means that GDP from the previous quarter is irrelevant to same extent current GDP is. The restriction used by Blanchard and Perotti (2002) is similar to ours in cutting the reverse causality from past GDP to future fiscal policy, but is different in that they apply it to a model that describes total government spending. This also explains their different theoretical justification, which can be considered less convincing than ours since it relies on the existence of a general decision lag for the policy makers that prevents them from acting in response to GDP before two quarters have elapsed.[14]

The estimation results allow us to produce IRFs and fiscal multipliers, distinguishing the two components of the effect of government R&D investments: the impact of the news (or announcement) anticipating by one period the exogenous government spending ε_{t+1}^{GI} and the impact of its actual occurrence. The sum of these two components gives us the dynamic response of the economy to an *anticipated shock* in GI_t. We use our model also to perform a counterfactual simulation where we assume that the shock to GI_t comes as a surprise and analyze the corresponding effects on the economy. To do that we modify our RE-SVAR model by removing ε_{t+1}^{GI} from the information set Ω_t, which is equivalent to considering only the impact of the actual shock occurrence (the second component) in the scenario where it is anticipated. In this way we are able to show the IRF to an *unanticipated shock* in GI_t. Strictly speaking, this simulation remains exposed to the Lucas Critique, because our model is estimated under the assumption that all historical spending events were fully anticipated by the private sector, and changing this assumption amounts to a modification of a structural feature of the economy with perhaps unpredictable consequences. However, such exercise can still be

[14] Estimation of the RE-SVAR model (5) is performed via maximum likelihood after the model is solved using the method of Sims (2002) and Lubik and Schorfeide (2003) and cast in state-space form. Confidence bands for the IRFs are calculated as for the SVAR model, using the normal quantiles and a residual-based recursive-design bootstrap procedure (with 500 replications) to obtain the standard deviations.

useful in offering an indication of what the effects on the economy would look like if private agents did not have the ability to anticipate future government R&D spending.

6. Results from the RE-SVAR model

We now present the results from estimating our leading identification, the *RE-SVAR model A*, and we also show how results change if we estimate the alternative identification, the *RE-SVAR model B*, where the contemporaneous causal relationship between government spending and taxes is reversed. We examine the robustness of our results to the sample period and the lag length of the VAR (both reported in the Appendix).[15]

The IRFs from the *RE-SVAR model A* to a one-unit shock are displayed in Figure 5. It is important to stress that all shocks are unanticipated except for ε_t^{GI}, which is instead fully anticipated one period in advance. This implies that the IRF for ε_t^{GI} starts at $t = 0$ with the news about an incoming increase in GI_t occurring at $t = 1$.

Both GI_t and GR_t display persistence after their own positive shock, although that of GI_t is much higher given that the variable remains above 2 dollars after six years, whereas GR_t is back to its pre-shock level after four years, as indicated by the time the lower confidence bound crosses the x-axis. The peak response to its own shock is 2.52 after eleven quarters for GI_t and 1.79 after one year for GR_t. Compared to GR_t, an exogenous increase in GI_t leads to the deployment of a larger total amount of public resources over time. Indeed, the lagged cross effect of these two spending components is very strong, although asymmetric: a GI_t shock is accompanied by a considerable and persistent increase in GR_t that peaks at 12.5 after two years, whereas a GR_t shock causes an increase in GI_t that builds up over time, although of much smaller size reaching 0.10 after six years. Compared to the *SVAR model A*, the increase in GI_t is smaller but statistically much more significant while that of GR_t is similar and less uncertain.

[15] The general conclusion from this robustness analysis is that there are some numerical variations in the exact size of the effects, although shape, timing, and order of magnitude of the impact of GI_t and GR_t on Y_t and RD_t remain fairly stable. In particular, the finding of a considerably stronger impact of GI_t relative to GR_t is confirmed across all estimations, while the reinforcing effect of private agents' anticipation of GI_t is a feature that persists in all but one case. We will highlight the main findings from this robustness analysis in the final Section 7.

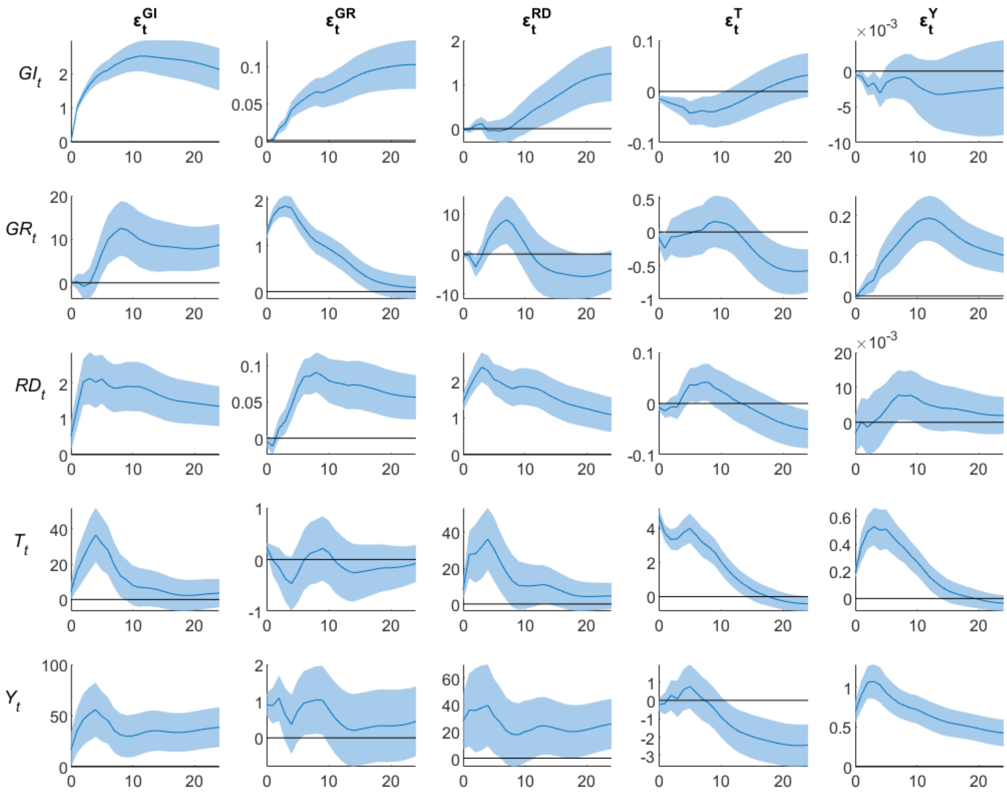

Figure 5. *IRFs to one unit shock from RE-SVAR model A with 68% confidence band.*

The superiority of government R&D spending in stimulating GDP is confirmed, and the impact is now much stronger than we found in the SVAR model. Indeed, at t = 0 the impact on Y_t is 16.48 for a GI_t shock, and 0.91 for a GR_t shock. The effect of a GI_t shock on GDP is strongly significant at all horizons building up over time until the peak of 55.75 after one year, while the effect of a GR_t shock loses size and statistical significance after ten quarters. A positive shock to RD_t produces a dynamic impact on Y_t that is similar in shape to that of a GI_t shock, but, overall, it is weaker and more uncertain in size. Indeed, the response of Y_t to an RD_t shock is greater at t = 0, when it reaches 27.65, but peaks at only 39.62 after one year and it remains lower than in the case of a GI_t shock throughout the rest of the six-year period.

The impact of a GI_t shock on RD_t is very similar in shape to that of an RD_t shock, so very persistent and statistically significant, though somewhat smaller in size. At t = 0 the response of RD_t is 0.57 for a GI_t shock and 1.43 for an RD_t shock. In both cases the impact builds up over time until quarter three when it reaches 2.13 in the first case and 2.38 in the second, before starting a slow decay.

These results demonstrate that even though the SVAR model disregards the role of private sector expectations, it can deliver an overall satisfactory qualitative picture of the impact on the economy of government R&D investments. On the other hand, the marked quantitative differences between the SVAR and RE-SVAR models reveal that only an explicit consideration of private agents' expectations about future government R&D investments can produce an accurate assessment of the magnitude and timing of these effects. This is confirmed by the estimates for the F_1 matrix in equation (6). In the RD_t equation, the coefficient f_{31} on $E[G_{t+1}|\Omega_t]$ is equal to 0.58 with a p-value of 0.035, while in the Y_t equation, the coefficient f_{51} on $E[G_{t+1}|\Omega_t]$ is 7.56 with a p-value of 0.55. So, government's decision to perform R&D investments has a considerable impact on the economy via its influence on private sector expectations.

We plot in Figure 6 the IRFs to a unit GI_t shock occurring at t = 1, in the case it was fully anticipated (as we assume) at t = 0, and in the hypothetical case it was unanticipated. The apparent difference between the two sets of plots is the additional stimulus produced by the news component. In particular, we notice how at t = 0 there is an increase in private R&D spending by 0.52 in response to the news of a future rise in government R&D investments in t = 1. This extra stimulus explains why the overall increase in private R&D across time is almost double the one produced in the absence of the news component. The role of expectations is even more evident for GDP. At t = 0 the expectations impact on GDP is 16.48, which is greater than 13.75, the impact of an unanticipated shock at t = 1. The peak effect on GDP is 55.75 taking into account the role of expectations, while it would be only 31.64 without such component.

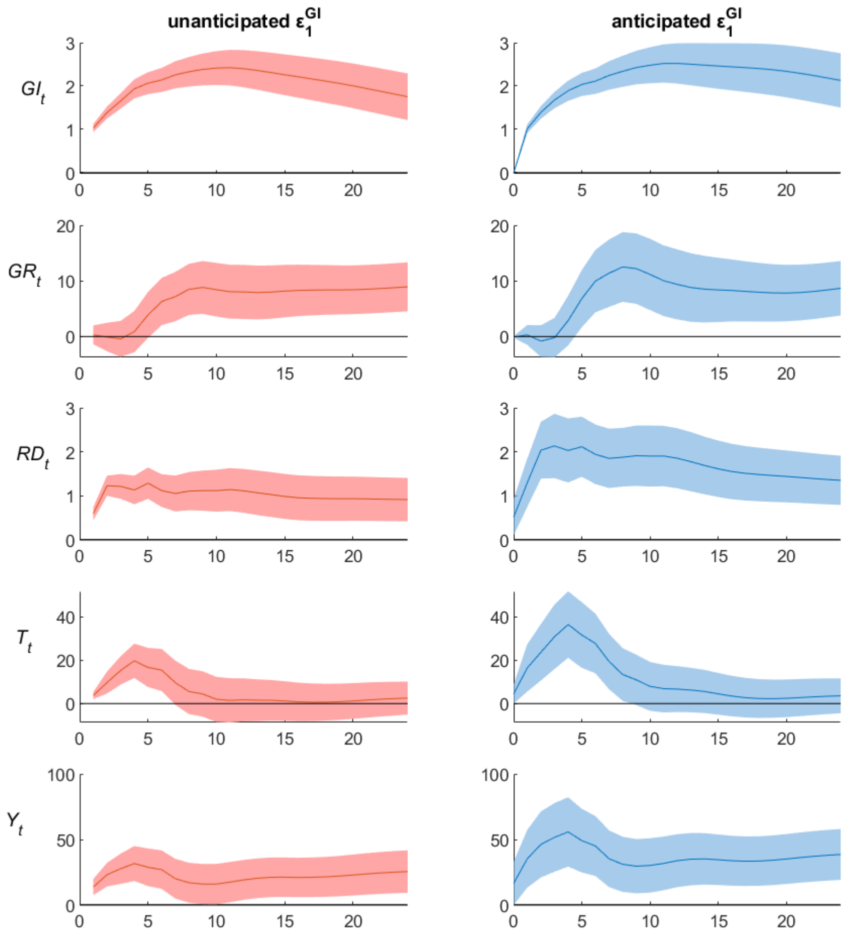

Figure 6. *IRFs to one unit shock from RE-SVAR model A, with 68% confidence band.*

When we reverse the contemporaneous direction of causality between government spending and taxes and we adopt the *RE-SVAR model B*, we obtain the IRFs displayed in Figure 7. The shape and timing of the dynamic effects remain unchanged compared to the *RE-SVAR model A*. Also, the dynamic interaction between GI_t and GR_t is unaltered. The only noticeable change concerns the relative strength of public versus private R&D stimulus, which is now higher for the latter. The impact of a GI_t shock on Y_t is 9.63 (instead of 16.48) at t = 0, and reaches a peak of 40.36 (instead of 55.75) after one year. The impact of an RD_t shock on Y_t is 35.59 (instead of 27.65) at t = 0, with a peak of 51.54 (instead 39.62) after one year. Finally, while the impact on RD_t of its own shock remains basically unchanged, the impact of a GI_t shock on RD_t is half the one obtained from the *RE-SVAR model A*, with a peak of 0.91 (instead of 2.13).

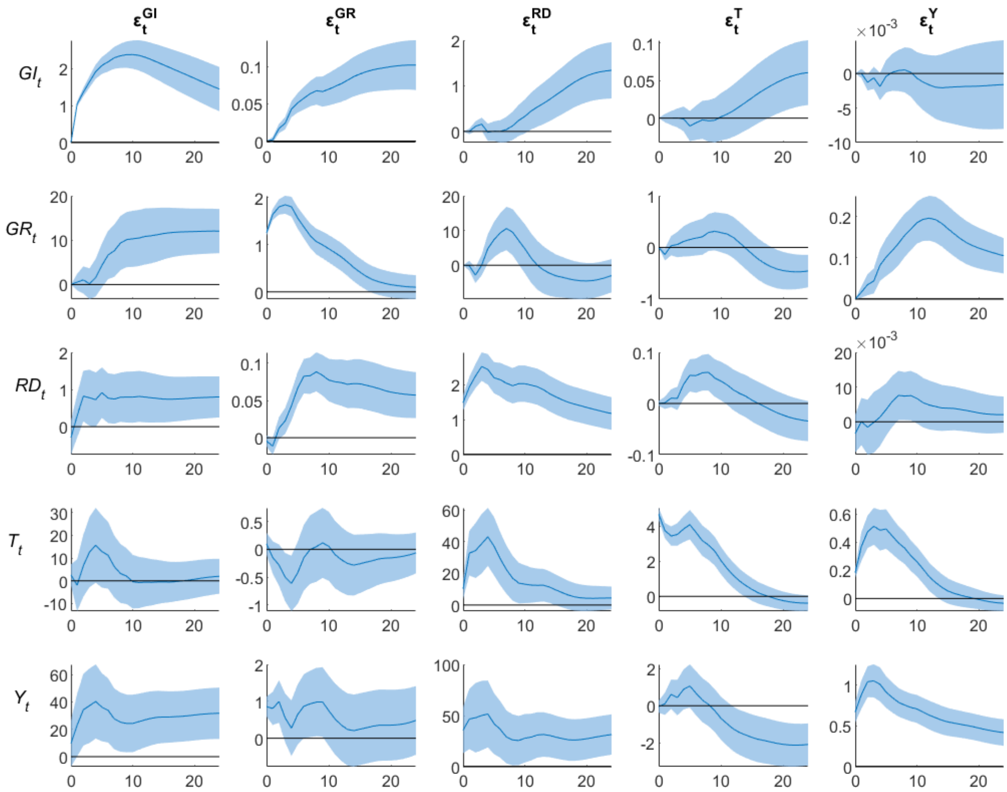

Figure 7. *IRFs to one unit shock from RE-SVAR model B, with 68% confidence band.*

The dynamic pure fiscal multipliers on GDP and private R&D investments are shown in Table 2 for intervals of 1 year and at the peak level. We calculate the multiplier of government R&D investments when the shock is anticipated (GI_t) and when it is not anticipated ($GI_t^{(s)}$). To facilitate comparisons, we assume that the actual spending occurs at t = 0, with the difference that in the first case the news about this shock has already produced some effects one period earlier, at t = – 1.

Under the *RE-SVAR model A*, the multipliers of government R&D investment on GDP are much larger when the shock is anticipated. The same multipliers in the case of no anticipation are very similar to the those obtained from the *SVAR model A*. The multipliers of government residual spending retain approximately the size we obtained from the *SVAR model A*, although this time statistical significance drops at longer horizons.

RE-SVAR model A		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y_t	**51.59**	**31.73**	**24.69**	**21.86**	**21.23**	**21.80**	**23.35**	**51.59 (0)**
	RD_t	**1.81**	**1.27**	**1.04**	**0.91**	**0.82**	**0.77**	**0.75**	**1.81 (0)**
$GI_t^{(s)}$	Y_t	**13.14**	**15.35**	**12.58**	**11.49**	**11.75**	**12.76**	**14.38**	**15.84 (3)**
	RD_t	**0.58**	**0.68**	**0.57**	**0.50**	**0.46**	**0.43**	**0.41**	**0.76 (1)**
GR_t	Y_t	**0.73**	0.44	**0.47**	0.51	0.46	0.45	0.44	**0.73 (1)**
	RD_t	-0.00	**0.01**	**0.03**	**0.04**	**0.05**	**0.06**	**0.08**	**0.08 (24)**
RE-SVAR model B		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y_t	**31.19**	**22.57**	**17.88**	**16.73**	**17.55**	**19.61**	**22.83**	**31.19 (0)**
	RD_t	-0.00	**0.40**	**0.35**	**0.31**	**0.27**	**0.24**	**0.22**	**0.40 (4)**
$GI_t^{(s)}$	Y_t	**9.73**	**11.85**	9.56	**9.06**	**9.79**	**11.17**	**13.06**	**13.06 (24)**
	RD_t	**0.56**	**0.63**	**0.51**	**0.44**	**0.41**	**0.39**	**0.39**	**0.73 (1)**
GR_t	Y_t	**0.68**	0.39	**0.42**	0.46	0.41	0.40	0.40	**0.68 (0)**
	RD_t	-0.00	**0.01**	**0.03**	**0.04**	**0.05**	**0.06**	**0.08**	**0.08 (24)**

Table 2. Dynamic pure fiscal multipliers from *RE-SVAR model A* and *RE-SVAR model B*. Significant values in bold, while peak indicates the maximum value with time horizon in parenthesis.

Within the first quarter, one dollar spent in GI_t produces its maximum impact, an increase in Y_t of almost 52 dollars, decreasing to around 22 after three years, and remaining around such level until the end of the six-year period. The multiplier of GI_t on RD_t is also highest at t = 0, when it reaches a value of 1.81. By contrast, one dollar spent in GR_t produces an increase in Y_t of 0.73 at t = 0, which is also its peak value, and then it stabilizes after one year at around 0.44.

The fact that the multiplier of $GI_t^{(s)}$ on Y_t and RD_t stays rather stable over time, while that of GI_t halves as time passes can be explained by the declining impact of the expectations component. This can also be seen from Figure 6, where it is possible to calculate that the approximate distance between the IRFs of Y_t to the anticipated and unanticipated shock is equal to 21 at t = 1, reaches its maximum level of 24 at t = 4, and then declines to 13 from t = 9 onwards.

If we adopt the alternative identification and consider the *RE-SVAR model B*, the multipliers on GDP become smaller at short horizons, but retain a very similar size at longer horizons. Within the quarter, one dollar spent in GI_t produces an increase in Y_t of 31.31 (instead of 51.59), but after six years the increase is 22.83 (so very close to 23.35). The multiplier of GI_t on RD_t is much smaller than the value obtained from the *RE-SVAR model A*, although still significant, and it is also smaller than that of $GI_t^{(s)}$, which implies a negative effect of expectations on private R&D spending. The multiplier of GR_t on Y_t is very close to the value obtained from the *RE-SVAR model A*, while that on RD_t is virtually identical.

7. Discussion

We can draw some general conclusions from the results of the previous section and provide an economic interpretation of the main findings. We give prominence to the results we obtained from our leading estimation, the *RE-SVAR model A*, estimated with six lags on the whole sample, but we will also underline which features are common across our sensitivity analysis. We focus on five aspects of the estimation outcome: the total amount of public resources being deployed, the impact on GDP, the impact on private R&D, the specific influence of expectations, and the comparison between the returns to public and private R&D investments.

Total deployment of public resources

As for the deployment of public resources, we notice that government R&D spending is much more persistent than generic government spending, a result confirmed across all alternative RE-SVAR estimations. After an exogenous one dollar increase, GI_t remains above 2 dollars after six years, whereas GR_t is back to its pre-shock level after four years. This time pattern confirms the knowledge that R&D investments are characterized by long-term commitments that necessitates prolonged funding. Also private R&D investment is persistent, although to a lower degree, perhaps reflecting the lack of that continuity which is typical of mission-oriented plans often guiding public R&D investments. Moreover, a typical government R&D spending decision appears to mobilize a much larger amount of total public resources than a typical generic government spending decision.[16] A unit GI_t shock is accompanied after one year by a

[16] Mowery (2012) points to the fact that defense R&D programs are often accompanied by additional large-scale procurements that expand the economic and technological impact of the R&D investment, and this is the result of the fact that the same government agencies financing the R&D projects are also the final users of the R&D output.

permanent increase in GR_t, which at its peak is five times the increase following a unit GR_t shock, which instead is temporary. As a consequence, over the six years that follow the one dollar increase, the cumulative total government spending ($GI_t + GR_t$) is 220 dollars in the case of an R&D investment, whereas it is just 22 dollars after a generic spending increase. Such a conclusion is robust across all RE-SVAR and SVAR estimations.

Effects on GDP

With regard to the impact on GDP, we found that government R&D spending produces a permanent increase, a robust finding across all RE-SVAR and SVAR estimations, while government generic spending produces a temporary rise, a robust outcome across all but one RE-SVAR estimation. In our leading estimation, government R&D effects on GDP build up during the first year reaching a peak of 56 dollars, then it declines a little stabilizing at around 38 dollars. The fiscal multiplier on GDP reaches its maximum of 52 dollars in the same quarter the spending rise is implemented (so one quarter after its anticipation), and then declines to 24 dollars after six years. The exact value of the multipliers changes across the alternative RE-SVAR estimations, but their time pattern and order of magnitude remain the same.

While we cannot empirically identify the precise underlying microeconomic mechanisms behind the increase in output at different time intervals, we can say something about which factors are likely to prevail at shorter and longer time horizons, and we are able to say something more explicit about the contribution of private sector anticipation of the public spending rise. Overall, the impact on economic activity of government R&D spending displays a plausible shape that is in line with what we would expect is the time profile of R&D investments.

There is very little previous evidence about fiscal multipliers of R&D spending at business cycle frequency. One exception is Deleidi and Mazzucato (2021), who estimate a recursively identified SVAR model where defense R&D spending is ordered first. They also find that the GDP multiplier is highest in the first quarter, reaching a value of 24 dollars.

Our very large multiplier at short horizon can be explained first by the role of expectations that we explicitly capture in the RE-SVAR model. In our leading estimation, at t = 0 the news about the forthcoming GI_t spending rise triggers an increase in Y_t of 16.48, while GI_t not only has yet to increase, but it even falls slightly as a result of the negative effect of rising taxes. So, the very high value of the fiscal multiplier is in part the result of an economic expansion that takes place earlier without an actual increase in spending, along with the fact that the fiscal foresight covers the whole amount of future government spending.[17]

Nevertheless, even setting aside the anticipation effect, the GDP multiplier of government R&D spending remains very large at short horizon, amounting to 13 dollars in the quarter the spending shock occurs. There are at least three factors that can explain such extensive stimulus on the aggregate economic activity. The first factor is the reduction in production costs that typically results from process innovation and that can easily materialize without long delays from the beginning of the R&D investment. The second factor is a likely intensification of the investment process at the very early stage of a research project as a consequence of pecuniary and non-pecuniary spillovers that trigger the entry of new firms into the market. There is a strong incentive for private co-investors to outrun competitors by undertaking the investment opportunity at a very early stage of the enterprise. As time passes, some of these firms will exit the market, and many initial research projects will end because they turn out to be unsuccessful. The third factor is the idea that innovation can be embodied in new physical capital, which means that R&D expenditure is accompanied by investment in new capital that incorporates the new inventions, reinforcing the overall stimulus on GDP.

Over the longer horizon, the GDP multiplier is more likely to reflect the final impact of R&D on the supply side in terms of aggregate productivity gains enhanced by knowledge spillovers across firms and sectors. The estimated long-run GDP multiplier is smaller than in the short-run, although its size remains large for both public and private R&D spending. One year after the anticipated GI_t shock occurs, the multiplier in elasticity is 0.34, before stabilizing around a value between 0.23 (after three years) and 0.25 (after six years). In the case of an RD_t shock, the multiplier is 0.18 after one year, before stabilizing around a value between 0.15 (after three years) and 0.16 (after six years).

[17] At t = 1 the actual implementation of the GI_t rise causes an expansion of 0.60 in RD_t, and of 13.75 in Y_t. The cumulative IRF of Y_t at t = 1 is then 16.48 + 35.33 = 51.81, while the cumulative IRF of GI_t is – 0.011 – 0.016 + 1.03 = 1.003. Hence, in the quarter of the actual spending implementation the GDP multiplier of GI_t is 51.85/1.003 = 51.65. The value is slightly different from the one in Table 2 since there we calculate pure fiscal multipliers. At t = 1, when the actual increase in GI_t takes place, the anticipation effect is responsible for an extra 21-dollar increase in Y_t. This expectations effect reaches the maximum after one year, when it is equal to 24 dollars, and then declines to 13 after approximately two years. The GDP multiplier of government R&D spending in the period of the actual spending is 13 in the hypothetical scenario in which there is no anticipation of the shock, and it is 52 once we correctly account for the anticipation effect one quarter in advance.

These values are very close to existing evidence from the literature that studies the returns to R&D.[18] Jones and Summers (2020) highlight the importance of using an aggregate measure of production, such as GDP, if we want to include the net effect of a large set of spillovers involved in the innovation process when estimating the social returns to R&D. Calculating the ratio between the present value of the permanent increase in productivity and the R&D investment that generates such increase, they conclude that the effect on GDP for each dollar spent in innovation can easily reach a value of 20.[19]

Private R&D and crowding-in

The impact of private R&D investments on GDP is also permanent in our leading estimation, but, contrary to its public counterpart, this feature is not confirmed in our robustness analysis. In terms of size, in our leading estimation the impact on GDP of private R&D spending is somewhat smaller than its public counterpart, reaching a peak of 40 dollars after one year and stabilizing at around 24 dollars after six years. As we mentioned earlier, this weaker stimulus generated by privately funded R&D relative to publicly funded ones is also evident in terms of multipliers, but it is not confirmed across our sensitivity analysis.

A set of potential factors can explain why we obtain a stronger stimulus for the public rather than the private R&D investment, and relates to the points discussed in Section 2. One is the breadth of the goals that typically motivates the public investment programs, which simultaneously involves a wider set of industries. A second aspect is the fact that public investment programs tend to be planned over a longer timeframe, which helps to reduce long-run uncertainty and encourage private investment. The importance of stabilizing private agents forward-looking expectations is highlighted by the significant effect we obtain from the anticipation of the policy shock. Third, entry requirements and transparency in the public funding procedure may convey a signal about the quality of research projects fueling private investors' anticipation of profitable investment opportunities. Finally, whenever the

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[18] We express our multipliers in elasticity knowing that the average GI_t/Y_t is 0.011 and the average RD_t/Y_t is 0.012. If we focus on the existing evidence at country level for G7 economies, we find, for instance: Coe and Helpman (1995), who obtain 0.22; Kao et al. (1999) who estimate a value of 0.20; Keller (1998) who gets 0.13; and Coe et al. (2009) who confirms the size obtained in Coe and Helpman (1995) using an updated sample. Such magnitude for output elasticity is not unusual, including for more microeconomic studies: Ornaghi (2006), for instance, obtains 0.24 for Spanish firms once he includes spillover effects. Bartelsman (1990) finds a value of 0.18 for industry-level data for the US. Most existing evidence suggests a stronger impact of private compared to public R&D spending, but conclusions are mixed if we consider more recent studies attempting to capture the social rate of returns to public R&D. Our relative results are consistent with Guellec and van Pottelsberghe (2004), who find an elasticity of 0.13 for private spending and 0.17 for the public one.

[19] Antolin-Diaz and Surico (2022) find a long-run GDP multiplier of defense spending equal to 2.08 using a recursively identified SVAR model where defense spending news is ordered first.

government agency is also the user as well as the funder of the project, the knowledge transfer that leads to the actual productivity gains is quicker, to which we add the fact that the core R&D investment is typically accompanied and supported by large-scale complementary government activities (Mowery 2012), which is confirmed by our estimation results.

When we look at the interaction between public and private R&D investments, we see strong evidence of a crowding-in effect. Indeed, the response of private R&D is a permanent increase in both the case of private and public initial stimulus, a finding confirmed across all RE-SVAR estimations. In our leading estimation, one quarter after the news, the multiplier of public R&D with respect to private R&D reaches its maximum value of 1.81, before falling after six years to 0.75, which translates into an elasticity of 0.72. This is not far from the value of 0.52 obtained by Moretti et al. (2021) using a production function approach for defense-related R&D activities conducted by OECD private businesses.[20]

This crowding-in effect offers empirical support for typical mechanisms believed to be triggered by government intervention: many private research projects become profitable once public funding covers a substantial part of the R&D fixed costs, such as laboratories and human capital building; public funding removes the obstacle represented by credit constraints; anticipated technological spillovers encourage private innovators to invest; the government funding decision conveys a signal about long-run profitability; and the partnership between public and private sector allows the asymmetric information problems, and the high riskiness that typically holds back private enterprise in R&D projects, to be overcome.

Final remarks

All these points taken together offer three important indications to policy makers interested in understanding the short-run and long-run macroeconomic implications of public R&D investments. First, we do not explicitly analyze the effects on knowledge creation, but it is clear from the very strong impact we find on aggregate output and aggregate innovation activities at long horizons that public R&D can be a highly effective policy instrument to stimulate the overall technological innovation efforts of a country. Second, we confirm that fiscal multipliers are class-specific, and in particular we discover that the public R&D spending possesses expansionary effects that outperform those of many other classes of public spending. The

[20] Deleidi and Mazzucato (2021) obtain a multiplier in dollars of public to private R&D of 0.74 in the first quarter and 0.65 after 6 years. Jaffe (1989) finds an elasticity of industry R&D to academic research equal to 0.70, but without distinguishing public from private funding.

absence of crowding-out and the very large short-run multipliers of public R&D confirm the idea that there is substantial unutilized production capacity due to market failures that prevent an efficient level of R&D investment. Hence, our results show that public R&D can be very effective also in expanding the short-run aggregate economic activity. Third, our finding that there is a strong positive anticipation effect highlights that studies that ignore such component risk under-estimating the actual impact of government R&D investments. The presence of this anticipation channel reinforcing the effects of R&D spending reminds us of the importance of policy announcements and their credibility as a device to stabilize private agents' expectations. In the context of R&D investments we expect that facilitating such anticipation by the private sector can reduce the inherent uncertainty surrounding such type of investment, and thus create the necessary conditions for the involvement of private investors and innovators. The ability to shape expectations distinguishes public from private R&D investment, and relates to the government's distinct capacity to mobilize the required large-scale funding and to its credibility in terms of stable long-run commitment.

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Appendix

Robustness analysis of SVAR: sample period

In this section we explore how results from the SVAR model change if we modify the sample period covered by the data. We estimate *SVAR model A* and *SVAR model B*, with 6 lags and using data that this time covers the period 1947Q1-2007Q4, so dropping the last part that begins with the 2008 financial crisis. All results are presented in comparison with those obtained from the leading estimation, that is the *SVAR model A* estimated on the full sample period.

The overall conclusion of this analysis is that, apart from minor quantitative variations and a reduced persistence of GI_t, the impact of a GI_t shock on Y_t and RD_t remains of similar magnitude, strongly significant on Y_t and somewhat less significant on RD_t.

The IRFs to one unit shock for *SVAR model A* are displayed in Figure A1.

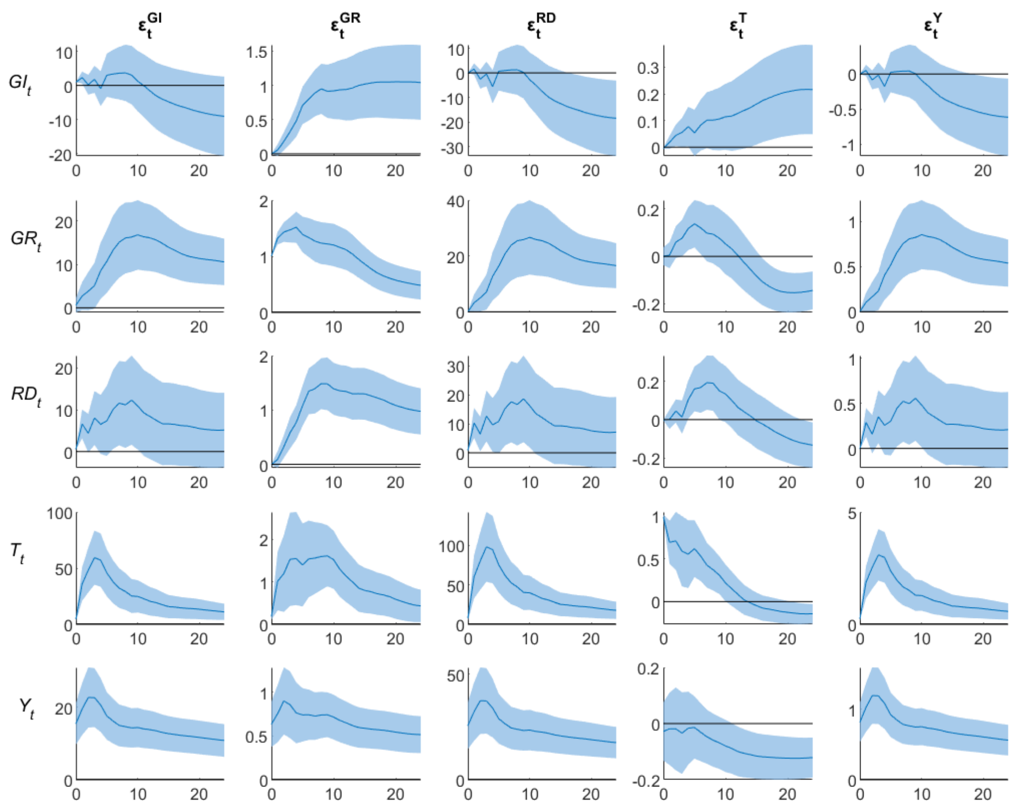

Figure A1. *IRFs to one unit shock from SVAR model A estimated on a subperiod with 68% confidence band.*

In response to its own shock GR_t keeps the same persistence and similar magnitude, peaking a 1.52 after one year, whereas GI_t is not followed by significant increases after its own shock, contrary to the leading estimation. As before, there is an important cross effect between the two spendings.

The impact of a GI_t shock on Y_t at t = 0 is 15.5 (instead of 13.54), while that of a GR_t shock is 0.63 (instead of 0.73). In both cases the effect on Y_t remains strongly significant for many years, and with a hump shape that peaks at 22.77 (instead of 20.87) after two quarters for a GI_t shock and at 0.90 (instead of 1.05) after two quarters for a GR_t shock.

The impact on RD_t of a GI_t shock is somewhat smaller than that of an RD_t shock, as in the leading estimation, but this time both impacts are smaller and less significant. The impact of a GI_t shock at t = 0 is indeed 0.54 (instead of 0.58), increasing over time up to a peak of 12.32 (instead of 17.1) after nine quarters.

The IRFs to one unit shock for *SVAR model B* are displayed in Figure A2.

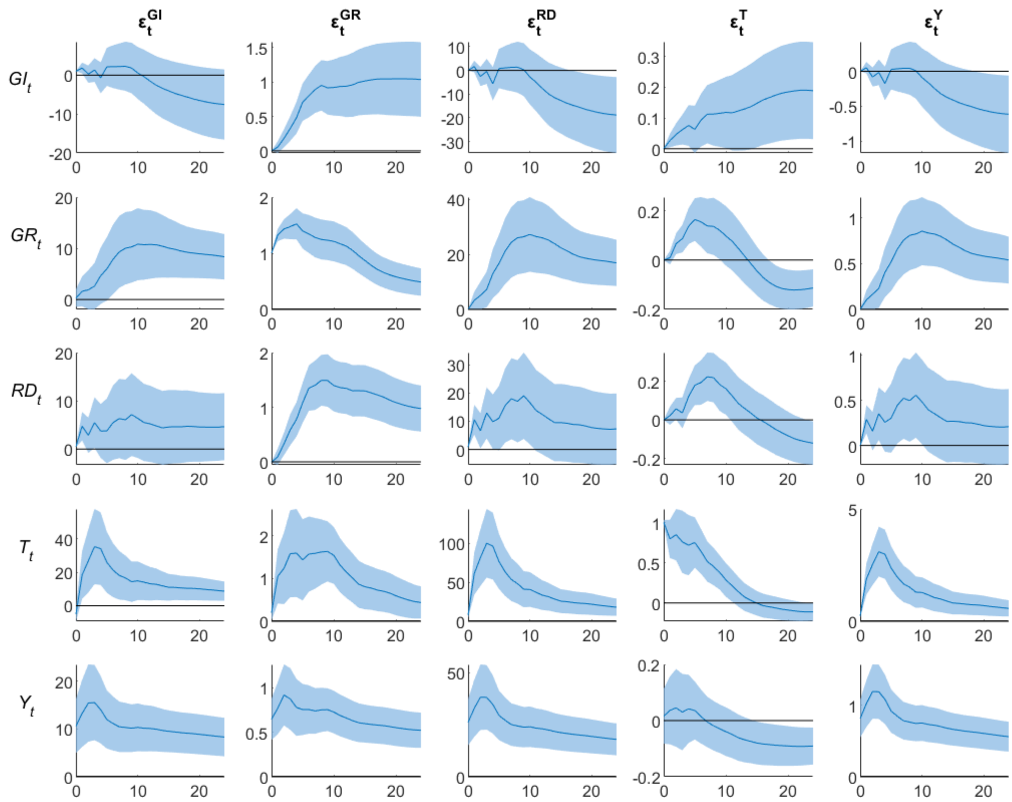

Figure A2. *IRFs to one unit shock from SVAR model B estimated on a subperiod with 68% confidence band.*

The dynamics of GR_t and GI_t is the same as in *SVAR model A*.

The impact of a GI_t shock on Y_t at t = 0 is 10.62 (instead of 13.54), while that of a GR_t shock is 0.64 (instead of 0.73). Like in the leading estimation, in both cases the effect on Y_t remains strongly significant for many years, and with a hump shape that peaks at 15.57 (instead of 20.87) after three quarters for a GI_t shock and at 0.92 (instead of 1.05) after two quarters for a GR_t shock.

The impact on RD_t of a GI_t shock is somewhat smaller than that of an RD_t shock, as in the leading estimation, but this time both impacts are smaller and less significant. The impact of a GI_t shock at t = 0 is indeed 0.52 (instead of 0.58), increasing over time up to a peak of 7.15 (instead of 17.1) after nine quarters.

The dynamic pure fiscal multipliers with respect to GDP and private R&D investments are shown in Table A1. The multipliers from both *SVAR model A* and *SVAR model B* are very similar to those obtained from the leading estimation, with the only noticeable difference represented by the effects on Y_t of one dollar spent in GR_t, which at t = 0 is a bit lower, 0.64 or 0.65 (instead of 0.73), while it becomes higher after three years, reaching 1.02 (instead of 0.45) after six years. For *SVAR model A*, the multiplier of GI_t on Y_t is slightly higher in the first three years and slightly lower in the following three years, whereas for *SVAR model B*, it is slightly lower at all horizons.

SVAR model A		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	**15.76**	**17.54**	**14.25**	**12.24**	**11.49**	**11.56**	**12.24**	**18.25 (2)**
	R&D	**0.55**	**0.63**	**0.54**	0.48	0.42	0.38	0.35	**0.71 (2)**
GR_t	Y	**0.64**	**0.47**	**0.65**	**0.82**	**0.87**	**0.94**	**1.02**	**1.02 (24)**
	R&D	0.00	**0.00**	**0.02**	**0.04**	**0.05**	**0.06**	**0.07**	**0.07 (24)**
SVAR model B		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	**10.62**	**12.98**	**10.99**	**10.14**	**10.23**	**10.89**	**11.99**	**13.32 (3)**
	R&D	**0.52**	0.59	0.48	0.43	0.40	0.37	0.35	**0.68 (1)**
GR_t	Y	**0.65**	**0.48**	**0.66**	**0.83**	**0.87**	**0.95**	**1.02**	**1.02 (24)**
	R&D	**0.00**	**0.00**	**0.02**	**0.04**	**0.05**	**0.06**	**0.07**	**0.07 (24)**

Table A1. Dynamic pure fiscal multipliers from *SVAR model A* and *SVAR model B* estimated on a subperiod. Significant values in bold, while peak indicates the maximum value with time horizon in parenthesis.

Robustness analysis of SVAR: lag length

In this section we explore how results from the SVAR model change if we modify the lag length including 8 lags (instead of 6), while using the whole available sample period 1947Q1-2017Q2. All results are presented in comparison with those obtained from the leading estimation, that is *SVAR model A* with 6 lags.

The overall conclusion of this analysis is that, apart from minor quantitative variations and a weaker persistence of GI_t, the impact of a GI_t shock on Y_t and RD_t remains of similar magnitude, again strongly significant on Y_t and significant on RD_t, whereas this time the impact on Y_t of an RD_t shock is not significant.

The IRFs to one unit shock for *SVAR model A* are displayed in Figure A3.

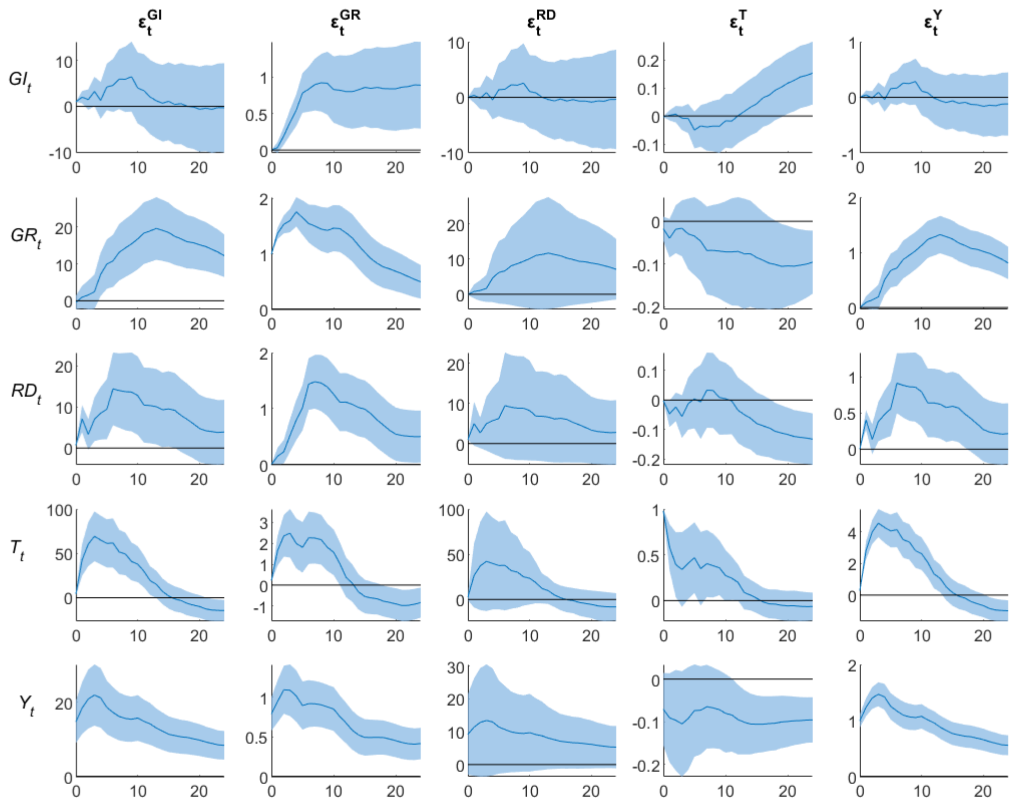

Figure A3. *IRFs to one unit shock from SVAR model A including 8 lags with 68% confidence band.*

In response to its own shock, GR_t keeps the same persistence and magnitude as in the leading estimation, peaking at 1.76 after one year, whereas GI_t is not followed by any significant increase after its own shock. As before, there is an important dynamic cross effect between the two spendings.

The impact of a GI_t shock on Y_t at t = 0 is 14.78 (instead of 13.54), while that of a GR_t shock is 0.79 (instead of 0.73). As in the leading estimation, in both cases the effect on Y_t remains strongly significant for many years, with a hump shape that peaks at 22 (instead of 20.87) after three quarters for a GI_t shock and at 1.10 (instead of 1.05) after two quarters for a GR_t shock. An RD_t shock produces no significant impact on Y_t, contrary to the leading estimation.

The impact on RD_t of a GI_t shock is somewhat greater than that of an RD_t shock, contrary to the leading estimation where the RD_t shock dominates, and this time only the former is significant. The impact of a GI_t shock at t = 0 is indeed 0.64 (instead of 0.58), increasing over time up to a peak of 14.35 (instead of 17.1) after six quarters.

The IRFs to one unit shock for *SVAR model B* are displayed in Figure A4.

In response to its own shock, GR_t keeps the same persistence and magnitude as in the leading estimation, peaking a 1.74 after one year, whereas GI_t is not followed by significant increases after its own shock. As before, there is an important dynamic cross effect between the two spendings.

The impact of a GI_t shock on Y_t at t = 0 is 11.14 (instead of 13.54), while that of a GR_t shock is 0.76 (instead of 0.73). As in the leading estimation, in both cases the effect on Y_t remains strongly significant for many years, with a hump shape that peaks at 16.67 (instead of 20.87) after three quarters for a GI_t shock and at 1.05 (the same value) after two quarters for a GR_t shock. An RD_t shock produces no significant impact on Y_t, contrary to the leading estimation.

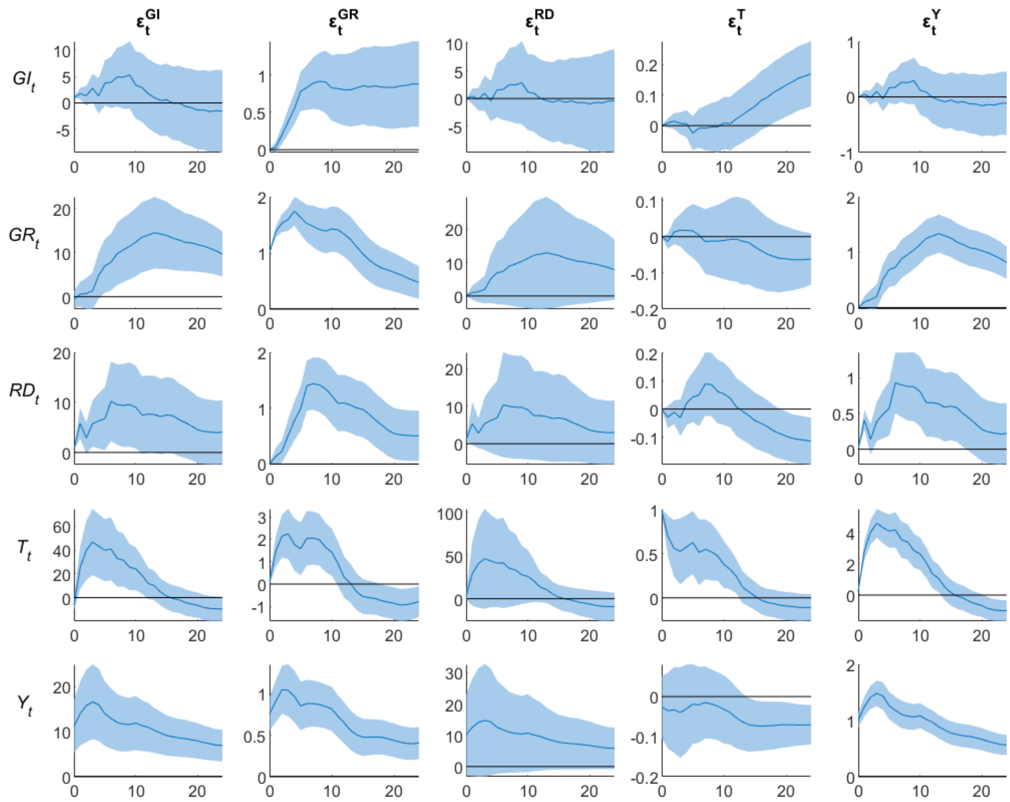

Figure A4. *IRFs to one unit shock from SVAR model B including 8 lags with 68% confidence band.*

The impact on RD_t of a GI_t shock is almost identical to that of an RD_t shock, contrary to the leading estimation, and this time only the former is significant. The impact of a GI_t shock at t = 0 is indeed 0.62 (instead of 0.58), increasing over time up to a peak of 10.21 (instead of 17.1) after six quarters.

The dynamic pure fiscal multipliers with respect to GDP and private R&D investments are shown in Table A2. The multipliers from both *SVAR model A* and *SVAR model B* are very similar to those obtained from the leading estimation, with the only noticeable difference represented by the effects on Y_t of one dollar increase in GR_t, which is now a bit higher at longer horizons, reaching at t = 24 a value of 0.74 using *SVAR model A* and 0.73 using *SVAR model B*, instead of 0.45. For *SVAR model A*, the multiplier of GI_t on Y_t is slightly higher in the first year and slightly lower in the following five years, whereas for *SVAR model B*, it is slightly lower at all horizons.

SVAR model A		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	**14.94**	**17.86**	**12.09**	**8.97**	**8.11**	**8.25**	**9.05**	**18.74 (3)**
	R&D	**0.64**	**0.79**	**0.68**	**0.60**	**0.55**	0.51	0.50	0.80 (2)
GR_t	Y	**0.79**	**0.54**	**0.59**	**0.71**	**0.64**	**0.67**	**0.74**	**0.79 (0)**
	R&D	0.00	**0.01**	**0.02**	**0.03**	**0.04**	**0.04**	**0.05**	**0.05 (24)**
SVAR model B		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	**11.15**	**14.91**	**9.43**	**6.79**	**6.51**	**7.07**	**8.19**	**15.74 (3)**
	R&D	**0.62**	**0.77**	**0.64**	**0.56**	**0.52**	**0.50**	**0.50**	**0.79 (2)**
GR_t	Y	**0.76**	**0.51**	**0.55**	**0.67**	**0.61**	**0.65**	**0.73**	**0.76 (0)**
	R&D	0.00	**0.01**	**0.02**	**0.03**	**0.04**	**0.04**	**0.05**	**0.05 (24)**

Table A2. Dynamic pure fiscal multipliers from *SVAR model A* and *SVAR model B* including 8 lags. Significant values in bold, while peak indicates the maximum value with time horizon in parenthesis.

Robustness analysis of RE-SVAR: sample period

In this section we explore how results from the RE-SVAR model change if we modify the sample period covered by the data. We estimate *RE-SVAR model A* and *RE-SVAR model B*, with 6 lags and using data that this time covers the period 1947Q1-2007Q4, so dropping the last part that begins with the 2008 financial crisis. All results are presented in comparison with those obtained from the leading estimation, that is *RE-SVAR model A* estimated on the full sample period.

The overall conclusion of this analysis is that shape, timing, and order of magnitude of the effects of a GI_t and GR_t shocks remain rather stable. Two noticeable differences under both *RE-SVAR model A* and *RE-SVAR model B* are the relative stronger impact of private over public R&D spending, and the negative effect of expectations on Y_t and RD_t under *RE-SVAR model B*.

The IRFs to one unit shock for RE-SVAR model A are displayed in Figure A5.

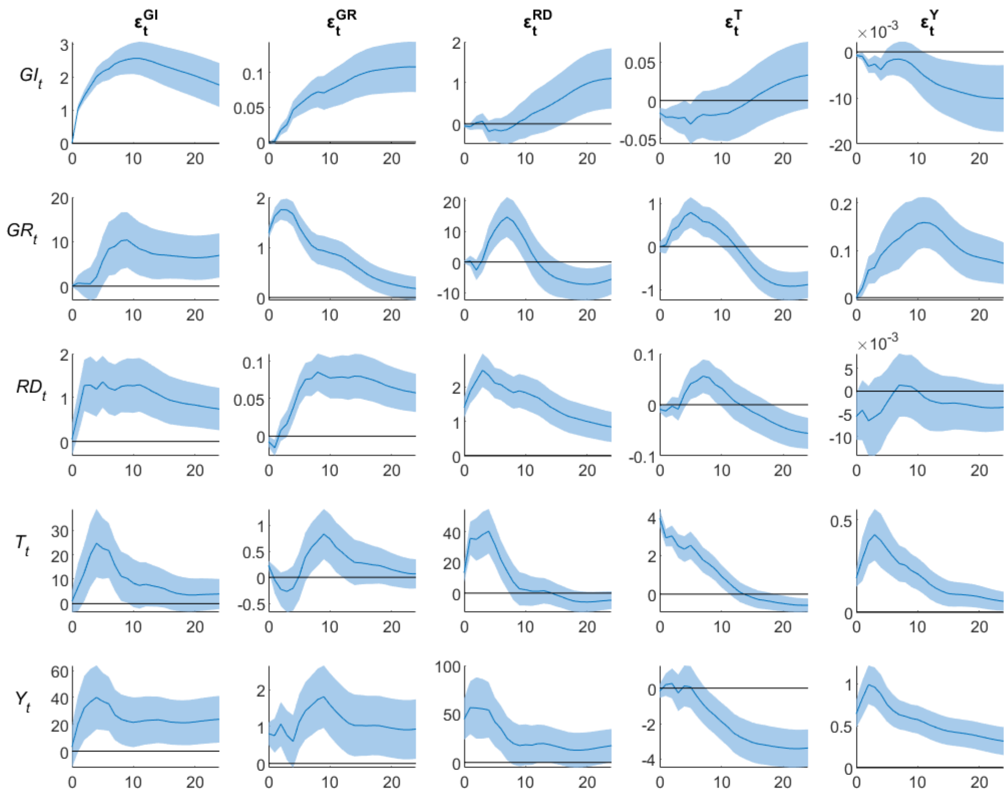

Figure A5. *IRFs to one unit shock from RE-SVAR model A estimated on subperiod with 68% confidence band.*

The dynamics of GI_t and GR_t in response to their own shocks remains almost identical.

The impact of a GI_t shock on Y_t is smaller at all horizons. At t = 0 it amounts to 3.28 (instead of 16.48) and it is not significant, but from t = 2 onwards it remains significant, with a peak of 40.09 (instead of 55.75) after one year. The impact of a GR_t shock is slightly smaller at t = 0, reaching 0.81 (instead of 0.91), but larger and more significant at longer horizons, with a peak of 1.81 (instead of 1.08) after nine quarters. The impact of an RD_t shock on Y_t is 44.64 (instead of 27.65) at t = 0, and reaches a peak of 56.46 (instead of 39.62) after one quarter.

The impact on RD_t of a GI_t shock retains its shape and timing, but it is now on average half that obtained from the leading estimation. At t = 0 it is indeed 0.05 (instead of 0.52), and reaches a peak of 1.36 (instead of 2.13) after five quarters. The impact on RD_t of its own shock is virtually identical.

The IRFs to one unit shock for *RE-SVAR model B* are displayed in Figure A6.

The dynamics of GI_t and GR_t in response to a GR_t shock remains very similar, but the response to a GI_t shock is somewhat different since the accompanying GR_t increase occurs later becoming significant only after three years, reaching 5.97 (instead of 12.5) after 2 years, although the level after six years is similar, 9.38 (instead of 8.67).

The impact of a GI_t shock on Y_t is very different and is significant only at long horizons. The response at t = 0 is -5.95 (instead of 16.48), which indicates a negative effect of the expectations component, and it reaches a peak of 21.49 (instead of 55.75) after one year. The impact of a GR_t shock is slightly smaller at t = 0, reaching 0.81 (instead of 0.91), but it is larger and more significant at longer horizons, with a peak of 1.82 (instead of 1.08) after nine quarters. The impact of an RD_t shock on Y_t is 45.87 (instead of 27.65) at t = 0, and reaches a peak of 58.35 (instead of 39.62) after one quarter.

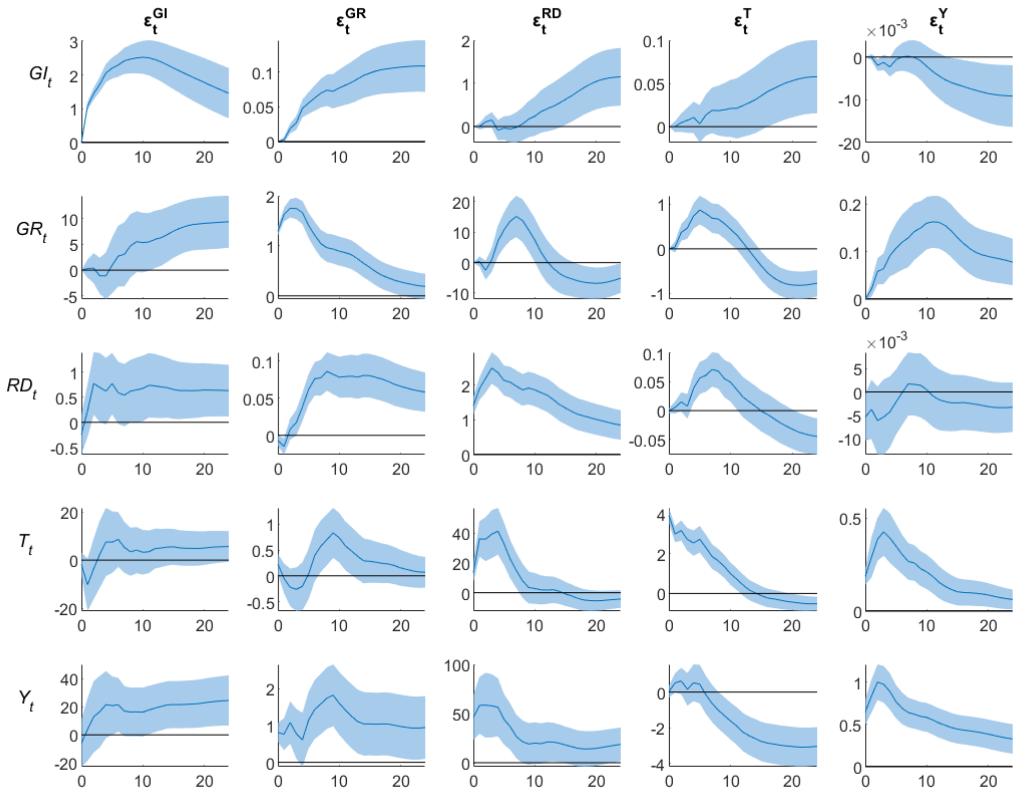

Figure A6. *IRFs to one unit shock from RE-SVAR model B estimated on subperiod with 68% confidence band.*

The impact on RD_t of a GI_t shock is -0.24 (instead of 0.52) at t = 0, again suggesting a negative impact of expectations, and reaches a peak of 0.77 (instead of 2.13) after one quarter. The impact on RD_t of an RD_t shock is virtually identical.

The dynamic pure fiscal multipliers with respect to GDP and private R&D investments are shown in Table A3. Results are comparable to those of the leading estimation if we adopt *RE-SVAR model A*. The effect of one dollar increase in $GI_t^{(s)}$ is of similar size with respect to both Y_t and RD_t. Once we include the news component and derive the effects of one dollar increase in GI_t, the multipliers increase but remains smaller than those from the leading estimation. The effect on Y_t of one dollar increase in GR_t is smaller at short horizons but larger at long horizons. Adopting *RE-SVAR model B* does not change much the multipliers of $GI_t^{(s)}$ and GR_t. By contrast, there is a substantial difference this time in the multipliers of GI_t, which are now much smaller than the ones from the leading estimation, and even negative at short horizons, signaling a negative effect of expectations on both Y_t and RD_t.

RE-SVAR model A		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	22.63	**20.49**	**16.34**	**13.97**	**13.07**	**13.10**	**13.84**	22.63 (0)
	R&D	0.65	**0.69**	**0.58**	**0.51**	**0.46**	**0.41**	**0.39**	**0.79 (1)**
$GI_t^{(s)}$	Y	**15.44**	**17.47**	**14.23**	**12.25**	**11.52**	**11.60**	**12.30**	**18.13 (2)**
	R&D	0.54	**0.63**	**0.54**	**0.48**	**0.42**	**0.38**	**0.36**	**0.71 (1)**
GR_t	Y	**0.63**	0.46	**0.64**	**0.81**	**0.86**	**0.93**	**1.01**	**1.01 (24)**
	R&D	0.00	**0.00**	**0.02**	**0.04**	**0.05**	**0.06**	**0.07**	**0.07 (24)**
RE-SVAR model B		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	-1.95	8.15	7.91	**7.89**	**8.42**	**9.28**	**10.48**	**10.48 (24)**
	R&D	-0.01	0.33	0.29	**0.27**	**0.25**	**0.23**	**0.21**	0.34 (2)
$GI_t^{(s)}$	Y	**10.50**	**12.90**	**10.94**	**10.10**	**10.21**	**10.88**	**11.99**	**13.23 (3)**
	R&D	**0.51**	**0.58**	**0.48**	**0.43**	**0.39**	**0.37**	**0.35**	**0.67 (1)**
GR_t	Y	**0.63**	0.46	**0.64**	**0.81**	**0.86**	**0.94**	**1.01**	**1.01 (24)**
	R&D	-0.01	**0.00**	**0.02**	**0.04**	**0.05**	**0.06**	**0.07**	**0.07 (24)**

Table A3. Dynamic pure fiscal multipliers from *RE-SVAR model A* and *RE-SVAR model B* estimated on a subperiod. Significant values in bold, while peak indicates the maximum value with time horizon in parenthesis.

Robustness analysis of RE-SVAR: lag length

In this section we explore how results from the RE-SVAR model change when we increase the lag length including 8 lags (instead of 6), while using the whole available sample period 1947Q1-2017Q2. All results are presented in comparison with those obtained from the leading estimation, that is *RE-SVAR model A* with 6 lags.

The overall conclusion of this analysis is that shape, timing, and order of magnitude of the effects of a GI_t and GR_t shocks remain rather stable. Two noticeable differences are the substantially stronger impact of public R&D spending on GDP under *RE-SVAR model A*, and the non-existent impact of private R&D spending on GDP under both *RE-SVAR model A* and *RE-SVAR model B*.

The IRFs to one unit shock for *RE-SVAR model A* are displayed in Figure A7.

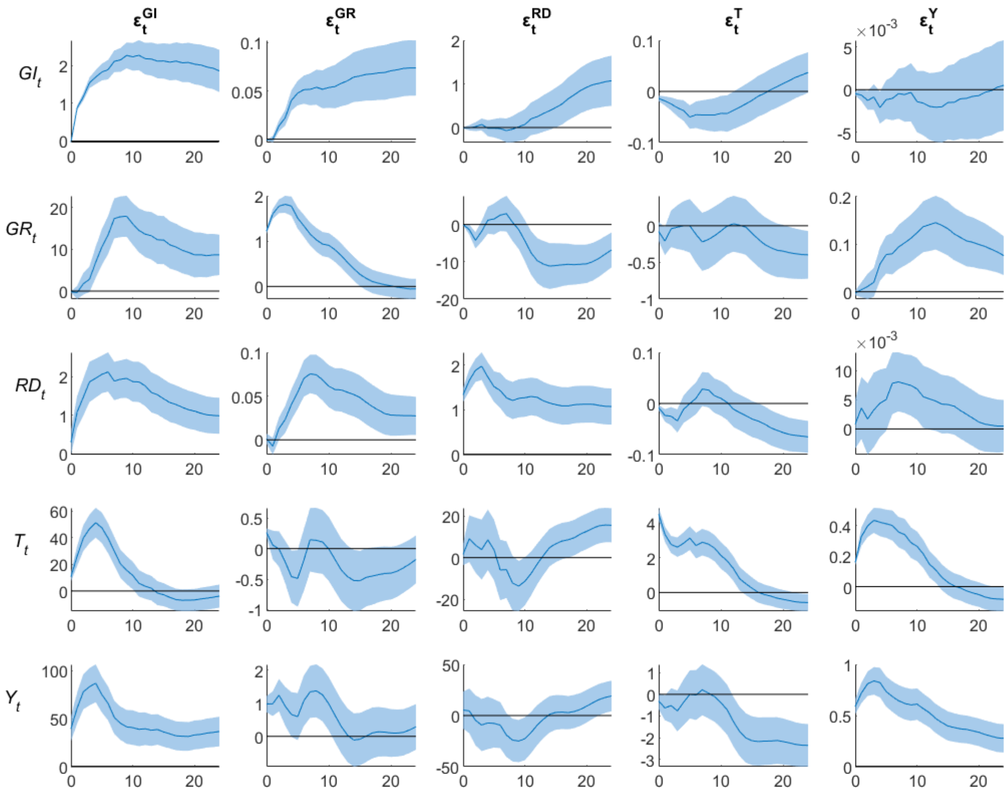

Figure A7. *IRFs to one unit shock from RE-SVAR model A including 8 lags, with 68% confidence band.*

The dynamics of GI_t and GR_t in response to their own shocks remains very similar.

The impact of a GI_t shock on Y_t is greater at short horizons but very similar at long horizons. At t = 0, this impact amounts to 39.53 (instead of 16.48), it is always very significant, with a peak of 86.8 (instead of 55.75) after one year. The impact of a GR_t shock is slightly greater at t = 0, reaching 0.98 (instead of 0.91), with a peak of 1.38 (instead of 1.08) after two years. The impact of an RD_t shock on Y_t is 5.38 (instead of 27.65) at t = 0, and hardly ever significant this time.

The impact on RD_t of a GI_t shock is very similar in both shape and size. At t = 0 it is indeed 0.30 (instead of 0.52), and reaches a peak of 2.12 (instead of 2.13) after six quarters. The impact on RD_t of its own shock is only slightly smaller in size, reaching a peak of 1.98 (instead of 2.38) after three quarters.

The IRFs to one unit shock for *RE-SVAR model B* are displayed in Figure A8.

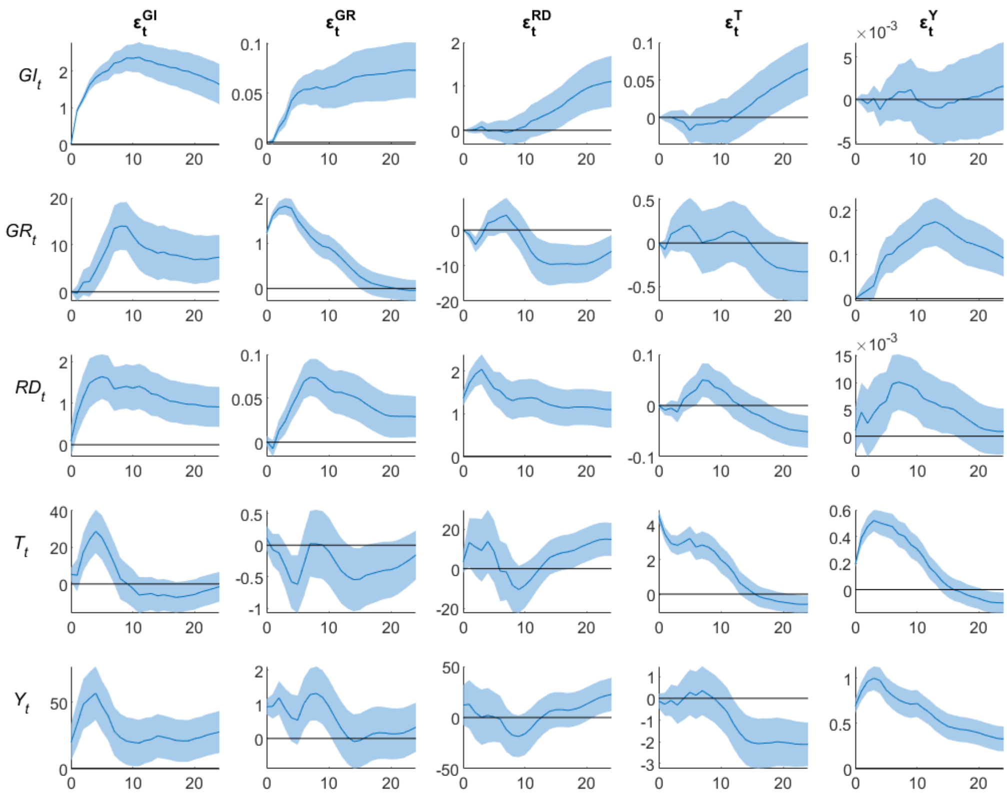

Figure A8. *IRFs to one unit shock from RE-SVAR model B including 8 lags, with 68% confidence band.*

The dynamics of GI_t and GR_t in response to their own shocks remains very similar.

The impact of a GI_t shock on Y_t is almost identical. At t = 0, this impact amounts to 19.64 (instead of 16.48), it is always very significant, with a peak of 56.65 (instead of 55.75) after one year. The impact of a GR_t shock is 0.93 (instead of 0.91), with a peak of 1.32 (instead of 1.08) after two years. One noticeable difference is the impact on Y_t of an RD_t shock, which is 12.17 (instead of 27.65) at t = 0, and hardly ever significant this time.

The impact on RD_t of a GI_t shock retains its shape and timing, but it is slightly smaller in size. At t = 0, this impact is indeed 0.09 (instead of 0.52), and reaches a peak of 1.64 (instead of 2.13) after five quarters. The impact on RD_t of its own shock is only slightly smaller in size, reaching a peak of 2.04 (instead of 2.38) after three quarters.

The dynamic pure fiscal multipliers with respect to GDP and private R&D investments are shown in Table A4. Results are comparable to those of the leading estimation if we adopt *RE-SVAR model A*. The effect of one dollar increase in $GI_t^{(s)}$ is of similar size with respect to both Y_t and RD_t. Once we include the news component and derive the effects of one dollar increase in GI_t, the multipliers with respect to Y_t increase considerably becoming much larger than those from the leading estimation, though this difference decreases at longer horizons. The multipliers with respect to RD_t are in line with the leading estimation in the case of $GI_t^{(s)}$, and slightly smaller in the case of GR_t. Adopting *RE-SVAR model B* does not change much the multipliers of $GI_t^{(s)}$ and GR_t. The multipliers of GI_t, on the other hand, become much smaller and in line with those from the leading estimation if we consider Y_t, and somewhat smaller if we consider RD_t.

RE-SVAR model A		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	**117.56**	**60.12**	**44.11**	**37.69**	**35.30**	**35.12**	**36.71**	**117.6 (0)**
	R&D	**1.62**	**1.24**	**1.09**	**0.97**	**0.88**	**0.81**	**0.78**	**1.62 (0)**
$GI_t^{(s)}$	Y	**13.82**	**17.43**	11.92	8.96	8.15	8.30	**9.10**	**18.20 (3)**
	R&D	**0.59**	**0.75**	**0.65**	**0.57**	**0.52**	**0.49**	**0.48**	**0.76 (2)**
GR_t	Y	**0.80**	**0.54**	**0.58**	0.69	0.62	0.65	0.71	**0.80 (2)**
	R&D	0.00	0.01	**0.02**	**0.03**	**0.04**	**0.04**	**0.05**	**0.05 (24)**
RE-SVAR model B		*Horizon*							
Shock	Response	*0*	*4*	*8*	*12*	*16*	*20*	*24*	*peak*
GI_t	Y	**56.68**	**34.36**	**24.20**	**19.96**	**18.86**	**19.28**	**20.80**	**56.68 (0)**
	R&D	**0.87**	**0.88**	**0.75**	**0.66**	**0.60**	**0.57**	**0.57**	**0.91 (2)**
$GI_t^{(s)}$	Y	**9.92**	**14.32**	9.12	6.66	6.44	7.03	**8.15**	**15.05 (3)**
	R&D	**0.57**	**0.73**	**0.60**	**0.53**	**0.49**	**0.47**	**0.47**	**0.74 (2)**
GR_t	Y	**0.76**	**0.51**	**0.54**	0.65	0.59	0.62	0.69	**0.76 (0)**
	R&D	0.00	**0.01**	**0.02**	**0.03**	**0.04**	**0.04**	**0.05**	**0.05 (24)**

Table A4. Dynamic pure fiscal multipliers from *RE-SVAR model A* and *RE-SVAR model B* including 8 lags. Significant values in bold, while peak indicates the maximum value with time horizon in parenthesis.

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