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Stagnation despite ongoing innovation: Is R&D expenditure composition a missing link? An empirical analysis for the US (1948–2019)

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ABSTRACT

Among the explanations for prolonged economic stagnation in advanced economies, we find those that highlight the role of technical progress and its weakening impact on potential growth. Several contributions stress the apparent paradox of technological development and innovation going hand in hand with slowing labour productivity growth. This issue is in turn linked to numerous factors, among which the pattern of research productivity that appears to be falling in the last decades. This article aims to analyse the role of innovation expenditures and their effects on productivity. Using an SVAR model on US data from 1948Q1 to 2019Q4, the study estimates the effects of public versus private innovation expenditures on productivity. The findings indicate that public innovation spending has a stronger positive impact on productivity than private spending and strongly crowds in private R&D investment. Thus, the sustained decrease in public innovation expenditure relative to private expenditure contributes to prolonged stagnation.

1. Introduction

It is a decade since the search for the causes of lasting (secular) stagnation is up and running (Gordon, 2015; Summers, 2015; Baldwin and Teulings, 2014). Among the main explanations for such a phenomenon, we find those which stress the relevance of the supply side, pointing the attention towards the evolution of technical progress and its weakening impact on potential growth. This echoes the now-distant, but still well-known Solow's (1987) paradox, who claimed that

> "[…] what everyone feels to have been a technological revolution, a drastic change in our productive lives, has been accompanied everywhere, including Japan, by a slowing-down of productivity growth, not by a step up. You can see the computer age everywhere but in the productivity statistics."

Indeed, the issue of technological development going hand in hand with slowing labour productivity growth is still at the centre of attention. For instance, Gordon, 2018a, p. 2) stresses

> "the paradox that innovative activity as measured by patent issuance has been increasing while productivity growth has been slower in the past decade than in any decade of recorded American history".

This issue is in turn linked, among other things, to the worrisome pattern of research productivity, which is claimed to be falling in the last decades, bringing about concerns about the evolution of productivity and GDP growth (Bloom et al., 2020; Cauwels and Sornette, 2022).

Such a far-reaching insight calls into question a long list of elements. Stagnation cannot be attributed to a single, comprehensive factor. The contribution of this article is to analyse the element of innovation expenditures (public and private), and their effects on productivity. We aim to study whether productivity stagnation can be (at least partially) explained by the fact that public expenditure in innovation is continuously falling with respect to private expenditure in the US, as well as in general in advanced economies (Goel et al., 2008; Archibugi and Filippetti, 2018). This is linked to the increasing attention given to the role of public research (and its close connection with basic research) in recent years, due to its wide-ranging beneficial effects on the economy (Bloom et al., 2019; Akcigit et al., 2021; IMF, 2021, 2024). Our work

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also aligns with the literature on Mission-Oriented Innovation Policies (MOIPs), which underscore the strategic importance of government investments in innovation in driving technological progress, fostering private sector innovation, and enhancing productivity (Mazzucato, 2018; Deleidi and Mazzucato, 2019). By entering these debates, this paper aims to provide a comprehensive understanding of how public and private innovation expenditures affect productivity, thus contributing to the broader discussion on economic stagnation.

Based on these premises, this study aims to provide several contributions. First, it examines the relationship between productivity stagnation and the concept of secular stagnation, as discussed by Gordon, and explores how innovation policies are connected to this phenomenon. Second, it differentiates between public and private expenditures in innovation, providing a more detailed understanding of their respective impacts by applying a Structural Vector Autoregression (SVAR) model to US quarterly data (1948Q1-2019Q4). Third, it analyses the impact of public expenditure in innovation on private R&D, thereby evaluating the presence of crowding-in or -out effects.

According to our results, public expenditure in innovation exhibits a positive, persistent, and non-negligible effect on productivity, and together with generic public expenditure, it has a greater effect than private expenditure in innovation. In addition to this, public expenditure in innovation exerts a strong crowding-in effect on private investment in R&D, remarkably stronger than generic public expenditure. Therefore, according to the evidence we find, we maintain that a prolonged and sustained fall of public expenditure in innovation in relation to private expenditure of the same type helps explain stagnation.

The paper is structured as follows. Section 2 reviews various strands of literature on Secular Stagnation and connects them with studies focusing on the macroeconomic effects of innovation expenditures. Section 3 provides an overview of empirical observations concerning innovation and productivity within the US economy. Section 4 outlines the data sources and methodology utilized in this study. Section 5 presents the empirical analysis of how public expenditure in innovation impacts labour productivity and compares its effects with those of private expenditure in innovation and general public expenditure. Finally, Section 6 concludes by drawing policy implications.

2. (Secular) Stagnation, innovation, and public research: An overview

When tackling the issue of Secular Stagnation, the first name to be mentioned cannot but be that of Alvin Hansen. In fact, he foresaw gloomy prospects for the US economy, predicted to be about to grapple with “sick recoveries which die in their infancy and depressions which feed on themselves and leave a hard and seemingly immovable core of unemployment” (Hansen, 1939, p. 4). Subsequently, it is worth noting that he revised his Secular Stagnation hypothesis even during the prosperous 1950s, and he maintained fiscal policy to be a powerful tool for sustaining growth even after the II World War phase (Hansen, 1954).

More recently, two main strands of analysis retrieved the debate on long-lasting stagnation. Summers (2015) demand-side Secular Stagnation theory retrieved Hansen’s gloomy prospects that would nowadays be due to a negative Wicksellian natural rate of interest coupled with the zero lower bound.[1] Gordon (2015), Gordon, 2016, Gordon, 2018a, Gordon, 2018b) Secular Stagnation theory does not encompass mechanisms hindering the realization of the full-employment output. Rather, potential output growth is considered to be on a much slower path than before. It also gives prominence to supply-side elements.[2] Generally speaking, a gloomy foreseeable future is due to several ‘headwinds’ the US economy is facing (Gordon, 2012, 2014, 2016). Among those, we find first, the progressive fading of a so-called ‘demographic dividend’ given by the baby-boom generation; second, the stasis reached by the diffusion of mandatory and higher education across the US population; third, the rise of inequality; fourth, the competition from countries featuring a much cheaper cost of labour; fifth, environmental concerns over climate change and global warming; sixth, mounting household and government debt levels. However, the fundamental factors appear to be two: unfavourable demographic trends and the sluggish growth of total factor productivity (Gordon, 2015). On the demographic side, population ageing and plummeting labour force participation rates are worrying trends. Yet, the weakening effect of technical improvements on productivity growth and the diminishing returns from human capital accumulation are the main sources of preoccupation. In particular, “[t]he central argument is that the digital electronics revolution has begun to encounter diminishing returns” (ibid., p. 54).

According to Gordon’s reconstruction, the 1920–1972 period witnessed sustained total factor productivity growth, something that was not replicated in later decades. Indeed, the first two industrial revolutions delivered a long list of ground-breaking innovations, creating a favourable environment for the subsequent full impact on productivity growth.[3] Gordon attributes the unsatisfactory productivity growth experienced in recent years to the supposition that the ramifications of the third revolution have already exhibited the bulk of their potential effect. This intuition can be found also in more recent works where the author goes deeper in the analysis of the role of innovation in fostering productivity and economic growth (Gordon, 2018a; Gordon, 2018b). In fact, Gordon singles out the paradoxical concomitance of fast innovation in terms of patenting and the slow growth of productivity. According to the author, again, the motive for this rests in the nature of the third industrial revolution, an episode that has brought about types of innovations that are not going to replicate the path-breaking pattern of past revolutions. Indeed, Gordon (2018b, pp. 16-17) maintains that

> “the Third (digital) Industrial Revolution generated a productivity boost of only a decade between 1996 and 2006, as contrasted to the five-decade (1920-70) interval of rapid productivity growth following the Second Industrial Revolution, because the earlier inventions had a more profound effect on every aspect of human existence”.

[1] The fact that the natural rate of interest can be negative in a long-run steady-state equilibrium generated several discussions (Bernanke, 2015; Di Bucchianico, 2020a, 2020b, 2021).

[2] These elements do not exhaust the list of possible causes for the productivity growth slowdown experienced by developed countries in the last decades. Among others, one factor that has concurred to economic and productivity stagnation is financialization, which has acted through several channels (Tridico and Pariboni, 2018; Barradas, 2022). In fact, most developed countries witnessed during the last decades an unregulated expansion in their financial systems. This phenomenon came along with severe adverse impacts on their economies. In this vein, Barradas (2023) investigates the evidence suggesting how the majority of EU countries witnessed sluggish economic growth, declining labor income shares and rising personal income inequality, and an intensification of financialization. To this end, the author analyses if and how these elements, with a particular focus on financialization, contributed to curb labor productivity dynamics. His findings show that income inequality and financialization adversely affected productivity growth. The negative effect on economic growth exerted by financialization and rising inequality is also discussed by Pariboni et al. (2020), who link these factors to the return of ‘secular stagnation’. The authors empirically assess the linkage among these topics in a panel of 21 OECD countries (1990–2016), thereby demonstrating that high levels of financialization, surging inequality, and weak labor market institutions all contribute to depress economic growth.

[3] Among those, we find for example railroads during the first revolution, and electricity during the second. The third revolution was mainly about digital electronic, and it delivered among other things computers.

On the same footing, neither foreseeable forthcoming innovations in artificial intelligence, robots, and biotechnologies will provide the type of stimulus needed to generate a new boost to growth. Recently, Ramey (2020) joined this strand of analysis by maintaining that the US is confronting economic stagnation due to a 'technological lull'. As also recalled by Gordon's (2012) first headwind, Ramey points out the relevant role of the progressive retirement of the baby boomers. In addition, the decline in labour productivity (measured as real output per hour worked) is entirely attributed to a decline in total factor productivity growth.

Such kinds of predictions are of course a contested terrain: Mokyr (2018) questions the validity of those gloomy prospects, believing that, to the contrary, we may well be facing a prospect of continuous innovations capable of raising living standards on a sustained basis. Furthermore, Eichengreen (2015) introduces the differentiation between the 'range of applicability' and the 'range of adaptation' of new technologies, and along with it the possibility for future productivity growth to accelerate once the momentary phase of reorganization arrives at completion, as in Pagano and Sbracia (2018) and Ramey (2020). Therefore, current predicaments might be "a harbinger of better things to come" (Eichengreen, 2015, p. 70).

An alternative explanation for weak productivity growth despite fast innovation, only briefly mentioned by Gordon (2018a, p. 9), is to consider the possibly rising cost of finding new major ideas.[4] Three contributions that explicitly address this point are those of Fernald and Jones (2014), Bloom et al. (2020), and Cauwels and Sornette (2022).[5] Fernald and Jones (2014) start from Romer (1990) endogenous growth model's clue about the capability of ideas to generate increasing returns due to non-rivalry in their consumption. Grounding on this, they resort to a production function of ideas combined with a standard Cobb-Douglas production function, which delivers a growth accounting formula in which labour productivity growth is driven by: the capital-output ratio, human capital per person, research intensity, and total population. Research intensity is shown to have been the major contributor to productivity growth, followed by human capital and population.[6] Given the fact that both educational attainments and research intensity cannot grow forever, and also considering the pattern of population ageing, the authors express concerns about the prospects ahead for growth. An agnostic judgement is left on what will the actual shape of the ideas production function in the future, another element that may considerably contribute to determining the future pace of innovation but that is difficult to accurately predict. In this sense, the authors appear less inclined to express a precise forecast, contrary to the (contrasting) takes of Mokyr (2018) and Gordon (2018a), Gordon, 2018b).

Similarly to Fernald and Jones (2014), Bloom et al. (2020) use as the cornerstone of their analysis a very simple equation according to which a period of steady growth can be interpreted as the balancing of two opposed forces: the tendency for research productivity to dramatically fall and the increasing efforts spent to offset such pattern via incremental research activity. Evidence about falling research productivity is found in many industries (such as IT, agriculture and medicine), and it is detectable at both the micro (industries) and the macro (aggregate economy) levels. In particular, the authors point out that research productivity at the aggregate level has been halving every 13 years. This goes hand in hand with the conclusion that, given the primacy they attribute to the idea production function in steering growth, "just to sustain constant growth in GDP per person, the United States must double the amount of research effort every 13 years to offset the increased difficulty of finding new ideas" (Bloom et al., 2020, p. 1138).

The sustained fall in research productivity is also tackled by Cauwels and Sornette (2022), who construct two indexes for scientific knowledge and research productivity and show their long-term decline over the last decades.

In what follows, we will address the issue of whether the relationship between R&D and productivity and GDP can be - partially - shaped and influenced by the type of innovation activity (public or private). Bloom et al. (2020, p. 1138) list some possible explanations for the gloomy trend of research productivity: the necessity to increase more and more research inputs (something that has not been done in recent decades), the fact that innovations of the 'follow on' kind have less impact than their originators, and the decline of basic, publicly funded research. In fact, the issue related to the composition of research expenditure is increasingly stimulating researchers to understand whether this can provide a key to rationalizing also the dynamics of innovation, productivity, and growth. Indeed, Archibugi and Filippetti (2018), after showing international data about the progressive retreat of the public sector from research funding and implementation, maintain that such a structural change is going to exert relevant adverse effects on future innovation and long-term growth given the different features that the two types of research enjoy. First, as Archibugi (2017, p. 541) states, "the major breakthroughs were generated in universities and in publicly funded research centres". Indeed, research guided by the private sector may not pursue targets that are beneficial from a social point of view. Second, privately generated research is much more characterized by rivalry in consumption and excludability in production with respect to public research. Third, path-breaking scientific innovations are usually provided by public research, and the authors mention the cases of electricity, chemicals, ICT, pharmaceuticals, GPS, and the internet. On a similar footing, Van Reenen (2020, p. 7; see also Van Reenen 2021) points out that

> "Private and government R&D are not interchangeable. Government R&D tends to fund higher-risk basic research that private investors are often reluctant to take on […]. Therefore, public R&D investment tends to produce higher value, as well as high spillover inventions over a longer period of time".

Furthermore, Archibugi et al. (2020) emphasise the primary role to be assigned to public investment in innovation which is liable to generate a return in terms of output which exceeds the basic multiplier because they have a wide scope for creating new markets and stimulating more productive sectors at once.[7] Similarly, international institutions and academic scholars advocate for implementing Mission-Oriented Innovation Policies (Mazzucato, 2018; European Commission, 2018; Larrue, 2021). This literature underscores the pivotal role of governments in fostering economic growth through strategic investments across the entire innovation chain and by creating new technological opportunities beyond merely addressing market failures (Mowery, 2010; Foray et al., 2012; Mazzucato, 2018). These policies entail substantial government expenditures in research and development to shape markets, catalyse technological advancements, and catalyse private sector involvement through spillover effects (Deleidi and Mazzucato, 2019; Chang and Andreoni, 2020). MOIPs facilitate collaboration across diverse sectors and stakeholders to develop technologies aligned with state-defined missions, thereby driving both technological and non-technological innovations. Consequently, they have significantly influenced the realization and diffusion of technological advancements (Van Reenen, 2020).

In this context, it is important to highlight that, along with the public sector, Big Tech companies are investing heavily in R&D. Given their substantial market capitalization, they can undertake numerous basic research projects, such as Elon Musk's plan for Mars exploration or Jeff

[4] Another strand of literature we will not cover enquires the relation between robotization and population ageing (Acemoglu and Restrepo, 2017).

[5] Similar evidence is also presented by Link and Scott (2021).

[6] Measured as the share of researchers over total workers.

[7] Archibugi et al. (2013) also note the detrimental impact of crises episodes on long-term investment patterns.

Bezos' space ventures. However, despite the already mentioned different nature between public and private research, it should be noted that the last few decades have seen a clear and increasing specialization in R&D. Universities have focused on research, while large corporations have tended to prioritize development (Arora et al., 2020). As Arora et al. (2018, p. 3) aptly summarize, "Large firms still value the golden eggs of science (as reflected in patents), but seem to be increasingly unwilling to invest in the golden goose itself (the internal scientific capabilities)".

These considerations can be read in conjunction with a broader literature which investigates the macroeconomic impacts of public and private innovation expenditures and their comparison (Deleidi and Mazzucato, 2021; De Lipsis et al., 2022; Fieldhouse and Mertens, 2023; Ciaffi et al., 2022, 2024).[8] For instance, Soete et al. (2022) show, by using country-specific VECM estimations in a panel of 17 OECD countries (1975–2014), the effect of both public and private R&D stocks on TFP. According to their estimates, public R&D in most cases shows a positive effect on TFP. Moreover, the authors discover tight complementarity between public and private R&D. Another contribution to this literature comes from Herzer (2021), who finds evidence of a strong impact of the stock of both public and private researchers on TFP. In addition to this, researchers employed in the public sector impart a stronger positive boost to TFP. Ziesemer (2021a) also finds considerable positive impacts of 'mission-oriented' R&D on public and private R&D, TFP, and GDP in a selected group of EU countries.

Furthermore, in close connection with the concerns about falling public-to-private R&D ratios, the literature stresses the presence of a similar pattern for the basic-to-applied R&D ratios. The IMF singles out the presence in the data of an alleged paradox which they frame in terms similar to those used by Gordon: "Productivity growth has slowed, even amid increased spending on research and development […]" (IMF, 2021, p. 65). Analogously to what Archibugi and Filippetti (2018) contend, IMF (2021) points out the intrinsic characteristics of basic R&D to be a key to understanding why it may matter so much in light of long-run productivity growth.[9]

Given the empirical evidence from the extant literature and the link with the literature on long-term stagnation, the next step is to carry out an analysis of what happened in the post-WWII period in the US economy. This case study consents to investigate the relationship between public and private R&D, and their effects on labour and total factor productivity, in the single most important OECD economy.

3. Stylized facts on innovation and productivity

Gordon's (2018a), Gordon, 2018b) preoccupation concerning the divergence in the pace of innovation (described by patenting dynamics) and labour productivity is well-grounded in empirical evidence. In fact, as recalled by the American economist, patenting in the US does not seem to experience a deceleration. Rather, as we can see in Fig. 1, patent applications and total R&D expenditure both appear to be on a rising trend. In particular, patent applications exhibit a surging trend, especially from the late Eighties/beginning of the Nineties.

An altogether different path is exhibited by labour productivity growth. Indeed, as it is ascertainable by having a glance at Fig. 2 and Fig. 3, the growth rate of labour productivity has been continuously decreasing on average over the decades. The exception is constituted by the so-called 'growth revival' of the Nineties (Gordon, 2015), which temporarily and partially reversed what can be seen to be a long-term issue in the US economy.

As Goel et al. (2008) pointed out, a comparison among different measures of R&D flows clearly shows a continuous decreasing pattern of the government component of research. This is true for generic government R&D, but it can be shown to be true also for defense R&D, which is the most important component of government-funded research in the US (Moretti et al., 2019).

As we can see in Fig. 4a, after a peak in the early Sixties, government R&D over total constantly declined over the decades by plummeting towards levels just above one-fifth in most recent years. In Fig. 4b, we can see that from the Nineties there is an increasing gap between private and public R&D. This means that the private share of R&D is now the bulk of US research. Although this is not always directly linkable to the behaviour of basic research, such patterns go hand in hand with a sustained fall of basic research vis-à-vis applied research, and more generally with an overall content of research in which scientific discovery enjoys less attention (as already discussed before in the contributions of IMF, 2021). Such trends are not confined to the US but can be shown to feature now many advanced economies as well (Ziesemer, 2021a; Archibugi and Filippetti, 2018). Indeed, this evidence is consistent with that of Filippetti and Vezzani (2022, p. 2), when showing data for 41 countries from 1981 to 2017 on public- and business-funded R&D as shares of GDP comment on the remarkable "reduction of aggregate public R&D coupled with an increase of business R&D, with the gap among the two steadily increasing over the past four decades".

4. Data and methodology

4.1. Data

In what follows we will try to investigate systematically whether these descriptive trends can be all linked together for the sake of pointing out one possible cause of the unsatisfactory behaviour of labour productivity in recent years. To do this, we make use of quarterly data for the US economy provided by the Bureau of Economic Analysis (BEA), United States Patent and Trademark Office (USPTO), Bureau of Labor Statistics (BLS), and Federal Reserve Economic Data (FRED) for the 1948–2019 period. Specifically, public investment in R&D (G_RD), government expenditures net of G_RD (G), private research and development expenditure (RD), the gross domestic product (Y), the number of patents per hour worked (PAT), labour productivity (LP), and total factor productivity (TFP) are the variables included in the dataset. Details on the construction of the variables and data sources are provided in Table 1. Appendix A provides detailed descriptive statistics and visual representations of the variables considered in the analysis.

The empirical analysis tries to investigate whether the paradox highlighted by Gordon (2018a, 2018b) can be understood, at least partially, as a consequence of the shifting composition of R&D expenditures. The number of patents offers a measure of the dynamics of innovation, but at the same time, the inclusion of different types of R&D expenditures (federal and non-federal) allows us to understand their relative effect on measures of productivity. Additionally, our empirical analysis investigates whether public investment in R&D (G_RD) and generic public expenditure (G) can influence private R&D expenditure (RD) and the number of patents per hour worked (PAT) (Deleidi and Mazzucato, 2021; Jørgensen and Ravn, 2022). We estimate two main models. In Model 1 as the main variable of interest, we use labour productivity, which is taken as real GDP per hour worked. In Model 2 we use total factor productivity (Soete et al., 2020; Moretti et al., 2019; Herzer, 2021).[10]

The work is based on two premises. First, we use the flows of R&D expenditure instead of the stocks built using the perpetual inventory

[8] See Becker (2015) and Ziesemer (2021b) for extensive literature reviews.

[9] As Van Reenen (2021, p. 16) aptly puts it, "[t]he good news is that we have abundant empirical evidence that faster technological innovation boosts productivity growth. The bad news is that we also know that the private sector will not provide enough research and development (R&D) if left to itself".

[10] However, we prefer labour productivity as an indicator of the productivity pattern given the interpretative difficulties that the use of TFP entails (Felipe and McCombie, 2007).

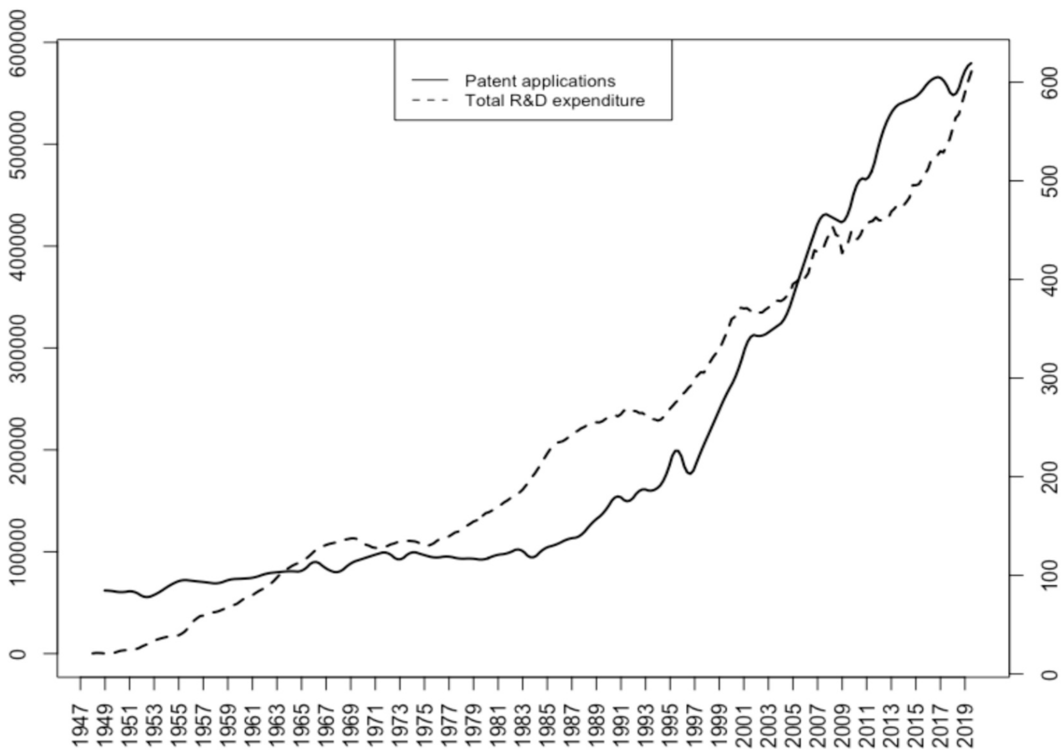


Fig. 1. Patent applications (left axis) and Total R&D expenditure (right axis) (public and private R&D, billions of dollars, deflated by GDP deflator) (1948Q1-2019Q4). *Source*: USPTO, Bureau of Economic Analysis.

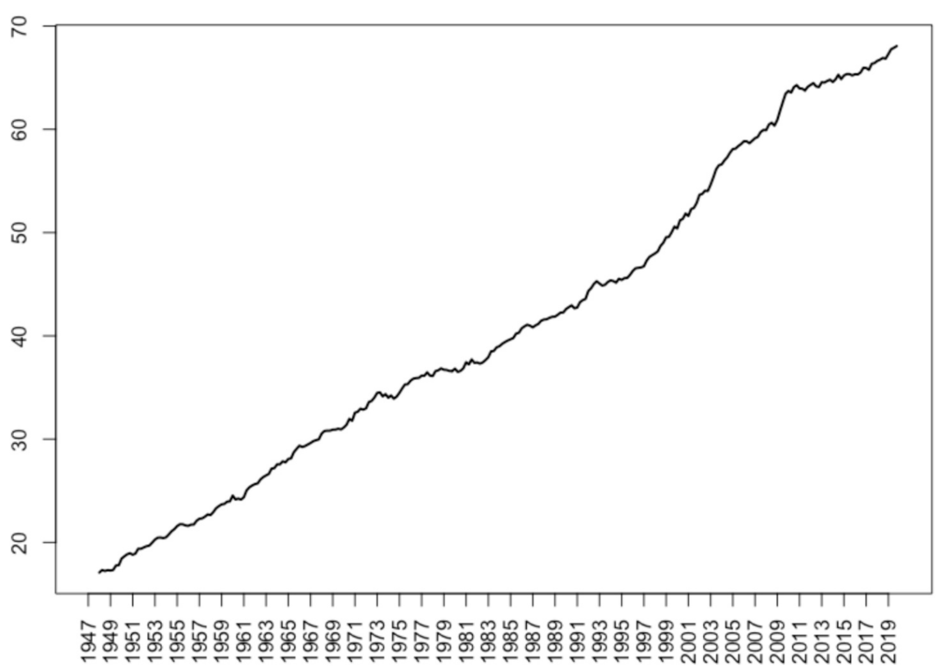


Fig. 2. Labour productivity calculated as real GDP per hour worked (US, 1948Q1-2019Q4). *Source*: FRED and Bureau of Labor Statistics.

method, as the literature generally does. This is because such a method produces series that are usually integrated, and with our data, the stocks take up orders of integration higher than one. This does not allow the inclusion of such a series in an SVAR analysis. Therefore, in this respect, we are closer to the type of analysis carried out by Goel et al. (2008), and Deleidi and Mazzucato (2021), as we use the flows of R&D.

Second, that the US can be treated as a relatively closed system. Such assumption is supported by empirical evidence and this point is relevant as it is common practice to address in this field of studies the cross-border spillover effects stemming from international R&D (Van Elk et al., 2019). As Ziesemer (2022) reports, the literature on international R&D spillovers on the US economy generally found them not to be relevant. Among others, see also Bernstein and Mohnen (1998), Atukeren (2007), and Luintel and Khan (2004).

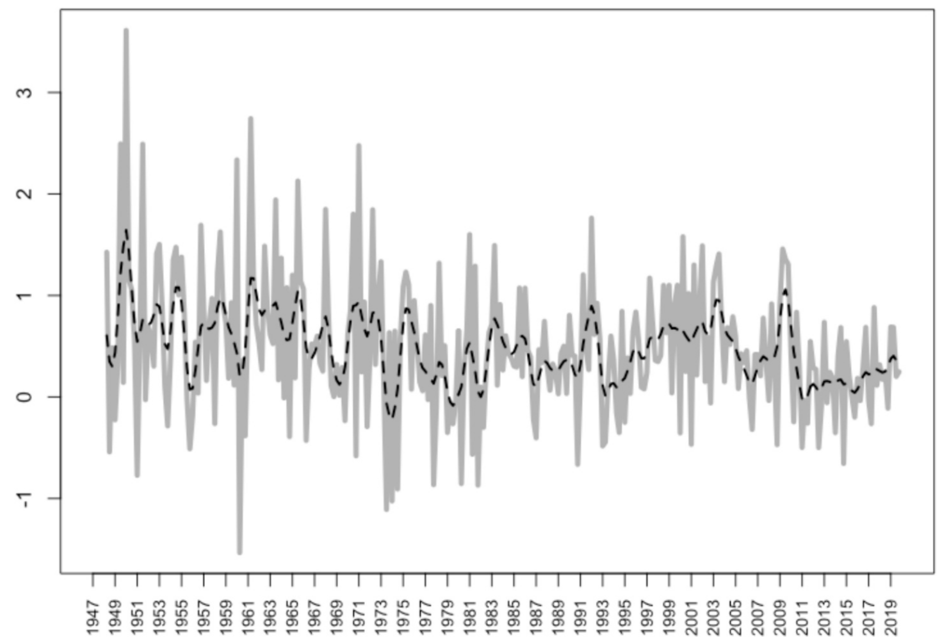


Fig. 3. Growth rates of labour productivity, percent change at an annual rate, quarterly (US, 1948Q1-2019Q4). Source: FRED and Bureau of Labor Statistics.

4.2. Methods

To detect the effect of different types of R&D expenditures, generic public expenditures, and the number of patents per hour worked on productivity, we use SVAR models. An SVAR is represented as follows in eq. (1):

$$B_0 y_t = a + \sum_{i=1}^{p} B_i y_{t-p} + w_t \tag{1}$$

Where y_t is the $k\,x\,1$ vector of considered variables, a is the constant term, B_i is the $k\,x\,k$ matrix of autoregressive slope coefficients, and w_t is the vector of structural shocks. To obtain structural shocks, an identification strategy needs to be implemented by imposing restrictions in B_0 that is the matrix of contemporaneous relationships among considered variables.[11] Once restrictions are imposed in B_0 and structural shocks are estimated, impulse response functions (IRFs) are computed to detect causality among considered variables and evaluate the effect produced by identified shocks on variables included in the model (Kilian and Lütkepohl, 2017). Standard errors are estimated through Hall's studentized bootstrap (1000 repetitions) and IRFs are reported with one and two standard error bands, namely considering a 68 % and 95 % confidence interval. Given the quarterly nature of the data, we chose $p = 4$.[12]

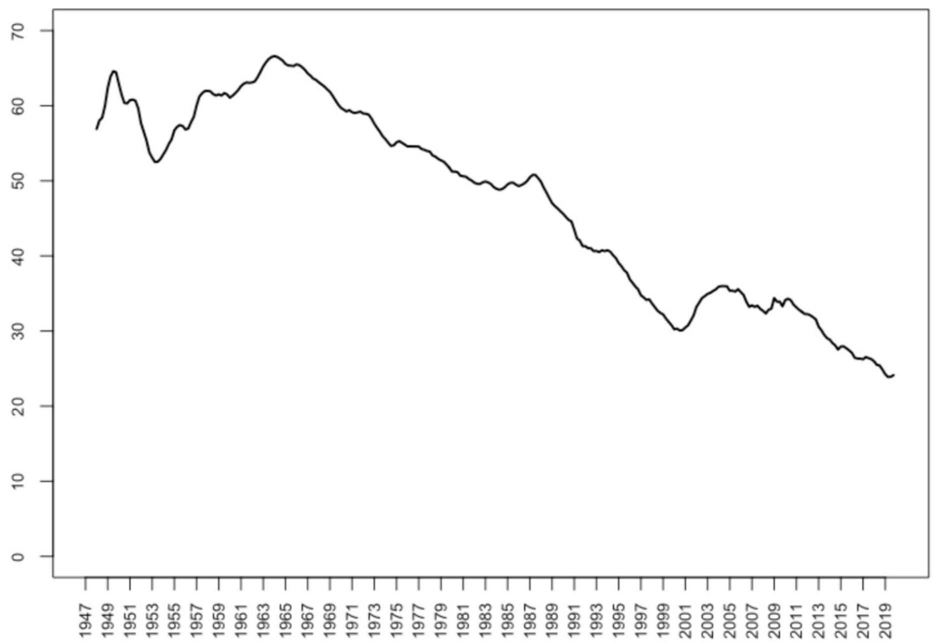
A fundamental step is the identification of structural shocks. For such sake, we make use of both short-run zero exclusion restrictions and a Cholesky factorization. This is shown through the identification presented in (2).

$$B_0 y_t = \begin{bmatrix} - & 0 & 0 & 0 & 0 & 0 \\ - & - & 0 & 0 & 0 & 0 \\ - & - & - & 0 & 0 & 0 \\ - & - & - & - & 0 & 0 \\ - & - & - & - & - & 0 \\ - & - & - & - & - & - \end{bmatrix} \begin{bmatrix} G\_RD_t \\ G_t \\ RD_t \\ Y_t \\ PAT_t \\ LP_t \end{bmatrix} \tag{2}$$

where ' – ' indicates an unrestricted parameter and '0' represents a zero restriction. In the identification strategy, we assume that within the quarter, public investment in R&D (G_RD) is independent of changes in G, RD, Y, PAT and LP. Changes in government R&D expenditures can be considered exogenous variations reflecting political priorities that are independent of GDP and productivity shocks (Mowery, 2010, 2012; Moretti et al., 2019; Deleidi and Mazzucato, 2021). Indeed, government R&D spending, in particular in the US where it is also largely tied to the defense sector, is carried out in light of considerations that "are largely independent of productivity shocks in different domestic industries" (Moretti et al., 2019, p. 2). G is the second ordered variable, considered less strategically relevant than G_RD. This is supported by the empirical literature on fiscal multipliers, in which the order of fiscal variables depends also on the policy relevance of considered spending components (e.g., Auerbach and Gorodnichenko, 2012; Deleidi et al., 2023b). The third variable is private R&D investment (RD). Such variable is supposed to be liable to be affected within the quarter by G_RD and G, but not by Y. Such choice is driven by the consideration that firms, before deciding to change their R&D investments, must at first perceive changes in the level of GDP as persistent. This strategic change cannot be based on events that happen only within the quarter. The fourth variable is GDP (Y) which is influenced by all spending variables within the quarter, while the last two ordered variables are the number of patents per hour worked (PAT) and labour productivity (LP). Following Romero and Britto (2017) and Ahmad (2021) we consider the number of patents per hour worked influenced within the quarter by all spending variables and Y. Finally, LP is the most endogenous variable that can be affected by different government spending components and output dynamics following the Kaldorian tradition (e.g., Kaldor, 1961, 1978) and the recent more empirically-based literature (McCombie and Spreafico, 2016), also using SVAR modelling (e.g., Bachmann and Sims, 2012; Jørgensen and Ravn, 2022; Deleidi et al., 2023a). Furthermore, productivity dynamics may be influenced by also more supply-side

[11] The covariance matrix of structural errors is normalized: $\mathbb{E}(w_t w_t') = \sum_w = I_K$.

[12] We ran diagnostic tests to assess the adequacy and completeness of the produced estimates. There is no serial and auto-correlation in estimated models. Results are available upon request.



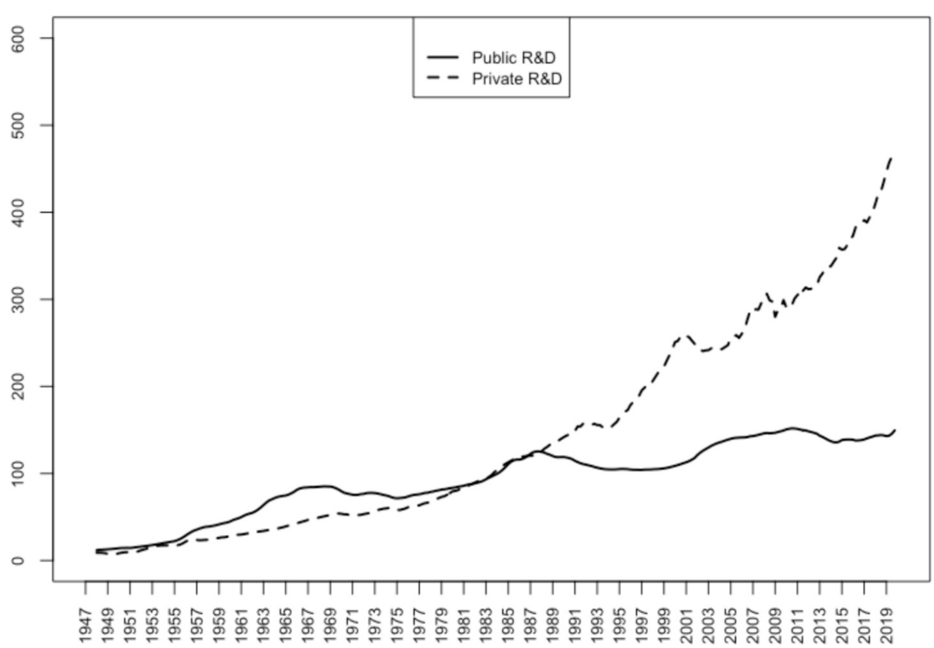


Fig. 4a and 4b. Ratio between public R&D and total R&D (public plus private R&D) (US, 1947Q1-2019Q4, real flows) (4a); Public and private R&D, billions of dollars, deflated by GDP deflator (US, 1947Q1-2019Q4, real flows) (4b). Source: Bureau of Economic Analysis.

variables, such as private R&D and patenting activities. Therefore, by assuming labour productivity as endogenous, we suppose that innovation processes may be determined both by supply and demand factors. While the demand factors are those related to government expenditures and GDP, supply factors are expressed via the inclusion of patents and private R&D. In Model 2 we replace labour productivity (LP) with total factor productivity (TFP) adopted as the most endogenous variable to be included in identification (5). Each model specification is estimated for the whole sample (1948Q1-2019Q4) and excluding the post-crisis period (1948Q1-2007Q4). This is made to understand whether the results are robust to a change in the period covered by the dataset.

5. Findings

In this section, we now show the results of our estimated models. Specifically, we display both the estimated IRFs as well as the cumulative responses of our variables of interest. Figs. 5 and 6 show the estimated IRFs of Models 1 and 2 for the whole period (1948Q1-2019Q4),

Table 1
List of variables used in the empirical analysis, and their description.

Variables	Description	Source
G_RD	Government gross investment: Research and development, billions of dollars, quarterly, seasonally adjusted annual rate. Deflated by DEFL.	BEA
G	Government consumption expenditures and gross investment net of G_RD, billions of dollars, quarterly, seasonally adjusted annual rate. Deflated by DEFL.	BEA
RD	Gross private domestic investment: Research and development, billions of dollars, quarterly, seasonally adjusted annual rate. Deflated by DEFL.	BEA
Y	Gross domestic product, billions of dollars, quarterly, seasonally adjusted annual rate. Deflated by DEFL.	BEA
PAT	Sum of patent applications of US residents, from annual to quarterly (Denton interpolation) divided by hours worked (H).	USPTO
LP	Gross domestic product (Y) divided by hours worked (H).	BEA, BLS
TFP	Level of TFP obtained from business sector TFP growth rates, quarterly, variable in percentage change at an annual rate.	FRED
H	Hours worked in total U.S. economy, billions, seasonally adjusted.	BLS
DEFL	Gross domestic product: Implicit price deflator, quarterly index, 2012 = 100, seasonally adjusted.	BEA

whereas Figs. B1 and B2 in Appendix B show the estimated IRFs of Models 1 and 2 over a shorter time horizon that stops before the unravelling of the Great Recession (1948Q1-2007Q4).

From estimated IRFs we obtain the elasticities of labour productivity (LP) with respect to government investment in R&D (G_IN), generic public expenditure (G_R), private R&D (R&D), and the number of patents per hour worked (PAT). We also have the elasticities of PAT with respect to public expenditure in R&D (G_IN), generic public expenditure (G_R), and private R&D (R&D). In the cases of the effects of public expenditure (G_RD and G) on private R&D (RD) from estimated elasticity, we also compute multipliers which quantify how much additional private research and development expenditure we obtain given one more dollar spent by the government. Therefore, to estimate the corresponding multipliers, it is necessary to multiply the estimated coefficient by an *ex-post* conversion factor equal to the average value of private R&D expenditure (RD) divided by the selected fiscal variable.[13] Following the literature on fiscal multipliers, we estimate the cumulative response of our variables of interest to the selected fiscal policy shocks (Ramey and Zubairy, 2018). The cumulative effect is estimated by dividing the cumulative change in the variable of interest $\Delta y_{i,t+h}$ by the cumulative change in the selected fiscal expenditure $\Delta x_{i,t+h}$. Using this method, we can calculate the response of our variable of interest per unit of spending. We show the results we got in the following tables.

In Table 2 we report the cumulative elasticities on labour productivity (LP) and total factor productivity (TFP) of shocks in public investment in R&D (G_RD), total public expenditure (G), private R&D investment (RD), and patent per hour worked (PAT). In Table 3 we display the cumulative elasticities on the numbers patent per hour worked (PAT) of shocks to public investment in R&D (G_RD), total public expenditure (G), and private R&D investment (RD). Finally, Tables 4 and 5 display the cumulative elasticities and multipliers on private R&D expenditure (RD) of the two different types of public expenditure (G_RD and G).

As Table 2 shows public expenditure in innovation (G_RD), generic public spending (G), private R&D (RD), and patent per hour worked (PAT) exhibit a positive effect, both on labour productivity (LP) and on total factor productivity (TFP). Public expenditure in innovation (G_RD) and generic public spending (G) exhibit a higher impact than that of private expenditure in innovation. The average cumulative elasticity for Model 1 is 0.08, 0.10, and 0.04 respectively for public R&D (G_RD), total public expenditure (G), and private R&D expenditure (RD) (Table 2). The corresponding elasticities for Model 2 in which total factor productivity is considered are 0.48, 0.25, and 0.22. The number of patents per hour worked (PAT) exert a positive cumulative elasticity that is on average equal to 0.24 both for labour productivity (LP) and total factor productivity (TFP) (Table 2). Table 2 shows that models on the shorter 1948Q1-2007Q4 horizon yield similar results. Table 3 displays the cumulative elasticities of PAT to public investment in R&D (G_RD), generic fiscal expenditure (G) and private R&D (RD). Our results suggest that generic fiscal expenditure (G) produces a higher impact on PAT, with an average cumulative elasticity equal to 0.44 for Model 1, and 0.42 for Model 2. Looking at the effect of the different R&D expenditure components, while G_RD does not seem to influence PAT, private R&D investment seems to have a positive, though not always significant, effect (Table 3). The results are robust also in the case of the shorter 1948Q1-2007Q4 horizon. Tables 4 and 5 analyse whether public expenditure in innovation (G_RD) and generic residual public expenditure (G) crowd in private expenditure in innovation (RD). Looking at the cumulative elasticities in Table 4 we find that Public expenditure in innovation (G_RD) exerts a positive cumulative elasticity that is on average equal to 0.48 and 0.43 respectively in Model 1 and 2 (Table 4). The corresponding cumulative elasticities for total public expenditure (G) are equal to 0.38 in Models 1 and 2. In Table 5 we report the multipliers which quantify how much additional private R&D expenditure (RD) we obtain given one more dollar spent by the government in public R&D and generic fiscal expenditure (G_RD and G). Our results suggest that public R&D investment (G_RD) generates the highest effect on private R&D investment (RD). The average cumulative multipliers are equal to 0.63 in Model 1 and 0.56 in Model 2. The corresponding value for generic public expenditure (G) is equal to 0.03 in Models 1 and 2. The results are robust also in the case of the shorter 1948Q1-2007Q4 horizon.

Our results illustrate that productivity dynamics are influenced by both demand- and supply-side measures. Specifically, we find that public investment in R&D, generic fiscal expenditure, private R&D investment, and the number of patents per hour worked positively impact labour productivity and total factor productivity. Additionally, from our estimates, we can see that labour productivity shows a neatly greater response to changes in the public types of expenditure rather than the private. In fact, we can see from Table 2 that on average public expenditure in R&D and residual generic public spending exhibit a higher positive impact than private R&D. Such kind of evidence adds to the results obtained by Goel et al. (2008), Deleidi and Mazzucato (2021), Ziesemer (2021a) for what concerns the positive impacts of public R&D on GDP and TFP. Considering the effect on PAT our results show that both generic public expenditure (G) and private R&D investment exert a positive impact. Public spending on R&D has no effect on the number of patents per hour worked. These results can be read in light of the fact that this type of public expenditure is more focused on basic research, which has fewer clear commercial applications (Van Reenen, 2021; Moss et al., 2020).

When we turn the attention to the possibility of crowding-in effects generated by government expenditures in innovation, other relevant outcomes arise. As we can see, the evidence appears to buttress the case for substantial crowding-in of public R&D with respect to private R&D (Aschhoff and Sofka, 2009). In both models, private research and development spending strongly reacts to public R&D, and they do it with a stronger response at impact, thereby pinning down an immediate crowding-in of private research. Analogously to Moretti et al. (2019), we find that public R&D is liable to generate a considerable share of private R&D. Thus, we can reconsider the adverse effects caused by subdued

[13] The ratios used in the ex-post transformation from elasticities to partial derivatives are calculated as follows: RD/G_RD; RD/G. They assume the following values respectively: 1.30; 0.07.

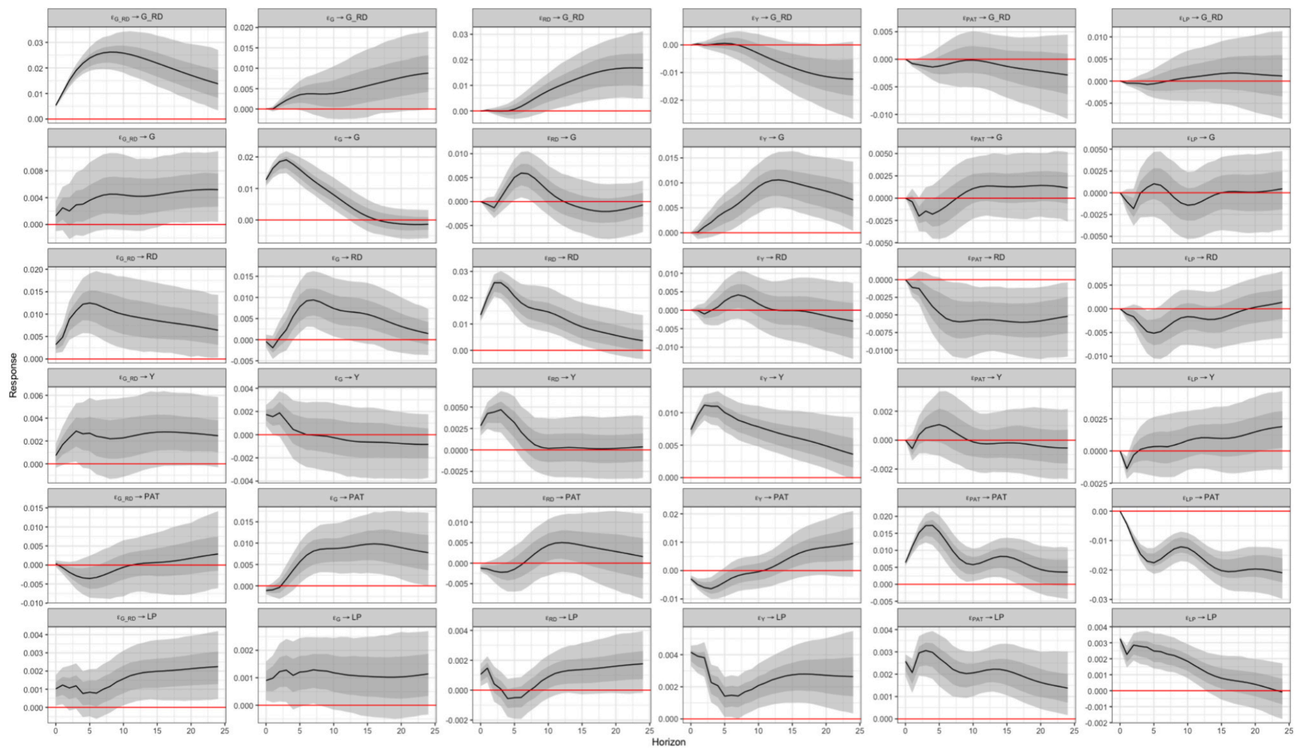


Fig. 5. Impulse response functions (IRFs) obtained from the SVAR estimation on Model 1 for the period 1948Q1-2019Q4. Shaded areas are 68 % and 95 % confidence bands estimated through a Bootstrapping procedure (1.000 repetitions). *Source*: author's elaboration.

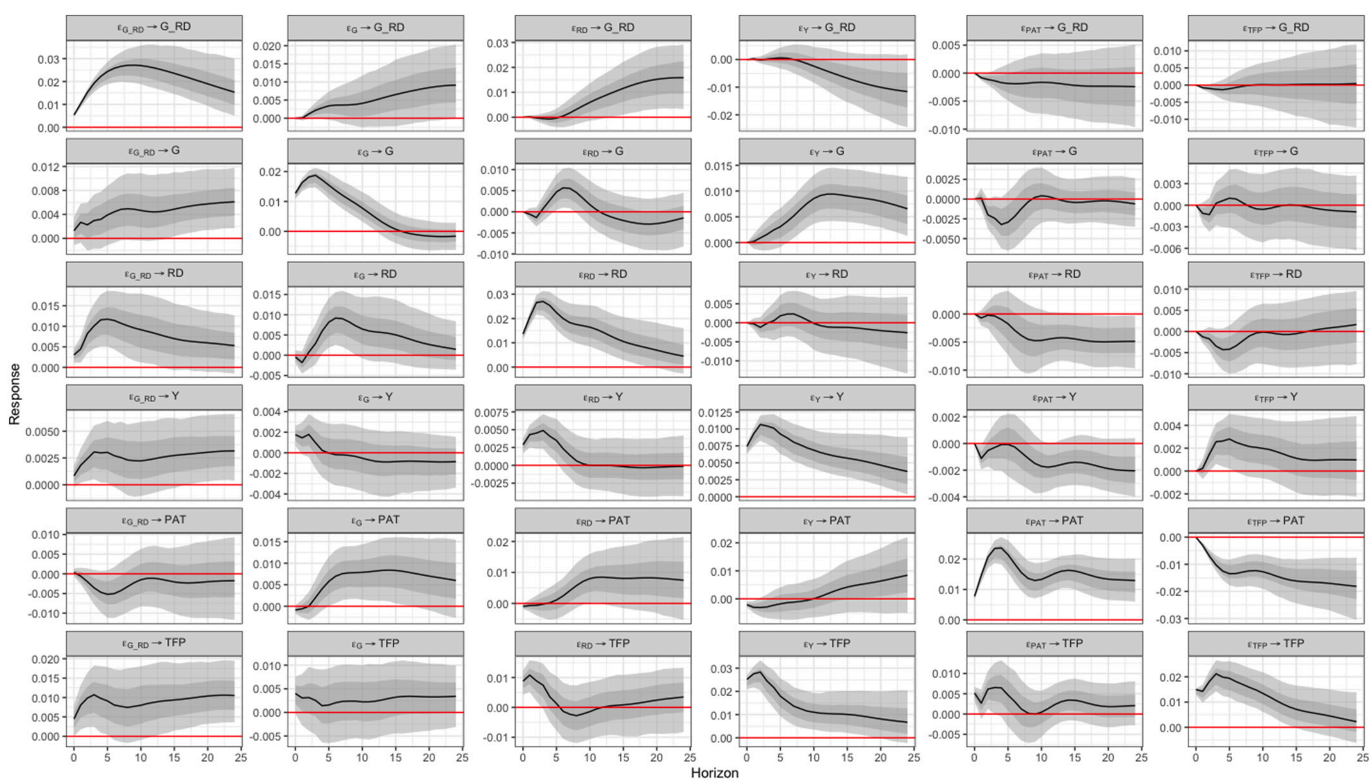


Fig. 6. Impulse response functions (IRFs) obtained from the SVAR estimation on Model 2 for the period 1948Q1-2019Q4. Shaded areas are 68 % and 95 % confidence bands estimated through a Bootstrapping procedure (1.000 repetitions). *Source*: author's elaboration.

public R&D expansion also in terms of the missing private R&D that a sustained expansion of the former type of R&D would have generated (ibid., p. 5).

Furthermore, at odds with the previous case, here we clearly see a different impact of different types of public expenditure on private R&D. Indeed, together with the remarkable effect of public R&D we also see a

Table 2
Cumulative elasticities of labour productivity (LP) and total factor productivity (TFP) with respect to government R&D (G_RD), generic public expenditure (G), private R&D (RD) and patent per hour worked (PAT) obtained from Models 1 and 2 for the horizon 1948Q1-2019Q4 and 1948Q1-2007Q4. In the last two columns peak elasticities and average elasticities are shown. Significative estimates are in bold (68 %). Source: author's elaboration.

	Cumulative Elasticities (LP)							
	1Q	5Q	10Q	15Q	20Q	25Q	Peak	Av 25Q
Model 1 (1948–2019)								
G_RD	**0.19**	**0.07**	**0.05**	**0.06**	**0.07**	**0.08**	0.19 (1)	0.08
G	**0.07**	**0.06**	**0.08**	**0.11**	**0.13**	**0.17**	0.17(25)	0.10
RD	**0.08**	0.02	0.01	**0.03**	**0.05**	**0.08**	0.08 (1)	0.04
PAT	**0.40**	**0.20**	**0.21**	**0.23**	**0.24**	**0.26**	0.40 (1)	0.24
Model 1 (1948–2007)								
G_RD	**0.22**	0.06	**0.03**	**0.04**	**0.05**	**0.05**	0.22 (1)	0.08
G	**0.05**	**0.05**	**0.07**	**0.08**	**0.11**	**0.14**	0.14(24)	0.08
RD	**0.09**	0.03	0.02	**0.03**	**0.05**	**0.08**	0.09 (1)	0.04
PAT	**0.39**	**0.20**	**0.22**	**0.25**	**0.28**	**0.32**	0.39 (1)	0.25
	Cumulative Elasticities (TFP)							
Model 2 (1948–2019)								
G_RD	**0.84**	**0.59**	**0.41**	**0.38**	**0.40**	**0.43**	0.84 (1)	0.48
G	**0.31**	0.17	0.17	0.22	0.33	**0.45**	0.45(25)	0.25
RD	**0.64**	0.35	0.15	0.11	0.12	0.15	0.64 (1)	0.22
PAT	**0.66**	0.30	0.21	**0.19**	0.19	0.18	0.66 (1)	0.24
Model 2 (1948–2007)								
G_RD	**1.01**	**0.60**	**0.38**	**0.34**	**0.35**	**0.37**	1.01 (1)	0.46
G	**0.21**	0.14	0.22	0.30	**0.43**	**0.57**	0.57(25)	0.30
RD	**0.76**	0.36	0.13	0.04	0.02	**0.04**	0.76 (1)	0.18
PAT	**0.68**	**0.31**	0.26	**0.30**	**0.34**	**0.38**	0.68 (1)	0.33

Table 3
Cumulative elasticities of patent per hour worked (PAT) with respect to government R&D (G_RD), generic public expenditure (G), private R&D (RD) obtained from Models 1 and 2 for the horizon 1948Q1-2019Q4 and 1948Q1-2007Q4. In the last two columns peak elasticities and average elasticities are shown. Significative estimates are in bold (68 %). *Source*: author's elaboration.

	Cumulative Elasticities (PAT)							
	1Q	5Q	10Q	15Q	20Q	25Q	Peak	Av 25Q
Model 1 (1948–2019)								
G_RD	**0.07**	**−0.12**	0.11	−0.06	−0.04	−0.01	−0.12(5)	−0.06
G	**−0.09**	**0.03**	**0.28**	**0.50**	**0.78**	**1.07**	1.07(25)	0.44
RD	**−0.09**	−0.08	−0.02	**0.09**	0.13	0.16	0.16(25)	0.03
Model 1 (1948–2007)								
G_RD	0.09	−0.10	−0.07	−0.02	0.01	0.03	−0.11(6)	−0.03
G	**−0.10**	**0.01**	**0.23**	**0.43**	**0.71**	**0.99**	0.99(25)	0.38
RD	**−0.12**	−0.07	**0.03**	**0.18**	0.26	0.29	0.29(25)	0.10
Model 2 (1948–2019)								
G_RD	**0.07**	**−0.14**	0.15	−0.11	−0.11	−0.11	−0.17(6)	−0.11
G	**−0.07**	**0.06**	**0.28**	**0.49**	**0.73**	**0.98**	0.98(25)	0.42
RD	−0.07	−0.02	**0.09**	**0.21**	**0.31**	**0.40**	0.40(25)	0.16
Model 2 (1948–2007)								
G_RD	0.11	**−0.13**	−0.13	−0.07	−0.07	−0.08	−0.14(8)	−0.08
G	**−0.07**	**0.06**	**0.27**	**0.45**	**0.69**	**0.94**	0.94(25)	0.40
RD	**−0.12**	−0.03	**0.11**	**0.28**	**0.40**	**0.51**	0.51(25)	0.20

Table 4
Cumulative elasticities of private R&D expenditure (RD) with respect to government R&D (G_RD) and generic public expenditure (G) obtained from Models 1 and 2 for the horizon 1948Q1-2019Q4 and 1948Q1-2007Q4. In the last two columns peak elasticities and average elasticities are shown. Significative estimates are in bold (68 %). *Source*: author's elaboration.

	Cumulative Elasticities (R&D crowding-in effect)							
	1Q	5Q	10Q	15Q	20Q	25Q	Peak	Av 25Q
Model 1 (1948–2019)								
G_RD	**0.60**	**0.56**	**0.49**	**0.45**	**0.44**	**0.44**	0.60 (1)	0.48
G	**0.00**	**0.07**	**0.34**	**0.48**	**0.63**	0.72	0.72(25)	0.38
Model 1 (1948–2007)								
G_RD	**0.79**	**0.73**	**0.61**	**0.54**	**0.50**	**0.49**	0.79 (1)	0.59
G	**−0.05**	**0.09**	**0.43**	**0.63**	**0.82**	0.94	0.94(25)	0.50
Model 2 (1948–2019)								
G_RD	**0.56**	**0.52**	**0.45**	**0.40**	**0.37**	**0.37**	0.56 (1)	0.43
G	**−0.03**	**0.09**	**0.34**	**0.47**	0.60	0.69	0.69(20)	0.38
Model 2 (1948–2007)								
G_RD	**0.75**	**0.71**	**0.60**	**0.52**	**0.48**	**0.46**	0.75 (1)	0.57
G	**−0.06**	**0.08**	**0.41**	**0.57**	**0.73**	0.83	0.83(25)	0.45

Table 5
Cumulative crowding-in multipliers of private R&D (RD) with respect to government R&D (G_RD) and generic public expenditure (G) obtained from Models 1 and 2 for the horizon 1948Q1-2019Q4 and 1948Q1-2007Q4. In the last two columns peak elasticities and average elasticities are shown. Significative estimates are in bold (68 %). *Source*: author's elaboration.

Cumulative Multipliers (R&D crowding-in effect)								
	1Q	5Q	10Q	15Q	20Q	25Q	Peak	Av 25Q
Model 1 (1948–2019)								
G_RD	**0.78**	**0.72**	**0.64**	**0.58**	**0.57**	**0.57**	0.78 (1)	0.63
G	**0.00**	**0.01**	**0.02**	**0.03**	**0.04**	0.05	0.05(20)	0.03
Model 1 (1948–2007)								
G_RD	**0.85**	**0.79**	**0.66**	**0.58**	**0.54**	**0.53**	0.85 (1)	0.64
G	**0.00**	**0.01**	**0.03**	**0.04**	**0.05**	0.06	0.06(25)	0.03
Model 2 (1948–2019)								
G_RD	**0.73**	**0.67**	**0.58**	**0.52**	**0.49**	**0.48**	0.73 (1)	0.56
G	**0.00**	**0.01**	**0.02**	**0.03**	0.04	0.05	0.05(20)	0.03
Model 2 (1948–2007)								
G_RD	**0.81**	**0.77**	**0.65**	**0.52**	**0.52**	**0.50**	0.81 (1)	0.62
G	**0.00**	**0.00**	**0.03**	**0.03**	**0.04**	0.05	0.05(25)	0.03

much lower, albeit positive, effect of generic public expenditure. This is not surprising as the specificity of research and development expenditures calls into play a type of complementarity between the public and private sectors which can hardly exist when we consider the generic residual expenditure of the government. Therefore, in light of Bloom et al. (2019) cookbook for innovation policies, it appears that a direct decision from the government side to carry out public research and development activities can be considered a very powerful tool to enhance overall domestic research and development.

6. Conclusions

The patterns of technical progress and its progressively waning impact on labour productivity growth are at the centre of the analysis for what concerns the issue of long-lasting stagnation. Solow (1987) in the past as well as Gordon (2018a), Gordon, 2018b), together with other authors, warned about the possibility for innovation and growth not to necessarily proceed hand in hand. These gloomy prospects recently found further backup from the studies on research productivity, which has been falling in the last decades, thereby adding concerns about the foreseeable trends of productivity and GDP growth (Bloom et al., 2020; Cauwels and Sornette, 2022). This latter phenomenon occurs in an environment in which we also witness a progressive retreat of the public sector from R&D activity (Goel et al., 2008; Archibugi and Filippetti, 2018). Our SVAR analysis of the US economy shows that public innovation spending exerts a positive effect on productivity, and together with generic public expenditure, it has a greater effect than private expenditure on innovation. Therefore, our findings suggest that a sustained decline in public innovation spending relative to private investments may contribute to stagnation. Our results align with academic and institutional literature advocating for increased research inputs and highlighting the decline in publicly funded basic research (European Commission, 2018; Mazzucato, 2018; Bloom et al., 2020; Van Reenen, 2021). Echoing recommendations from the IMF (2021, 2024), our study underscores the importance of governments allocating resources to R&D activities. Public research institutions and universities play a crucial role in driving major scientific breakthroughs and high-risk innovations, such as electricity, chemicals, ICT, pharmaceuticals, GPS, and the internet, areas less pursued by private sector research focused on immediate commercial applications and patents (Archibugi, 2017; Van Reenen, 2020, 2021). Such strategic innovation policies have the potential to drive structural economic transformations by attracting private R&D investment and fostering new market opportunities beyond current technological paradigms (Mazzucato, 2018).

Before concluding, we must point out that we performed our empirical investigation using productivity measures as our main indicators to assess the economic impact of public and private expenditures on innovation. Nonetheless, we mention the following considerations as food for thought and possible future offsprings. First, in a service-oriented society, these measures may not fully capture relevant dimensions of economic progress. One way to look at this issue is by recalling Baumol (1967) seminal contribution stressing that tertiarisation can undermine aggregate productivity growth. Recently, Rial and Fernández (2023) empirical analysis of major advanced economies confirms Baumol's insight by showing that in the long term tertiarization engenders falling employment in the more technologically advanced sectors. In light of our enquiry, it is relevant to note that those sectors are exactly those more likely to be impacted by public and private expenditures in innovation. Another way is to evaluate the possibility of exploring also alternative measures, such as life expectancy, to assess innovation's impact. In this vein, Kuhn et al. (2023) pay specific attention to the role of innovation in the medical sector and how it can positively affect health, life expectancy, and in turn also economic growth.

Moreover, further research is needed to extend our findings beyond the US, exploring non-linear dynamics, conducting sector-specific analyses, and considering different measures of technological progress.

Credit authorship contribution statement

Giovanna Ciaffi: Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. **Matteo Deleidi:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Stefano Di Bucchianico:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Validation, Writing – original draft, Writing – review & editing.

Data availability

All data are publicly available.

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Declaration of competing interest

The authors declare that they have no competing interests.

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