Should the US increase subsidies to R&D? Lessons from an endogenous growth theory

By Manuel A. Gómez* and Tiago Neves Sequeira[y]

*Departamento de Economía Aplicada II, Universidad de A Coruña, Campus de Elviña, 15071 A Coruña, Spain; e-mail: mago@udc.es
yDepartamento de Gestaˇo e Economia and CEFAGE-UBI, Universidade da Beira Interior, Estrada do Sineiro, 6200-209 Covilhaˇ; e-mail: sequeira@ubi.pt

In this article we devise an endogenous growth model with R&D, physical capital, and human capital with several externalities. The model is calibrated to the US economy and used to quantitatively evaluate the effect on growth and welfare of implementing different budget-neutral policies. The welfare effects of different policies are calculated by taking into account the transitional dynamics of the economy after the policy reform. Our main findings have policy implications; mainly, subsidies to research are the most welfare-increasing amongst the budget-neutral policies, and the optimal structure of subsidies entails substantially increasing the subsidy to R&D, maintaining a zero subsidy to production, and reducing the subsidy to education, so as to keep the intertemporal government budget balanced. A detailed sensitivity analysis shows the robustness of these results.

JEL classifications: H20, H60, O30, O40.

1. Introduction

Policy-makers should have theoretical guidance on how to allocate tax revenues in subsidizing the different activities in the economy. The goal of this article is to determine the effects of different budget-neutral fiscal policies on growth and welfare. In particular, we analyse the optimal subsidies structure that could be set using the current tax scheme in the US. We address this issue by using a model that includes R&D and human and physical capital as engines of endogenous growth, which also encompasses the most relevant taxes and subsidies. The model is calibrated using US data to provide quantitative policy implications. Our focus on budget-neutral policies gains more importance in the current discussion on the paths to overcome the current crisis in the developed countries, which have large deficits and low growth as the two major issues.

Considering different engines of endogenous growth is important given our wish to evaluate the effect of different types of subsidy policies. We therefore consider an extension of the endogenous growth model devised by Arnold (2000) and Funke and Strulik (2000), which incorporates physical capital accumulation, human capital accumulation, and R&D. Another important issue is the adherence to reality of the market failures associated with these sources of growth. Regarding the innovative activity, empirical evidence supports the existence of R&D spillovers and an external effect associated with the duplication and overlap of research effort (e.g., Jones, 1995; Porter and Stern, 2000; Pessoa, 2005). Regarding human capital, two main types of external effects have been proposed in the literature. One is linked with the effect of average human capital on income and thus on returns to education. However, Acemoglu and Angrist (2000) and Ciccone and Peri (2006) showed that empirical evidence does not support its existence. The other is linked with the peer-effects in the educational system, i.e., students within better classes and with better educated parents achieve higher results. This externality seems to be empirically plausible, as shown by Rangvid (2003), Lefgren (2004), and Calvó-Armengol et al. (2009). Based on the former evidence, our model includes the standard duplication externalities and spillovers in R&D à la Jones (1995) as well as creative destruction associated with the innovation activity; monopolistic competition and the surplus appropriability problem associated with the capital intermediate goods sector, and learning externalities in human capital accumulation. The subsidies considered are directed to the sources of these inefficiencies: a subsidy to R&D costs, a subsidy to intermediate-goods production costs and a subsidy to education costs.

The main distinctive features of our analysis are the following. First, we implement our analysis studying not only steady-state features but also transitional dynamics. This will prove to be essential in accounting for the overall effects of different policies. Second, we jointly study and compare the effects of policies linked with R&D and human and physical capital. Third, we start from a realistically calibrated model, considering actual values for the fiscal system in the US. Fourth, we focus on budget-neutral policy reforms that keep the intertemporal government budget balanced. As growth and deficits are amongst today's concerns, focusing on budget-neutral policies contributes to the discussion of the most useful policies to promote growth and welfare without compromising the government budget. Fifth, we depart from the usual procedure of comparing the influence on welfare (i.e., lifetime utility) and growth of a given percentage change in each subsidy or tax rate. The base to which this change applies may be quite different, so the same percentage points change may have quite different effects on the government budget depending on the tax or subsidy chosen. Hence, as a normalization procedure, we assume that the government reduces its lump-sum expenditures by a given percentage share of GDP (say, a 0.5%), and that this revenue is used to finance an increase in a subsidy or a reduction in a tax in a budget-neutral manner, while keeping constant the other tax and subsidy rates. We also provide policy advice concerning the budget-neutral welfare-maximizing subsidy scheme for the given tax structure; i.e., we compute the subsidy rates that maximize the agent's utility while keeping the intertemporal government budget balanced. Sixth, in order to study the robustness of our results, we perform a detailed sensitivity analysis, which is not only constrained to change some parameter values, as usually is, but also includes changing several important characteristics of the model. In particular, we extend the model to incorporate a different type of learning externality and the labour-leisure margin of choice.

Analysing the effect of compensated changes on the taxes or subsidies that are present in our economy, we find that the most welfare-increasing budget-neutral policy change is to increase the subsidy to R&D costs. Hence, a government seeking to increase welfare without compromising its budget should rely more on the research policy. In contrast, the most long-run growth-improving policy would be to increase the subsidy to education. Subsidies to both R&D and education have long-lasting positive effects on economic growth, but only the subsidy to human capital has a permanent effect on growth. This means that the stronger welfare effect of R&D subsidies along the long-lasting transitional phase more than compensates the lower long-run effect relative to education subsidies, which yield a higher long-run growth rate. This amply justifies the consideration of transitional dynamics. We also compute the optimal budget-neutral structure of subsidies and we find that a slight decrease in the subsidy to education and a great increase in the R&D subsidy would be optimal. The robustness of these results is tested against important alternative assumptions on both the calibration side and on the functional side; in particular, to the introduction of leisure in utility. Our results prove to be robust to these changes.

Some related research has been recently reported. Sequeira (2008) compares the growth and welfare effects of R&D and education subsidies. However, duplication externalities and R&D spillovers are absent from the model, so innovation depends only on effective labour, which leaves a small role for R&D subsidies. Furthermore, fiscal reforms are not budget-neutral and the optimal subsidy structure is not computed. Grossmann *et al.* (2013) characterize the optimal subsidies to R&D and to capital costs taking into account transitional dynamics, financed by lump-sum taxation or factor income taxation. However, they consider a semi-endogenous growth model *à la* Jones (1995) which does not include human capital as an engine of growth. In particular, this means that there is no role for learning externalities and the subsidy to human capital accumulation. Grossmann *et al.* (2010) analyse the optimal subsidy structure in a model that incorporates human capital. However, they consider a semi-endogenous growth model in which economic growth is driven solely by exogenous population growth, so it is independent of the government policy. This has important implications for the role of the fiscal policy. Another major difference is that they do not consider budget-neutral policies. Thus, in net terms some form of lump-sum taxes (or transfers) is necessary to balance the intertemporal government budget. Other related research (e.g., Jones and Williams, 2000; Alvarez-Pelaez and Groth, 2005; Steger, 2005; Strulik, 2007) has assessed the differences between the market outcome and the social optimum focusing only on the stationary equilibria and, thus, has, disregarded transitional dynamics. Finally, none of these works analyse the sensitivity of their results to key structural features of the model, as we do in this paper.

The rest of the paper is organized as follows. In Section 2 we characterize the model and its market equilibrium. In Section 3 we calibrate the model with data for the main macroeconomic variables in the US. In Section 4 we numerically evaluate the impact of implementing several policies. In Section 5 we perform a detailed sensitivity analysis of the results. Finally, in Section 6 we present our conclusions.

2. Model

As a benchmark we consider an endogenous growth model with physical capital, human capital and R&D. The economy is inhabited by a constant population of identical representative agents. For simplicity, population is normalized to one, so we may read all variables as *per capita* values. There are three production sectors in the economy: a competitive final-good sector, a monopolistic intermediate-goods sector, and a competitive R&D sector. The government taxes income, consumption, and firms profits. The revenue raised is used to subsidize intermediate-goods production costs, R&D costs and education costs, as well as to provide lump-sum transfers to agents representing welfare programmes. This model combines features studied in Gómez (2011) and Gómez and Sequeira (2012), but additionally introduces a complete fiscal system.

2.1 Agents

The representative agent derives utility from consumption, C, according to

$$U = \int_0^{\infty} \frac{C^{1-\theta}-1}{1-\theta} e^{-\rho t} dt, \quad \rho > 0, \quad \theta > 0, \qquad (1)$$

where ρ denotes the time preference rate, and $1/\theta$ is the elasticity of intertemporal substitution. The agent is endowed with one unit of time per period that can be allocated to final goods production, u_Y, R&D activities, u_n, or education, u_H. The time constraint is then

$$1 = u_Y + u_n + u_H. \qquad (2)$$

Human capital, H, is accumulated according to

$$\dot{H} = (u_H H)^{\varepsilon} (\overline{u_H H})^{1-\varepsilon} - \delta_H H, \quad > 0, \quad 0 < \varepsilon \le 1, \quad \delta_H > 0. \qquad (3)$$

The term $\overline{u_H H}$ represents a peer-effects externality measured by the average effective time devoted to education, which is taken as given by the agent. The parameter ε measures the relative weight of individual effort when compared to peer-effects in human capital accumulation, and δ_H is the rate of depreciation of human capital.

The agent earns an interest rate r per unit of financial assets, A, and a wage rate w per unit of effective labour employed, ð1 u_HÞH. Financial wealth evolves according to

A_ ¼ ð1 $_r$ÞrA þ ð1 $_w$Þwð1u_HÞH

þs_Hwu_HH ð1 þ $_C$ÞC þ T: ð4Þ

Here, $_r$ is the flat-rate tax on bond yields, $_w$ is the flat-rate tax on labour income, $_C$ is the flat-rate tax on consumption, s_H is the flat-rate subsidy to education costs—which, in this model, are forgone earnings—and T are lump-sum transfers (or taxes).

Given the initial endowments of wealth assets, A_0, and human capital, H_0, the agent's problem is to choose C, u_H, A, and H to maximize (1) subject to (3), (4), Ð ^{t} ð1$_r$ÞrðsÞds and the no-Ponzi game condition, lim$_{t!1}$ AðtÞe $_0$ 50, taken as given the paths of prices (r and w) and the fiscal policy parameters.[1] The current-value Hamiltonian is

H ¼ $\frac{C^1 \ 1}{1}$ þl½ð1 $_r$ÞrA þ ð1 $_w$Þwð1 u_HÞH þ s_Hwu_HH ð5Þ

ð1 þ $_C$ÞC þ T þ ½ðu_HHÞ" ðu_HHÞ$^{1"}$ $_H$H:

The first-order conditions with respect to C, u_H, A, and H are:

C ¼ ð1 þ $_C$Þl, ð6Þ

lð1 $_w$ s_HÞwH ¼ "ðu_HHÞ$^{"1}$ ðu_HHÞ$^{1"}$H, ð7Þ

l_ ¼ l lð1 $_r$Þr, ð8Þ

_ ¼ l½ð1 $_w$Þwð1 u_HÞ þ s_Hwu_H

½"ðu_HHÞ$^{"1}$ ðu_HHÞ$^{1"}$ u_H $_H$, ð9Þ

together with the transversality condition lim$_{t!1}$ e^{t}lA ¼ lim$_{t!1}$ e^{t}H ¼ 0:

Hereinafter we shall use the fact that u_HH ¼ u_HH in equilibrium. From (7) and (9), we obtain

_ ¼ $\frac{1 \ _w}{1 \ _w \ s_H}$" $_H$: ð10Þ

Let gₓ denote x's growth rate, gₓ ¼ x_=x. Log-differentiating (6) and using (8) we have

$$g_C ¼ \frac{1}{}\_½ð1 \ {}_rÞr \ : \qquad ð11Þ$$

Log-differentiating (7), using (8) and (10), yields

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[1] The constraint (2) has been used to express $u_Y þ u_n ¼ 1 \ u_H$ in eq. (4).

$$g_w ¼ ð1 \ {}_rÞr \ \frac{1 \ {}^w}{1 \ {}_w \ s_H}" \ þ \ {}_H: \qquad ð12Þ$$

Equation. (11) is the standard Ramsey rule. Equation. (12) indicates that the overall return on human capital, $g_w þ \frac{1 \ w}{1 \ w s_H}" \ {}_H$, is equal to the return on financial assets ð1 ${}_r$Þr. The tax on wealth assets ${}_r$ decreases the return on asset holdings while the subsidy to human capital accumulation s_H—and also the wage tax ${}_w$ if $s_H > 0$—increases the return from human capital.

2.2 Firms

The final good, Y, which we take as numeraire, is produced according to

$$Y ¼ Dðu_Y HÞ^1 n \quad , \quad 0 << 1, \quad > 0: \qquad ð13Þ$$

Here, $u_Y H$ is effective labour devoted to the final good production, D is an index of intermediate capital goods, and n denotes the number of available varieties of intermediate goods. Thus, the parameter captures the specialization gains in final good production, is the share of physical capital, and 1 is the share of human capital. Following Alvarez-Pelaez and Groth (2005), the composite index D is a CES aggregate of quantities of specialized capital goods,

$$D ¼ n \ \_ \ \frac{1}{} ðn \ x_i \, di \ , \ \ ^{1=} \qquad ð14Þ \ n_0$$

where x_i is the intermediate capital good i, and determines the elasticity of substitution between varieties.

The representative firm in the final-good sector rents effective labour at the wage rate w and intermediate inputs at the price, p_i, i 2 ½0,n. Taking as given the wage rate, intermediate inputs prices and the number of available varieties, the firm chooses intermediate inputs and effective labour used to maximize its profits:

$$\max_{\{x_i\}_{i=0}^{n}, u_Y H} \; {}_Y \; ð1 \;\; {}_cÞ \quad Dðu_Y HÞ^1 n \quad wu_Y H \quad \overset{ðn}{\underset{0}{}} p_i x_i di \, ,$$

where $_c$ is a flat-rate tax on corporate profits. The solution to this problem yields

$$w ¼ ð1 \;\; ÞY = ðu_Y HÞ, \qquad ð15Þ$$

and the demand curve for intermediate good i,

$$\frac{1}{n} \; \frac{Y}{D\, p_i} \; 1{=}ð1 \;\; Þ \; x_i ¼ \, , \qquad ð16Þ$$

whereas the resulting profit is zero.

Each intermediate input x_i is produced by a monopolist who owns an infinitely-lived patent for its design, purchased at a price v. One unit of the intermediate good can be produced with one unit of physical capital, so $K ¼ Ð_0^n x_i di$. The government subsidizes the firm's capital costs at a rate s_K. The monopolist firm faces the demand for its product given by (16) and, taking as given the cost of capital goods and the fiscal policy parameters, chooses the price of the intermediate good to maximize its profits:

$$\max_{p_i} \; {}_i \; ð1 \;\; {}_cÞp_i \; ð1 \;\; s_KÞðr þ {}_KÞx_i ¼ ð1 \;\; {}_cÞ_i, \qquad ð17Þ$$

where $_K$ is the rate of depreciation of capital. Each intermediate-goods firm faces the same problem, so they will produce the same quantity of intermediates $x ¼ x_i ¼ K{=}n$ (and, hence $D{=}\;K$) and set the same price[2]

$$p ¼ p_i ¼ ð1 \;\; s_KÞðr þ {}_KÞ{=}\; , \qquad ð18Þ$$

where 1= is the markup over marginal cost. Using eq. (16), we can readily obtain $p ¼ Y{=}K$ and, therefore,

$$r ¼ \;\; Y{=}½ð1 \;\; s_KÞK \;\; {}_K: \qquad ð19Þ$$

and the (before-tax) profit of each firm is

$$¼ {}_i ¼ ð1 \quad ÞY{=}n: \qquad ð20Þ$$

Using $D ¼ nx ¼ K$, the production function of the final good can be re-written as

$$Y ¼ Kðu_Y HÞ^1 n \quad : \qquad ð21Þ$$

Production of a new intermediate good requires the invention of a new blueprint, which is done in the R&D sector. The generation of new ideas is determined by effective labour devoted to R&D, $u_n H$, and the stock of disembodied knowledge n according to the Jones and Williams (2000) technology:

ð1 þ Þn_ ¼ _ ðu$_n$HÞ ¼ ðu$_n$HÞ^{1}nðu$_n$HÞ, ð22Þ

where > 0, > 0, 0 <41 and < 1. The term $u_n H$ represents average effective time devoted to innovation, so this specification incorporates the potential of (negative) externalities associated with the duplication of research effort—when < 1. The parameter measures spillovers in R&D. At each point in time ð1 þ Þn_ new varieties are generated, but n_ represents an upgrade of existing ones, which are then replaced by the new ones. Thus, measures the creative destruction effect.

The government subsidizes R&D costs at a rate s_R. Thus, the representative firm in the R&D sector chooses the effective labour hired to maximize its profits

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[2]In order to calibrate the markup according to empirical estimates, several authors (e.g., Jones and Williams, 2000; Grossmann et al., 2010, 2013) introduce a competitive fringe which does not allow intermediate-good firms to charge a markup higher than 2 ð1,1= . However, the specification (14) for D allows for disentangling the gains from specialization, , from the markup, 1= (see eq. (21)), and so, this assumption is not needed to obtain a realistic value of the markup in the calibration—though it could be easily incorporated in the model without any practical consequence.

max $_n$ ð1 $_c$Þ½ð1 þ Þn_ ð1 s$_R$Þwu$_n$H $_{u_n H}$

ð23Þ

¼ ð1 $_c$Þ½_ ðu$_n$HÞ ð1 s$_R$Þwu$_n$H,

taking as given the value of an innovation, the wage rate, and the productivity parameter . This yields that, in an equilibrium with innovation,

ð1 s$_R$Þw ¼ ¼ ðu$_n$HÞ^{1}n, ð24Þ

and profits are zero.

2.3 Government

On the expenditure side, the government subsidizes (at a constant rate) intermediate-goods production costs, R&D costs, and education costs (foregone earning), and provides a constant fraction s of income as lump-sum transfers to agents, representing welfare programmes. Thus, current government expenditure, G_E, is given by

G$_E$ ¼ s$_H$wu$_H$H þ s$_K$ðr þ $_K$Þnx þ s$_R$wu$_n$H þ sY: ð25Þ

On the revenue side, the government taxes (at a constant rate) income from bond yields and wages, consumption, and profits of intermediate-goods firms,[3] so that current government revenues are

$$G_R = \tau_r rK + \tau_w w(1 - u_H)H + \tau_C C + \tau_c n: \qquad (26)$$

The intertemporal government budget must be balanced, so that the present discounted value of government expenditure equals the present discounted value of government revenue,

$$\int_0^\infty G_E(t) e^{-\int_0^t (1-\tau_r) r(s) ds} dt = \int_0^\infty G_R(t) e^{-\int_0^t (1-\tau_r) r(s) ds} dt: \qquad (27)$$

Lump-sum taxes (or transfers if negative), $b = G_E - G_R$, are used if needed to balance the government budget constraint in each period so that[4]

$$\int_0^\infty b(t) e^{-\int_0^t (1-\tau_r) r(s) ds} dt = 0: \qquad (28)$$

Hence, b is a measure of the current fiscal imbalance, whereas is a measure of the intertemporal fiscal imbalance (Bruce and Turnovsky, 1999). At each period, the economy incurs a primary deficit ($b > 0$) or a surplus ($b < 0$) as needed to balance its current budget constraint. The primary deficits are financed by lump-sum taxes and the primary surpluses are rebated to consumers as lump-sum

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3 As shown above, profits in the final-goods sector and in the R&D sector are zero.

4 For simplicity we do not explicitly consider financing by debt issue as, because of Ricardian Equivalence, the lump-sum tax is equivalent to debt.

transfers.[5] However, the present discounted value of the primary deficits/surpluses is zero, so that the intertemporal government's budget constraint is balanced even if the current budget is unbalanced at some (or each) period. Thus, only seven of the eight fiscal policy instruments $(\tau_r, \tau_w, \tau_C, \tau_c, s_H, s_R, s_K, s)$ can be set arbitrarily, while the eighth must be set to balance the intertemporal government budget. Any other government policy that allows for > 0 implies that in net terms some form of lump-sum taxation is necessary to balance the budget.

2.4 Equilibrium

A market equilibrium in this economy consists of time paths for the quantities

$\{C(t), u_Y(t), u_H(t), u_n(t), \{x_i(t)\}_{i=0}^{n(t)}, \{f_i(t)\}_{i=0}^{n(t)}, A(t), Y(t), K(t), H(t), n(t), b(t)\}_{t=0}^{\infty}$ and prices

$\{r(t), w(t), \{p_i(t)\}_{i=0}^{n(t)}, (t)\}_{t=0}^{\infty}$ such that (i) the agent maximizes her intertemporal welfare, (ii) firms in the final-good, the intermediates-goods, and

the R&D sectors maximize profits, (iii) $u_H H = u_H \overline{H}$ and $u_n H = u_n \overline{H}$ at each point in time, (iv) all markets clear, (v) the government obeys its budget constraint, and (vi) assets have equal returns, so that

$$(1 - {}_r)r = \frac{(1 - {}_c) + \dot{n} - \dot{n}}{n} : \qquad (29)$$

A balanced growth path (or steady-state) equilibrium is a competitive equilibrium along which all variables grow at constant (but possibly different) rates, and the time devoted to the different activities is constant. The equilibrium condition (29) is obtained as follows. Financial wealth of the individual is given by physical capital and ‘intellectual’ capital, $A = K + n$. The after-tax return to physical capital is $(1 - {}_r)rK$, and the after-tax return to intellectual capital comprises after-tax profits plus capital gains, minus the (lost) value of existing intermediates that have been replaced by new ones, $(1 - {}_c)n + \dot{n} - \dot{n}$. In equilibrium asset non-arbitrage entails that the returns to one unit of both assets must be equal, so we get (29).

Let us abstract for the moment from the intertemporal government budget constraint and consider that all the (constant) tax and subsidy rates can be set arbitrarily. In what follows, g_x will denote the growth rate of x; i.e., $g_x = \dot{x}/x$. The Appendix shows that the dynamics of the economy can be expressed in terms of the variables $q = H^{1+ / (1)} K^{(1)}$ (adjusted human to physical capital ratio), $= C/K$ (consumption to capital ratio), u_Y (time devoted to production of the final good), $= H/n^{1}$ (adjusted human capital to technologies ratio), and g_n (the technological growth rate), which are constant in the steady state:

$$g_q = (1 + \frac{}{1})[(1 - u_Y - u_n)_H - (1)(u_Y)^{1-} q^{(1)} - _K], \qquad (30)$$

[5] Note that lumpsum transfers in the law of motion of financial assets (4) are then given by $T = sY + b$.

$$g = \frac{1}{} - \frac{1 - {}_r}{1 - s_K} u_Y^{1-} q^{(1)} - (1 - {}_r)_K \qquad (31)$$

$$1 \; \underline{\quad} ð1 \quad þ$$
$$u_Y \, q \, þ \; þ \, _K, \; "$$

$$g_{u_Y} ¼ \frac{1}{1 \;\; s_K} \quad \frac{1 \;\; r}{} \quad 1 \; ð \underline{\quad} 1 \;\; þ \quad u_Y \, q \, þ \, ð1 \;\; _r Þ_K \; ð1 \;\; u_Y \;\; u_n Þ$$

$$\#$$

$$ð32Þ \; 1 \; \underline{\quad} ð1 \qquad þ \qquad ð1 \;\; _w Þ"$$

$$þ \qquad g_n \, þ \, ðu_Y \, q \quad _K Þ \, þ \, \underline{\qquad\qquad} 1 \;\; _w \;\; s_H \; ð1 \;\; Þ_H \, ,$$

$$g \, ¼ \, ð1 \;\; u_Y \;\; u_n Þ \;\; _H \; ð1 \;\; Þ g_n, \qquad ð33Þ$$

$$" $$

$$\underline{\qquad} \quad \frac{1 \;\; _w \, g_{g_n} ¼}{1 \;\; 1 \;\; _w \;\; s_H} \, " \;\; _H$$

$$\# \qquad ð34Þ$$

$$\frac{ð1 \;\; _c Þð1 \quad Þð1 \, þ \, Þ u_Y g_n}{Þ u_n} \; þ \; 1 \; þ \; \frac{1}{\qquad} g_n \, , \; ð1 \;\; s_R Þ ð1$$

where time devoted to R&D should be replaced by $u_n ¼ ð1 \; þ \; Þ^{1=1= \; 1=} g_n^{1=}$.

A hat over a variable will denote its steady-state value. The Appendix shows that the steady state of the economy is described by

$$($$

$$’\wedge ¼ \frac{ð1 \;\; s_K Þ}{} \quad ð1 \;\; _r Þ_K \, ð1 \;\; _r Þ$$

$$) \qquad (35)$$

$$+\frac{1}{(1+M)\ 1\quad 1_{w}\ s_H}(1+M)\ \frac{(1\quad)''}{\ }{}^{w}\ {}_{H},$$

$$Y$$

where $M = (1\quad)(1\quad)/(\quad)$. Several results can be derived from the steadystate equations (35)–(43).

$$\frac{M\ 1}{M)\ 1\ 1_{w}\ s_H}\ \frac{\hat{g}_H}{\ }{}^{w\,''}{}_{H} = \,,\ (1+ \qquad (36)$$

$$\hat{g}_Y = \hat{g}_C = \hat{g}_K = (1+1/M)\hat{g}_H, \qquad (37)$$

$$\hat{g}_n = \hat{g}_H/(1\quad), \qquad (38)$$

$$(39)$$

$$\hat{\ } = \hat{'}\ {}_K\ \hat{g}_K,$$

The subsidy to the intermediate capital goods (s_K) decreases '^ and ^ through the increase of physical capital in the economy, whereas $_r$ has the opposite effect on those variables.

$$\hat{\ } = (1+)\hat{g}_n/\hat{u}_n, \qquad (42)$$

$$\hat{q} = \hat{u}_{(1)}\ \hat{\ } \quad /(1)'\hat{\ }, \qquad (43)$$

$$\hat{u}_n = \frac{\frac{(1\quad_c)(1\quad)(1+)+}{(1\quad s_R)(1\quad)}\,\hat{g}_n\ \ 1\qquad \hat{g}_H+\ _H}{\frac{(1\quad_w)''}{1\quad_w\ s_H}\ \ _H\quad \hat{g}_H+(1+)\hat{g}_n+\frac{(1\quad_c)(1\quad)(1+)\ +}{(1\quad s_R)(1\quad)+}\hat{g}_n}, \qquad (40)$$

$$\hat{u}_Y = 1\quad \hat{u}_n\quad \frac{\hat{g}_H+\ _H}{\ }, \qquad (41)$$

The wages tax $_w$ has a positive effect on '^, and also on $\hat{g}_H$ if there is positive subsidy to education. As expected, the subsidy to R&D (s_R) increases time devoted to innovation, while $_c$ has an uncertain effect on it. The subsidy to education (s_H) contributes to increase '^ and $\hat{g}_H$. As expected, it increases time devoted to education and reduces time devoted to R&D. In this model a consumption tax ($_C$) at a constant rate acts as a lump-sum tax, so it has no effect either in the transitional dynamics or in the steady state.

Regarding the stability of the steady state, the system (30)– (34) features three jump variables, , u_Y, and g_n, and two state variables, and q, whose initial values are historically given by the initial values of the predetermined variables $K(0)$, $H(0)$, and $n(0)$. Hence, local saddle-path stability requires that the linearization of system (30)–(34) around its steady state has two stable eigenvalues, so the stable manifold would be two-dimensional.[6] This entails, in particular, that the economy may converge to its steady state in a non-monotonic fashion, as will be shown in Section 4.

Up to this point we have considered that the flat-rate fiscal policy parameters can be set arbitrarily. However, given our focus on budget-neutral fiscal experiments, only seven of the eight fiscal policy instruments $(_r, _w, _C, _c, s_H, s_R, s_K, s)$ can be set arbitrarily, while the eighth must be chosen so as to balance the intertemporal government budget (27). Using (15), (19), and (20), in equilibrium, government expenditures and revenues can be expressed as

$$Y \qquad n \qquad\qquad K$$

and G_E ¼ ________ð1 Þs_H þ ______ þ s_Rð1 Þ __ⁿ þ s Y, u_Y ð44Þ

u_Y 1 s_K

r K u_Y þ u_n

G_R ¼ ______ __ ________þ ð1 Þ$_w$ þ __$_c$ þ ð1 Þ$_c$ Y, ð45Þ

1 u u s u

1 s_K ’ u_Y ’

where the output-capital ratio, ’, can be obtained from ’ ¼ Y=K ¼ u^1_Y =ð1Þq. The former expressions clearly show that the value of the compensating tax or subsidy rate to balance the intertemporal government budget depends on the time paths of the economic variables. Hence, this value must be jointly computed with the equilibrium time paths after instituting the fiscal reform. This can be done as follows.

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6 Given the complexity of this fifth-dimensional dynamic system and the high number of parameters involved, necessary and sufficient conditions for stability are probably unreachable. However, a simple sufficient condition for stability is that ’^5 ð1 s_KÞ$_{rK}$=½ð1 s_KÞ ð1 $_r$Þ and 4ð1 Þ—a full derivation is available upon request. All the simulations performed in this paper feature two stable eigenvalues, so there is a locally unique saddle-path stable equilibrium.

At time t =0, when the new fiscal policy is instituted, the system jumps to the two-dimensional stable manifold associated with the new parameter values. The initial point in this stable manifold is determined by the initial values of the predetermined variables, ð0Þ ¼ ^ and qð0Þ ¼ q^. Thereafter, the economy moves toward the new steady state along this stable manifold, obeying the laws of motion given by (30)–(34). Once the time paths of the variables , g_n, u_Y, and q have been computed, we can solve for the time path of physical capital by solving the resources-constraint differential equation (see eq. (48) in the Appendix):

K_ðtÞ ¼ ½’ðtÞ ðtÞ $_K$KðtÞ,

assuming without loss of generality, that the initial value of the capital stock is normalized to unity, Kð0Þ ¼ 1. We then compute the time path of output YðtÞ ¼ ’ðtÞKðtÞ and, subsequently, the value of in eq. (28) by using the former expressions for G_E and G_R. An iterative root-finding process allows us to obtain the equilibrium paths and the value of the compensating tax/subsidy rate that balances the government budget. Finally, we can compute the adjustment path of consumption as

CðtÞ ¼ ðtÞKðtÞ, as well as the time paths of the remaining variables and, therefore, the agent's intertemporal utility in (1).

3. Calibration of the model

For the calibration exercise, we mostly use values from OECD and the Penn World Table (PWT) for the US economy. Table 1 shows the synthesis of our calibrated values. It is divided into different sets of parameters. The first two sets are the fiscal instruments in the economy. For the tax system, we set values according to the OECD tax database (2010) and we pick values for the US. The corporate and individual capital income tax rates are equal in the US, so we will consider henceforth that $_r$ ¼ $_c$. Their value is 39.2% in the US.[1] Using the same source, the labour income tax, $_w$, is set equal to the total tax wedge (wage income tax rate including all social security contributions and from all levels of governments combined) which applies to average wage income. Its value is 34.4% in the US. Although the US has no VAT tax on consumption, according to the OECD tax database, taxes on goods and services amounted to 4.5% of GDP in 2009. In this model this corresponds to taxation revenues, so we calibrate the value of $_C$ to match this value.

We may note that the value for the subsidy to physical capital costs (s_K) is difficult to calculate, as there are different forms of capital costs deductions. The investment tax credit of 10% was abolished in the US in 1986 although similar systems remain in countries such as United Kingdom and Australia. We thus set s_K ¼ 0. Following Grossmann et al. (2010, 2013), the subsidy to R&D (s_R) is taken

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Table 1 Calibration in the benchmark model

Fiscal policy parameters		Data to match		Literature-based parameters		Data-based parameters	
$_r$	0.392	Kd=Y	3		0.234		1.4068
$_c$	0.392	g^$_Y$	0.0166	$_H$	0.035	'	0.8847
$_C$	0.344	savc	0.151		0.5		0.1156
$_w$	0.053	F	20		0.1	$_K$	0.0337
s_R	0.066	g^$_H$	0.0066		0.02		1.7463
s_H	0.0792	u^$_n$ / u^$_Y$þu^$_n$	0.01068		0.33		0.9548
s_K	0	$_C$Cd=Y	0.045	"	0.52		

[1] We considered overall statutory tax rates on dividend income for $_r$ and the basic combined central and sub-central (statutory) corporate income tax rate given by the adjusted central government rate plus the sub-central rate for $_c$. Although these values are quite stable over time, we select values from 2010.

b 0

from the OECD statistics on ‘OECD Science, Technology and Industry: Scoreboard 2007’ (the variable is the rate of tax subsidies for USD of R&D, for large firms), which is 0.066 for the US. Finally, to calibrate the education subsidy rate (s_H) we follow Choi (2011). From (4) we see that the subsidy to education is $s_H w u_H H$, which by (15) is equal to $s_H(1 -)u_H Y/u_Y$. As Choi (2011) concluded, using data from 1960 to 2005, the subsidy to education is 4.7% of GDP.[8] Thus, $s_H(1 -)u_H/u_Y = 0.046(1 - {}_w)$.

We determine several parameter values in order to match real data for the US. The *per capita* output growth rate given by PWT 7.0 between 1980 and 2009 is $g_Y = 1.66\%$. From the OECD countries database, we average the US savings rate from 1991 and 2009, from which we obtain 15.1%, so that $sav = (g_K + {}_K)K/Y$. We consider the growth rate of output in the education sector to be equivalent to human capital growth rate, $g_H = 0.66\%$, as calculated by Jorgenson and Fraumeni (1993, Table 8) for the US (1979-86). For the capital-output ratio, we take averages over the period 2003-10 calculated from data of the US Bureau of Economic Analysis. The capital stock is taken to be total fixed assets (private and public structures, equipment, and software), implying a value for the ratio near three. Thus, we set $K/Y = 3$. Following Grinols and Lin (2006, 2011), we set the patent life at 20 years, $F = 20$, so that $g_n = 1/F = 1/20$. This is the patent life established in the USPTO (United States Patent and Trademark Office) ‘Manual of Patent Examining Procedure (MPEP), June 2010 (Latest Revision)’.[9] Important data to match when we go to evaluate the effect of different R&D policies is time devoted to this activity. Using data from the US Bureau of Labor Statistics and from the 2008 Business R&D and Innovation Survey,[10] the share of domestic R&D employment to total employment is 1.068%, which is our target value for $u_n/(u_Y + u_n)$.

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[8] We excluded the 0.1% attributed to subsidies to R&D.

[9] It is available at http://www.uspto.gov/web/offices/pac/mpep/documents/2700_2701.htm.

[10] It is available at http://www.nsf.gov/statistics/infbrief/nsf10326/.

Due to the scarcity of empirical sources for some parameters, we set values that were used in earlier literature as follows. The value $= 0.33$, for the capital share in income is standard in the literature. We set the gains of specification parameter as $= 0.234$ following Coe and Helpman (1995), and ${}_H = 0.035$ following Choi (2011). This value is also consistent with empirical evidence analysed by Heckman (1976). The parameter can be set arbitrarily, so we choose the usual value of $= 0.1$, and we also set a typical value for ¼ 0:02.[2] We choose as the benchmark calibration for the duplication parameters, , a value of 0.5, as is usual in earlier contributions (e.g., Jones and Williams, 2000). This value is in line with the estimations of Pessoa (2005) for this parameter for the most developed OECD countries (0.556 and 0.596 in regressions with fixed-effects) and in the median of the interval of Porter and Stern (2000), that presented values for l between 0.2 and 0.85. For the parameter that governs the learning externalities, we consider 1 " ¼ 0:48, as predicted by the estimations presented in Choi (2011, p. 28) using data from 1963 to 2005. In a non-completely comparable setup concerning human capital accumulation technology, Calvo´-Armengol et al. (2009) estimate a value of 0.56 for the peer-effect (in this case individual effects are not reported) in the US. However, empirical estimates by Rangvid (2003) for learning externalities seem to attribute similar coefficients to individual effort and to peer-effects (in Denmark) and Lefgren (2004) reached small peer-effects for Chicago schools. Facing still contradictory evidence we decided to follow Choi (2011) estimations for a law of motion similar to (3).

These values allowed us to calculate all the other parameters. We use eqs (30)–(34) together with the values for the saving rate, the output growth rate, the share of the subsidy to education in GDP, the taxes on goods and services as a percentage of GDP, the capital-output ratio, the human capital growth rate, the patent life, and the share of domestic R&D employment to total employment to determine the remaining parameters in the model (, $_K$, , , , , $_C$ and s_H) as well as the stationary values of the variables q, , u_Y, and g_n. Finally, we assume that the government budget is initially balanced, b ¼ G_E G_R ¼ 0. Using (25) and (26), we then obtain the share of GDP claimed by the government for lump-sum transfers representing welfare programmes, s.

Steady-state values resulting from this calibration and the calibrated parameters are also shown in Table 2. It is interesting to note that even in non-calibrated macroeconomic variables, the model fits the available data well. In the model, given , the growth rate of TFP is 0.0067 (¼ g_n), while in the data it is 0.008 between 2007 and 2010 and about 0.005 between 1987 and 1995 (Bureau of Labor Statistics).[3] The estimated value for the markup, 1= ¼ 1:047, almost replicates the estimate of 1.049 reported by Norrbin (1993, Table 3). The (pre-tax) interest

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Table 2 Steady-state values in the benchmark model

$\hat{u}_Y$	$\hat{u}_H$	$\hat{u}_n$	$\hat{g}_n$	$\hat{v}$	$\hat{w}$	$\hat{r}$	s

[2] These values are typical in calibration exercises of endogenous growth models (e.g., Jones and Williams, 2000; Strulik, 2007; Grossmann et al., 2010, 2013). Numerical simulations with a higher value of —not reported in the paper but available upon request—yield qualitatively similar results.

[3] From the 1987-2010 Major Sector Multifactor Productivity, http://www.bls.gov/mfp/mprdload.htm.

0.6332	0.3600	0.0068	0.0286	0.283	9.511	0.0713	0.3370

Table 3 Budget-neutral policies compensating a $r_s = 0.5\%$ (in percent)

Compensating tax/subsidy	s_R	s_H	s_K	s_r	s_w
Tax/subsidy rate	64.881	9.061	2.132	37.276	33.657
Income growth rate	1.660	1.831	1.660	1.660	1.647
Welfare gain	14.496	2.335	0.044	0.427	–0.179

rate of 7.13% is consistent with the values reported in Mehra and Prescott (1988). The value obtained for the elasticity of intertemporal substitution is also in line with the empirical estimates (e.g., Alan et al., 2009, Engelhardt and Kumar, 2009). Our results indicate that approximately one third of non-leisure time is devoted to human capital accumulation, and the other two thirds to work, which broadly accords with an average of 14 years spent on education and 35 years in work (e.g., Angelopoulos et al., 2008). Even though we have performed a thorough calibration exercise forcing parameters to fulfill a considerable number of macroeconomic variables, we also reach quite reasonable values for the 'free' variables in the model.

4. Simulation results

In this section, we examine the consequences of undertaking budget-neutral reforms to the fiscal structure. We assume that the economy evolves initially along its balanced growth path where, in particular, the primary budget deficit is zero, $b = 0$. At time $t = 0$, the government undertakes a permanent, unanticipated change in the (time-invariant) fiscal structure. Here, fiscal structure refers to the mix of flat-rate taxes and subsidies, as well as the ratio of lump-sum transfers to GDP representing welfare programmes which keeps the intertemporal government budget balanced according to (27); i.e., that keeps the present discounted value of the lump-sum taxes (or transfers) necessary to balance the government's budget in each period equal to zero according to (28). After the fiscal reform is instituted, the economy evolves toward its new balanced growth path. As explained above, the compensating value of the tax or subsidy rate needed to balance the intertemporal government budget is jointly computed with the equilibrium time paths of the variables of the economy after instituting the fiscal reform. Once computed, we compare the utility before and after the reform.[13]

The welfare gain of a reform is measured as the constant permanent percentage increase in consumption that leaves the household indifferent between remaining in the pre-reform balanced growth equilibrium or undertaking the reform. Let $C_O(t)$

denote the time path of consumption along the pre-reform balanced growth path, and let $C_N(t)$ denote the time path of consumption after the new fiscal structure is instituted at time $t=0$.[14] Hence, the welfare gain (or loss) of instituting this policy is measured as the value such that

$$\int_0^{\infty} \frac{[(1+\Delta)C_O(t)]^{1-\theta}-1}{1-\theta} e^{-\rho t}\,dt = \int_0^{\infty} \frac{C_N(t)^{1-\theta}-1}{1-\theta} e^{-\rho t}\,dt.$$

4.1 Budget-neutral policies for a given change in expenditures

In this section we want to compare the effects of the alternative fiscal instruments on the performance of the economy. To this end, the usual experiment consists of evaluating and comparing the effect of a given percentage point change in a given tax or subsidy. However, the base to which this change applies may be quite different, so the same percentage points change—say a one percentage point—in the tax or subsidy rate may have quite different effects on the government budget depending on the tax or subsidy chosen. Thus, as a normalization procedure, we assume that the government reduces its lump-sum expenditures representing welfare programmes by a given percentage share of GDP, say 0.5% (i.e., we set $s = 33.20\%$), and that this revenue is used to finance an increase in a subsidy or a reduction in a tax in a budget-neutral manner, while keeping constant the other tax and subsidy rates. The value of the residually determined tax or subsidy rate is, therefore, the one that keeps the intertemporal government budget balanced, $= 0$, according to (28). We will call them budget-neutral compensating policies. Thus, for example, we calculate the reduction in the tax rate on labour income that compensates a 0.5% drop in the ratio of public transfers to GDP so as to maintain the government budget balanced.

In Table 3 we report the budget-neutral compensating tax and subsidy rates and their respective growth and welfare effects.[15] For example, for a 0.5% drop in the ratio of lump-sum transfers to GDP, reducing the tax on interest income to 37.276% is budget-neutral as well as increasing the R&D subsidy to 64.881%. The results clearly show that the subsidy to R&D is the most welfare-increasing

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13 The transitional dynamics are computed by using the relaxation algorithm (Trimborn et al., 2008). Codes used to obtain quantitative results in this paper are available from the authors upon request.

14 In Section 2.4 we explained how the post-reform consumption path $C_N(t)$ can be computed. As $K(0) = 1$, the pre-reform consumption time path would be simply given by $C_O(t) = \hat{}e^{\hat{g}_K t}$.

15 This experiment is not made with the (flat-rate) tax on consumption because it acts as a lump-sum tax in this model, so it would have no effect.

from all the budget-neutral policies examined, with a welfare increase of 14.496%. The second most welfare enhancing policy is the subsidy to education, with a welfare gain of 2.335% after increasing this subsidy rate from nearly 8% to 9.061%. In this case, the greater incentives to accumulate human capital would imply a reallocation from the final good production to the human capital production and would result in an increase of the long-run growth rate of output to 1.831%. Interestingly, the subsidy to R&D has greater effect than the subsidy to education even though the former does not affect the long-run growth rate and the latter does. The reason is that there is a slow convergence to the steady state and, therefore, the effect along the transition dominates the long-run effect. This clearly justifies our emphasis on the transitional dynamics analysis. In order to keep its budget balanced, a drop in lump-sum transfers by 0.5 percentage point should be off-set by instituting a subsidy to intermediate capital goods (s_K) of 2.132%, with a negligible welfare gain of 0.044%, or lowering the tax rate on capital income ($_r$) to 37.276%, which induces a small increase in welfare of 0.427%. Interestingly, decreasing the tax on labour income ($_w$) incurs a small welfare loss of 0.179%, whereas the long-run growth rate of output falls slightly to 1.647%. As discussed above, a tax on labour income has no effect on the absence of a subsidy to education but in its presence it affects both growth and welfare. In terms of the effects on economic growth, however, only those policies affecting the incentives to accumulate human capital—the ultimate source of growth—have a positive effect on long-run growth: the subsidy to education, s_H, and the wages tax, $_w$ (if $s_H > 0$). In contrast, the R&D subsidy, s_R, does not affect the long-run growth rate, though it may have important short-run effects.

These results clearly suggest that the R&D subsidy is the best single policy instrument to increase welfare and that its rate should be increased, in agreement with earlier literature reporting that it would be welfare-improving to subsidize R&D (e.g., Jones and Williams, 2000; Steger, 2005; Strulik, 2007). Thus, we will now study the transitional dynamics that the introduction of a budget-neutral compensating subsidy to R&D would imply. This will allow us to analyse the impact of those policies on different macroeconomic variables such as the output, human capital and TFP growth rates, the allocation of labour to different activities, and the consumption to output ratio.

Figure 1 shows the evolution of key macroeconomic variables when the budgetneutral R&D subsidy policy described above (s_R ¼ 64:881%, s ¼ 33:20%) is instituted. Given the higher subsidy to R&D, time devoted to R&D, and the ‘ideas’ growth rates increase sharply at the outset. To allow for an immediate positive effect in the R&D sector, human capital flows away from the final good sector, which also entails lower savings, whereas education time remains almost unchanged. As the economy evolves, the increase in the stock of ‘ideas’ has a positive effect on goods production and, therefore, less time is devoted to education and more time to working and, accordingly, the growth rate of physical capital increases. Eventually, the economy enters a phase of monotonic and slow convergence to the steady state. While the trade-off between time devoted

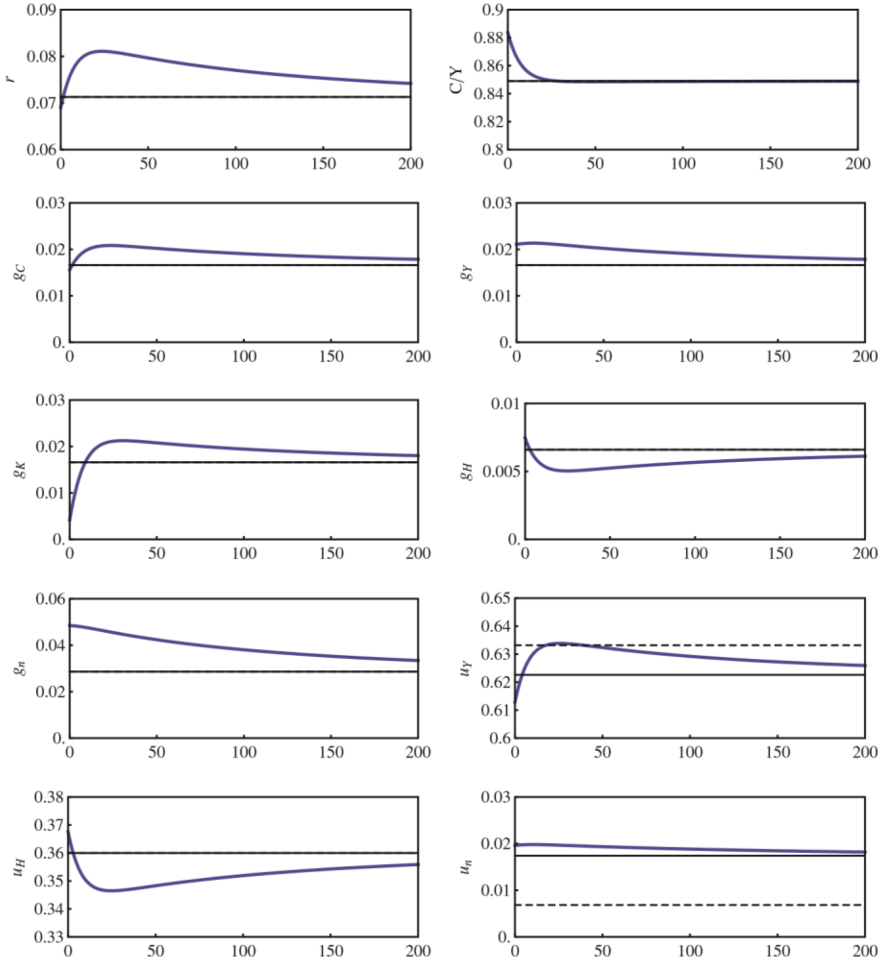

Fig. 1 Adjustment paths of representative variables after increasing the subsidy to R&D.

Note: Parameter values are shown in Table 1, except for s_R ¼ 64:881%. The black dashed and solid lines represent the initial and final steady-state values, respectively. When there is only one black line, it means that both steady-state values coincide.

to R&D and to the production of the final good is maintained in the long run, time devoted to education recovers from the initial drop and comes back to its pre-reform steady-state value. The growth rates of income and consumption lie above their pre-reform values throughout the long transition involved, benefiting from the new technologies available due to the increase in the R&D activities. As a consequence, even though the long-run growth rates remain unchanged, the welfare effect of the reform is quite high.

4.2 Budget-neutral optimal subsidy structure

The preceding section has illustrated the different growth and welfare effects of alternative subsidies. In this section, we will compute the welfare-maximizing budget-neutral mix of subsidies given the actual tax structure. To this end, we must determine the values of s_K, s_H and s_R, maintaining constant the tax rates and the ratio of lump-sum transfers to GDP, that maximize welfare keeping the intertemporal government budget balanced. Only two of the three subsidy rates can be set arbitrarily—say, s_K and s_R—while the third one—say, s_H—must be chosen so as to balance the government budget constraint (27). For each s_K and s_R, we can compute the compensating subsidy rate s_H, the equilibrium paths of the variables and, therefore, the corresponding welfare as explained in Section 2.4. Then, a direct-search maximization method is used to find the optimal values of s_K and s_R—and the corresponding value of s_H—that maximizes welfare in a budget-neutral manner. The results are shown in Table 4.

Given the current tax rates in the US, the government should reallocate subsidies from the education sector to R&D, and keep the intermediate goods production unsubsidized. In particular, s_H should be lowered by almost five percentage points and s_R should be increased by more than 75 percentage points. This policy scheme would increase welfare by 16.114%, whereas the long-run rate would fall noticeably to around 1%.

Figure 2 shows the evolution of the economy after the introduction of the optimal subsidies scheme. Due to the dominance effect of the R&D subsidy in the optimal subsidy scheme, the qualitative behaviour in Fig. 2 resembles that of Fig. 1. However, as a result of the decrease in the subsidy to education, the post-reform long-run growth rates are all lower than the initial ones. Notwithstanding, given the higher incentives to accumulate R&D, along the earlier stages of transition the growth rate of 'ideas', income, and consumption—and, eventually, the growth rate of physical capital as well—evolve above their respective pre-reform steady-state values. The drop in the subsidy to education causes a fall in the growth rate of human capital. However, the overall result of a higher technological growth rate and a lower human capital growth rate on the output growth rate is positive in the short run. As a result of the new subsidies scheme, there is a re-allocation of time from education to innovation and working. In the long run, however, working time returns to a value similar to its pre-reform value, whereas the great increase in innovation time is compensated by a similar reduction in time devoted to education. As the figure shows, the transition is very long-lasting, so that the transitional positive effects on welfare of greater transitional growth rates of consumption and income override the long-run negative effect of lower long-run values relative to the pre-reform equilibrium.

In spite of the notable differences in both the framework considered and in the type of policy reforms made, the optimal value for the subsidy to R&D is remarkably similar to the values reported by Grossmann et al. (2010, 2013). In Table 4 Optimal budget-neutral subsidy structure (in percent)

s_R	s_H	s_K	$g^{\wedge}_Y$	Welfare gain
81.687	3.175	0	1.014	16.114

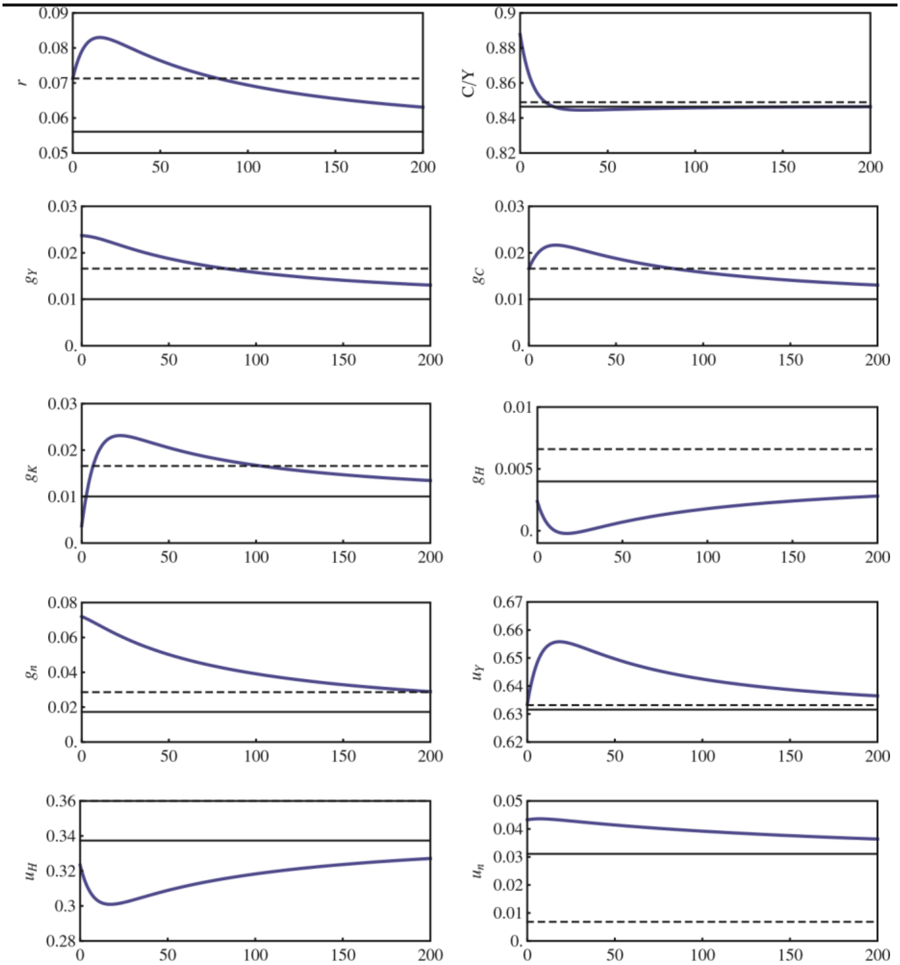

Fig. 2 Adjustment paths of representative variables after introducing the optimal subsidies scheme.

Note: Parameter values are shown in Table 1, except for s_R ¼ 81:687%, s_H ¼ 3:175% and s_K ¼ 0. The dashed and solid lines represent the initial and final steady-state values, respectively.

fact, Grossmann et al. (2013) find that the long-run optimal subsidy to R&D is 81.5%, practically identical to ours, in a model without human capital. For a duplication parameter of 0.5—as assumed here—and a R&D intensity of 7%, Grossmann et al. (2010, Table 2) report an optimal long-run R&D subsidy rate of 81%, which increases to 86% when the transitional dynamics are also taken into account. In contrast, they obtain an optimal value for the education subsidy of 30%—similar to the wages tax. This noticeable difference is driven by the fact that in their model the R&D subsidy can be financed with lump-sum taxation, whereas in our model an increase in the subsidy to R&D must be compensated with a reduction in the subsidies to education to keep the government budget balanced. There are also important differences in the welfare gains of implementing the optimal policy. In the comparable case reported above, they find a welfare gain of 125%, much higher than ours. This can be explained because in our budget-neutral reforms the subsidy to education falls in order to accommodate the increase in the subsidy to R&D. Unlike Grossmann et al. (2010), who consider a semi-endogenous growth model in which taxes and subsidies do not affect long-run growth, human capital is a true engine of growth in this model and, therefore, the lower subsidy to education provokes a reduction in long-run growth. Hence, there is a trade-off between a positive transitional effect and a negative long-run effect, which entails a lower overall welfare effect—though the transitional effect dominates the long-run one.

5. Sensitivity analysis

In this section we perform a thorough sensitivity analysis of the obtained results to several choices. Checking robustness of the result against assumptions relative to the parameter values is the standard method followed in the literature. Thus, given the uncertainty about the true value of the duplication externalities, we will first analyse how the previous results are affected by setting a higher value for the duplication parameter.

However, one may wonder whether the results presented so far concerning the relative importance of the R&D subsidy are due to the specific formulation of the benchmark model used in this article. Therefore, we will also test the robustness of our results to significant changes in the structure of the model. Two specific features that could affect our main results are the specific functional form of the human capital law of motion and how the learning externality is modelled, and the absence of leisure in utility. In fact, the externality to human capital was the strongest candidate to bet R&D subsidies as the most welfare-enhancing policies (see, e.g., Sequeira, 2008). A change in the externality form and the possibility of including leisure in the model could influence the incentives to accumulate human capital when compared to other investments, namely R&D, and thus could switch the order of importance of subsidies. Following this reasoning, we have changed our benchmark model in order to test for these two alternatives. As suggested by Engen et al. (1997), the model is recalibrated so as to reflect the original long-run data reported in Table 1. The results obtained are shown in Table 5.

5.1 Higher duplication externality

Given the uncertainty regarding the value of the duplication externalities parameter, λ, we report the results for $\lambda = 0.355$, the minimum value estimated by Pessoa (2005) for the most developed OECD countries sample. The change in this parameter is important to assess the robustness of our results according to which the R&D subsidy is the most welfare-enhancing policy available. Increasing the value of duplication externalities, Table 6 shows that the results remain largely unchanged aside from the extent of the welfare effects, which are now much lower. Thus, the R&D subsidy continues to be the best policy.

5.2 Different human capital externality

We now calculate the growth and welfare effects in an environment in which the learning externality is due to the whole stock of human capital and not just to the average human capital dedicated to education. Differently from our benchmark model, this means that human capital will benefit not only from peer-effects, but also from home education and overall education of the community.[4] Thus, an alternative law of motion of human capital (see, e.g., Lucas, 2009, and Choi, 2011) is the following one:

$$\dot{H} = (u_H H)^{\varepsilon} H^{1-\varepsilon} \; {}_H H, \; > 0, \qquad 0 < \varepsilon \leq 1, \; {}_H > 0. \qquad (46)$$

The budget-neutral policies using this alternative model are shown in Table 7. The importance of subsidies to R&D as a welfare-enhancing policy relative to subsidies to education is even reinforced when compared with the benchmark model. In fact, a budget-neutral subsidy to R&D that compensates a drop in lump-sum transfers by 0.5% of GDP would increase welfare by 17.381%, which is more than in the benchmark situation. The welfare effects of alternative policies are all less than 1%. The optimal subsidy structure confirms the same idea. In this case, if the government aims at reallocating subsidies given the tax structures, it should increase the R&D subsidy to 87.350% and keep unsubsidized both the education sector and the intermediate goods sector. Growth effects are similar to those in the benchmark case, but the implied welfare gain of switching to the optimal subsidy structure is more than doubled.

[4] Although we are not presenting the detailed model in this case in order to provide broader readability, it is available upon request.

5.3 Including leisure in the model

In this section we consider that the agent derives utility from both consumption and raw time devoted to leisure, u_L, according to

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Table 5 Calibration results in the alternative models

Parameter and steady-state values	Higher duplication externality k = 0.355	Learning externality linked to H	Leisure in utility
	1.4068	1.4068	1.4068
	0.9182	0.8847	0.8847
	0.1156	0.0708	0.3467
κ	0.0337	0.0337	0.0337
	1.7463	1.7463	1.7463
	0.9548	0.9548	0.9548
	–	–	1.5528
s_H	0.0792	0.0792	0.0792
c	0.0530	0.0530	0.0530
$u\hat{}_Y$	0.6332	0.6332	0.2110
$u\hat{}_H$	0.3600	0.3600	0.1200
$u\hat{}_n$	0.0068	0.0068	0.0023
$u\hat{}_L$	–	–	0.6667
^	0.283	0.283	0.283
^	4.6159	9.5107	16.473
$g\hat{}_n$	0.0286	0.0286	0.0286
s	0.3370	0.3370	0.3370

Table 6 Budget-neutral policies with higher duplication externality (in percent)

Budget-neutral policies compensating a rs ¼ 0:5%

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Compensating tax/subsidy	s_R	s_H	s_K	s_r	s_w

Tax/subsidy rate 61.352 9.056 2.134 37.288 33.656 Income growth rate 1.660 1.830 1.660 1.660 1.647 Welfare gain 8.138 2.277 0.055 0.313 0.176

Optimal budget-neutral subsidy structure

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s_R	s_H	s_K	$g\hat{}_Y$	Welfare gain
73.412	5.291	0	1.289	6.454

U ¼ ð1 ______________ C1uLð1Þ 1etdt, > 0, > 0, > 0, ð47Þ 0 1 so the agent's time constraint should be replaced with $u_Y + u_n + u_H + u_L = 1$. The additional parameter $= 1.5528$ is set in such a way as to obtain a share of time devoted to leisure of 2/3, which is the typical value considered in the literature.[17] It

[17] Again, we are not presenting the detailed model in this case in order to provide broader readability, but it is available upon request.

Table 7 Budget-neutral policies with learning externality associated with H (in percent)

Budget-neutral policies compensating a rs = 0.5%

Compensating tax/subsidy	s_R	s_H	s_K	s_r	s_w
Tax/subsidy rate	66.053	9.002	2.137	37.268	33.653
Income growth rate	1.660	1.752	1.660	1.660	1.653
Welfare gain	17.381	0.407	0.220	0.656	0.035

Optimal budget-neutral subsidy structure

s_R	s_H	s_K	$\hat{g}_Y$	Welfare gain
87.350	0	0	1.056	36.282

is interesting to note that the steady-state share of time dedicated to work ($u_Y + u_n$) is 21.11% and the values reported by OECD for US lie between 21.1% in 1996 and 20.2% in 2010.[18]

Using this alternative model, we calculate the budget-neutral policies that are shown in Table 8. The subsidy to R&D continue to be the most welfare-increasing policy. Thus, reducing lump-sum transfers by a 0.5% of GDP to increase the R&D subsidy in a budget-neutral manner yields a welfare gain of 13.982% compared with a gain of 4.868% led by education subsidies. Though education subsidies have a lower welfare effect, this is the model in which its effect is closer to the effect of R&D subsidies. A noticeable difference with the no-leisure model is that now subsidizing R&D has a positive effect on long-run income growth, which increases by around 0.093 percentage points. The increase is greater and amounts to 0.232 percentage points if the compensating instrument is the subsidy to education. Subsidizing the intermediate goods sector induces a sizeable gain in welfare of 0.798% and, unlike the no-leisure case, long-run growth slightly increases to 1.682%. On the revenue side, decreasing the capital income tax rate has a positive welfare effect of 1.125%. Another important difference with previous results is that in this model reducing the wage tax increases welfare by 1.769%. The reason is that now a wages tax distorts the labour-leisure margin of choice, which is absent in the previous models. While in the previous models in which labour supply is inelastic a consumption tax ($_c$) at a constant rate is not distorting, here it affects the trade-off between working and

[18] Values were computed dividing average annual hours actually worked per worker by the total number of hours of a 365 days' year (8760). The period analysed was from 1990 to 2010. Values used by Glomm and Ravikumar (1998, p.318-20) to estimate the share of resources dedicated to learning point to a percentage of worked hours of 20.77% of the total available time (dividing 34.9 by the weeks' 168 hours), consistent with our steady-state results.

Table 8 Budget-neutral policies with leisure in utility (in percent)

Budget-neutral policies compensating a r s = 0.5%

Compensating tax/subsidy	s_R	s_H	s_K	s_r	s_w	s_C
Tax/subsidy rate	64.982	9.133	2.180	37.237	33.612	4.693
Income growth rate	1.753	1.892	1.681	1.682	1.705	1.690
Welfare gain	13.982	4.868	0.798	1.125	1.769	1.031

Optimal budget-neutral subsidy structure

s_R	s_H	s_K	$g^{\wedge}_Y$	Welfare gain
75.561	5.019	0	1.291	9.579

enjoying leisure, so we also tested its importance. The consumption tax rate should be reduced to 4.693%, and the welfare gain obtained by a budget-neutral change would be around 1.031%, so that it would be the less-effective welfare-enhancing tax instrument. On the optimal-subsidies structure the recommendation is somewhat weaker than in the benchmark model but qualitatively similar: given the tax structure, subsidies should be reallocated from education to R&D.

6. Conclusion

We built an endogenous growth model with physical capital, human capital and R&D in which we consider all of the leading fiscal policy instruments, and calibrate it to the US economy. We analyse the growth and welfare effects of budget-neutral policy reforms, taking into account the whole transitional dynamics.

First, we analysed the effect of compensated changes in the taxes or subsidies that are present in our economy. We found that the most welfare-increasing budget-neutral policy change is to increase the subsidy to R&D. The nearest best policies, in terms of welfare, although with a significantly lower welfare effect, are the subsidy to education (rises) and the capital income tax rate (decreases). This finding has a strong policy implication: governments seeking to increase welfare, without compromising their budgets, should rely more on the research policy. Subsidies to both R&D and education would have long-lasting positive effects on economic growth, although only the subsidy to human capital has a permanent effect on growth. This means that the strong effect of R&D subsidies on their long transition path compensates the lower or null effect they have on the long-run equilibrium, which clearly justifies the need for taking transitional dynamics into account. The computation of the optimal budget-neutral structure of subsidies showed that, with the current tax structure in the US, a significant increase in the R&D subsidy compensated by reduction in the subsidy to education would yield a significant welfare gain. This policy reform would imply a reallocation of resources from the human capital sector to the R&D and the industrial sector. Our findings proved to be robust to different assumptions on the parameter values and, more importantly, to significant changes in the structure of the model, which included different learning externalities and including leisure in utility.

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Appendix

Derivation of the transitional dynamics

We shall take into account that, in equilibrium, $u_H H = \overline{u_H H}$ and $u_n H = \overline{u_n H}$. Using (4), (25), (26), $b = G_E - G_R$, $T = sY - b$, and $A = K + n$, we obtain

$$\dot{K} + \dot{n} + \dot{n} = rK + (1 - {}_r)rn + w(1 - u_H)H - C - s_K(r + {}_K)nx - s_R w u_n H + {}_c n.$$

Using the non-arbitrage condition (29) to substitute for $\dot{n}$ yields, after simplification,

$$\dot{K} + (1 +)\dot{n} - n = rK + wu_Y H + (1 - s_R)wu_n H - C - s_K(r + {}_K)nx.$$

Using (22) and (24), and taking into account that $nx = K$, we obtain

$$\dot{K} = (r + {}_K)K + wu_Y H - C - s_K(r + {}_K)K + n - {}_K K.$$

Finally, using (15), (19), and (20), we have the resources constraint

$$g_K = Y/K - C/K - {}_K. \quad (48)$$

Some equations that will be needed for solving the model are presented below. Log-differentiating (21) and (15), respectively, we obtain

$$g_Y ¼ g_K þ ð1 \;\; Þðg_{uY} þ g_H Þ þ \qquad g_n, \qquad ð49Þ$$

$$g_w ¼ g_Y \;\; g_{uY} \;\; g_H: \qquad ð50Þ$$

Log-differentiating (22) yields

$$g_{gn} ¼ ðg_{un} þ g_H Þ \;\; ð1 \;\; Þg_n: \qquad ð51Þ$$

Log-differentiating (24), substituting g from (29), from (17), w from (15), and from (24), we have

$$g_w ¼ ð1 \;\; _r Þr þ g_n þ ð \;\; 1Þðg_{un} þ g_H Þ \;\; \frac{ð1 \;\; _c Þð1 \;\;\; Þu_Y}{Þu_n} g_n þ g_n: ð52Þ \; ð1 \;\; s_R Þð1$$

Along a balanced growth path (or steady-state) equilibrium, all variables grow at constant but possibly different rates, and the time devoted to the different activities is constant. Constancy of $g^\wedge_C$ implies, by (11), constancy of r, i.e., $g^\wedge_r$ ¼ 0. Therefore, $g^\wedge_Y$ ¼ $g^\wedge_K$, from (19), and ¼ C=K is also constant in the steady state, $g^\wedge$ ¼ 0, from (48). Hence, $g^\wedge_Y$ ¼ $g^\wedge_C$ ¼ $g^\wedge_K$. Constancy of $g^\wedge_n$ implies, by (22), constancy of , i.e., $g^\wedge$ ¼ 0. The output-capital ratio ' ¼ Y=K can be expressed as

$$' ¼ Y=K ¼ ðu_Y H=KÞ^1 n \qquad ¼ u^1_Y \; ð\_\_\_^1 \qquad Þq, \qquad ð53Þ$$

where q ¼ $H^{1þ}$ $^{=ð1Þ}K^{ð1Þ}$. At the steady state, constancy of r entails constancy of ' which, together with constancy of u_Y and , entails that q is also constant, $g^\wedge_q$ ¼ 0.

The dynamic system (30)–(34) in terms of the variables q, , u_Y, , and g_n is determined as follows. We have used u_H ¼ 1 u_Y u_n, (53) and r =

qu^1_Y $^{=ð1Þ}$=ð1 s_KÞ $_K$. Using g_q ¼ ½1 þ =ð1 Þg_H ð1 Þg_K, eq. (30) results from (48) and (3). eq. (31) is obtained from (11) and (48). From (50), using (49) and (12) to substitute for g_Y and g_w, respectively, and then using (48) and (3), we can obtain (32). From g ¼ g_H þ ð 1Þg_n, using (3), we obtain (33). eq. (34) results from (51), (52), and (12), using (3). The steady-state equilibrium can be found as follows. Evaluating (3), (48), and (51) at the steady state we obtain (41), (39), and (38), respectively. From (49) and (38), we arrive at (37). Using (37) to express $g^\wedge_C$ as a function of $g^\wedge_H$ in (11) and (50), using (50) to eliminate g_w from (12), and solving the resulting system for $r^\wedge$ and $g^\wedge_H$, yields (35) and (36). Finally, eq. (40) results from (52), using (12) and (41), eq. (42) is obtained from (22), and eq. (43) results from its definition.