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Endogenous Growth and Monetary Policy: How Do Interest-Rate Feedback Rules Shape Nominal and Real Transitional Dynamics?

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Abstract

Monetary authorities have followed interest-rate feedback rules in apparently different ways over time and across countries. The literature distinguishes, in particular, between active and passive monetary policies in this regard. We address the nominal and real transitional-dynamics implications of these different types of monetary policy, in the context of a monetary growth model of R&D and physical capital accumulation. In this setup, well-behaved transitional dynamics occurs under both active and passive monetary policies. We carry out our study from three perspectives: the convergence behaviour of catching-up economies; a structural monetary-policy shock (i.e., a change in the long-run inflation target); and real industrial-policy shocks (i.e., a change in R&D subsidies or in manufacturing subsidies). We uncover a new channel through which institutional factors (the characteristics of the monetary-policy rule) influence the economies' convergence behaviour and through which monetary authorities may leverage (transitional) growth triggered by structural shocks.

JEL: O41, O31, E41

Keywords: Endogenous growth, cash-in-advance, feedback rule, inflation, monetary policy, physical capital, R&D, transitional dynamics.

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1. Introduction

Monetary-policy feedback rules have widespread use in modern economies. Yet, monetary authorities have followed these rules – either implicitly or explicitly – in apparently different ways over time and across countries (e.g., Clarida *et al.* 2000; Carare and Tchaidze 2005; Sauer and Sturm 2007; Mehra and Sawhney 2010; Hofmann and Bogdanova 2012; Caporale *et al.* 2018; Haque *et al.* 2019). In particular, diverse degrees of the sensitivity of the nominal interest rate to the inflation gap seem to occur, with the literature usually distinguishing, in this regard, between *active* and *passive* monetary policies.^{1,2}

Besides the much debated implications of this fact from the business-cycle perspective, following the seminal works by Clarida *et al.* (2000) and Lubik and Schorfheide (2004), this may have consequences from a more structural perspective, as it may affect the economies' transitional dynamics arising from changes in the structural stance of monetary policy (e.g., changes in the long-run inflation target) or from real industrial-policy shocks. It may also affect the convergence behaviour of catching-up economies by impacting the shape of their transition paths.³

The main goal of this paper is to theoretically address these conjectures, echoing the debate in the literature on *active* versus *passive* monetary policies and on the way they may induce different reactions of the nominal and real macroeconomic variables to shocks.

With this in mind, we analyse a growth model of R&D and physical capital accumulation (e.g., Howitt and Aghion 1998; Howitt 2000; Gil *et al.* 2017), extended with a monetary sector in line with a very recent literature where money demand is incorporated via cash-in-advance (CIA) constraints on R&D activities and on production and physical investment (Chu and Cozzi 2014; Gil and Iglésias 2019).⁴ In our model, however, the monetary authorities follow an interest-rate

1. Under an active (respectively, passive) monetary policy, a one percentage point increase in inflation is matched by a *more (less)* than one percentage point increase in the nominal interest rate.

2. The understanding in the literature is that interest-rate feedback rules are broadly good descriptions of the monetary-policy decision process and, thus, may be seen as benchmarks for the assessment of the stance of monetary policy (e.g., Orphanides 2003; Jung 2018). In the recent context of a binding zero lower-bound for nominal interest rates and of unconventional monetary policies, shadow interest-rate models (i.e., models of *notional* short-term interest rates) have been used to summarise the stance of monetary policy and characterise the feedback rules followed in the new environment (e.g., Krippner 2012; Wu and Xia 2016).

3. Modern (postwar) economies have experienced a rich pattern of transition paths of the economic growth rate and other real macroeconomic variables (see, e.g., Loyaza *et al.* 2000; Fiaschi and Lavezzi 2007; Gil *et al.* 2017). The economies have also observed diverse relationships over transition between inflation, money growth, and real macroeconomic variables such as economic growth, R&D intensity, and velocity of money (e.g., Gillman *et al.* 2004; Pintea and Thompson 2007; Benk *et al.* 2010; López-Villavicencio and Mignon 2011; Gil *et al.* 2013; Chu *et al.* 2015).

4. Empirical evidence clearly suggests that R&D investment is severely affected by liquidity requirements, even more so than physical investment (see, e.g., Brown *et al.* 2012; Falato and Sim

feedback rule (similarly to, e.g., Meng and Yip 2004, Yip and Li 2006, and Chen *et al.* 2008), instead of keeping the level of the nominal interest rate (or another nominal variable) fixed over the whole time horizon of the model.⁵

The simultaneous consideration of R&D and physical capital follows from both a substantive (economic) and a formal (technical) argument. As for the former, such a setup enables us to address the close interrelation between physical and technological inputs empirically observed along growth processes (e.g., Dowrick and Rogers 2002, and Tamura *et al.* 2019) by allowing physical capital accumulation and R&D to complement each other as engines of long-run growth. On the formal side, this setup is a natural extension to the neoclassical growth model of endogenous investment, where the transitional behaviour is driven by the decreasing marginal returns to physical capital (e.g., Barro and Sala-i-Martin 2004, ch.2). In our model, aggregate dynamics is characterized by a second-order dynamical system in appropriately scaled variables, with one jump-like and one state-like variable, where the latter reflects the interaction between the physical-capital stock and the technological-knowledge stock resulting from R&D activities. Given the initial conditions on the state-like variable, transitional dynamics then arises due to the interplay between the process of knowledge accumulation and that of physical capital accumulation. Similarly to the standard neoclassical growth model, endogenous investment and decreasing marginal returns to physical capital pin down the dynamics, thereby guaranteeing, in our model, equilibrium uniqueness and local determinacy under both active and passive monetary policies.⁶ This result is in line with that in Meng and Yip (2004) (see also the references therein), while extending it to a setting of endogenous growth and R&D. Thus, our setup allows us to investigate the role played by the differences in the interest-rate feedback rules in a context where well-behaved (saddle-path) transitional dynamics occurs under both types of monetary policy.

We study the transitional-dynamics effects on nominal and real macroeconomic variables of interest for policymakers – namely the nominal interest rate, inflation

2014; Brown and Petersen 2015). This motivates a growth model that features CIA requirements in both R&D activities and physical investment.

5. The assumption that the monetary authorities fix the level of a selected nominal variable (e.g., the nominal interest rate, inflation or money growth) has been common in the literature of monetary growth models – e.g., Chu and Cozzi (2014) and Gil and Iglésias (2019), among many others; see also Gillman and Kejak (2005) for a survey of earlier contributions on this topic.

6. The R&D-physical capital setting we adopt, where the latter exhibits decreasing marginal returns as in the standard neoclassical growth model, is common to several other papers in the literature (e.g., Romer 1990; Howitt and Aghion 1998; Howitt 2000; Sedgley and Elmslie 2013; Gil *et al.* 2017). Alternatively, e.g., Iwaisako and Futagami (2013) and Chu *et al.* (2019b) consider both R&D and physical capital accumulation as engines of growth in a setting that features constant returns to physical capital. That is, these models combine R&D with an AK structure and, therefore, do not display the typical neoclassical transitional-dynamics mechanism. Also, the growth rates of physical capital and of the technological-knowledge stock are determined independently; in this sense, capital accumulation and R&D do not exhibit the type of complementary found in our model.

rate, economic growth rate, real interest rate, R&D intensity, and velocity of money. We take three perspectives: the convergence behaviour of catching-up economies (i.e., the transition paths given initial conditions off the steady state); a structural monetary-policy shock (i.e., a change in the long-run inflation target); and real industrial-policy shocks (i.e., a change in subsidies to R&D or to goods manufacturing).⁷

As mentioned above, considering an active versus a passive monetary policy does not change the properties of the long-run equilibrium as regards existence and stability in our model. Yet, the magnitude of the sensitivity of the nominal interest rate to the inflation gap does matter for the type of transition paths – increasing, decreasing or even non-monotonic – of the macroeconomic variables, for a given exogenous shock or initial conditions. Our paper features an extensive set of results; in what follows, we highlight some of them.

We first notice that, in the case of the nominal variables (inflation and nominal interest rate), there is a qualitative change in the dynamics – the slope of the transition path switches sign – when we compare an *active* with a *passive* monetary policy. This pattern arises from the interplay between the interest-rate feedback rule and the well-known Fisher equation,⁸ as this interplay determines how the transition paths of inflation and the nominal interest rate relate to the path of the real interest rate. But, in the case of the real variables, the patterns are distinct, because their transition paths reflect the joint effect of the dynamics of the nominal variables (as they impact the real variables through the CIA-related costs) and of physical-capital accumulation (which impacts the real variables either directly or through the determination of the real interest rate). For instance, there is a qualitative change in the dynamics of the economic growth rate – which may even become non-monotonic – only in the case of a *mildly active* monetary policy and a change for the R&D intensity and the velocity of money only in the case of a *mildly passive* monetary policy.⁹ This implies disparate cross-correlations of the variables along their transition paths for different scenarios of the sensitivity of the nominal interest rate to the inflation gap. For instance, a *mildly passive* monetary policy strongly exacerbates the typical negative relationship over transition between physical capital and economic growth, to be found in neoclassical growth models

7. In any case, it should be underlined (as a preview of the model to be presented in Section 2) that the endogenous shifts in the nominal variables over transition are driven by the arbitrage between nominal and real assets conducted by the households as a reaction to shocks or to given initial conditions off the steady-state. This, in turn, is connected to the way money demand enters the model (via CIA constraints in the production and technological side of the model, as mentioned earlier). Thus, these are structural-driven shifts in the nominal variables and which accord with longer time horizons than the business-cycle frequency.

8. As will be shown later on, the Fisher equation is derived as a no-arbitrage condition in the household's dynamic optimisation problem in models such as ours.

9. Under a mildly active (respectively, mildly passive) monetary policy, a one percentage point increase in inflation is matched by *slightly more* (*slightly less*) than one percentage point increase in the nominal interest rate. In Section 4, we will provide precise numerical illustrations.

with decreasing marginal returns to capital (see, e.g., Barro and Sala-i-Martin 2004, ch. 2, for the case of exogenous growth, and Howitt and Aghion 1998, or Gil *et al.* 2017, for endogenous growth). Yet, a *mildly active* monetary policy overturns that result, generating a positive correlation between capital and growth, which is an important expansion of the set of results in the literature that studies the diversity of growth dynamics. All in all, our results – applied to the context of given initial conditions – may help explain the diversity of convergence behaviour observed in postwar economies, with the characteristics of the monetary-policy rules adding to the set of institutional factors identified by the literature as determinants of the shape of transition paths (see, e.g., Jones and Romer 2010, and Gil *et al.* 2017). Our results may also contribute to explaining the disparate relationships between inflation, money growth, and key real macroeconomic variables along their transition paths. In particular, they may help justify why inflation has been reported to have so different “growth effects” in different countries when looking into panel and time-series data (e.g., Gillman *et al.* 2004; Omay and Kan 2010; López-Villavicencio and Mignon 2011).¹⁰

The described sensitivity of the transitional behaviour to the type of monetary policy is also a key determinant of the response of the real and nominal variables to shocks in our model and, in particular, whether there will be an *overshooting* behaviour (or over-reaction) of those variables in the *short-run*.¹¹ In the case of a structural monetary-policy shock, the other key factor determining the response of the variables is the relative degree of the CIA constraint on R&D vis-à-vis manufacturing. Since the empirical literature suggests the former exceeds the later (see fn. 4), we take this as our baseline case. In such a scenario, a positive monetary-policy shock (i.e., an increase in the long-run inflation target) will induce an (upward) over-reaction of inflation and the nominal interest rate in the short run – and, consequently, a decrease of these variables over transition towards the new (higher) steady state – under an *active* monetary policy. Yet, regarding say the economic growth rate, there will be a (downward) over-reaction to the shock – and subsequently an increase towards the new (lower) steady state – only under a *mildly active* monetary policy. In contrast, under a *mildly passive* monetary policy, there will be a *dampened* short-run response of all the variables above to the shock, at the expense of a more pronounced transitional-dynamics effect, in subsequent

10. Since, in our dynamic general-equilibrium setup, both inflation and economic growth are endogenous over transitional dynamics, any co-movements reflect their respective responses to a given exogenous shock or initial conditions off the steady state. Bearing in mind the slow transitions typically observed in the data, our results help reconcile the wide range of often conflicting correlations that have been estimated in the literature (see fn. 3).

11. As is well known, in face of a structural shock, the optimal response of some variables may be to exhibit an immediate jump preceding the transition path towards the new steady-state level. That is, there is an immediate (or *short-run*) effect that adds to the transitional-dynamics effect. Under some circumstances, this short-run effect may exceed the size of the shift in the steady-state level, that is, there is an *overshooting* of the variable in the short run. This, then, implies that the ensuing transitional-dynamics effect will have to partially undo the short-run effect.

periods. This suggests monetary authorities should favour a *mildly passive* policy if they seek short-run stability of inflation and growth in face of shifts in the structural stance of monetary policy.

However, in the case of a positive real industrial-policy shock, policy authorities may wish to seek a strong short-run response of the variables in a certain direction. A positive shock under the form of an R&D subsidy will induce a short-run *downward* jump of inflation and the nominal interest rate – and subsequently an *increase* towards the (unchanged) steady state – under an *active* monetary policy. But there will be an (upward) *over-reaction* of the economic growth rate to the shock – and subsequently a *decrease* towards the new (higher) steady state – only under a *mildly active* monetary policy. Overall, this suggests that the authorities should favor a *mildly active* monetary policy say if they wish to maximise growth and minimise inflation (above a certain level) over transition. Yet, for a positive shock under the form of an increase in the manufacturing subsidy, the same sort of response requires, for inflation and the nominal interest rate, a *passive* monetary policy and, for the economic growth rate, either a *passive* or a *strongly active* monetary policy. Thus, differently from the R&D-subsidy scenario, the authorities should favor a *passive* monetary policy to maximise growth and minimise inflation over transition.

To sum up, the set of results above uncovers two possible trade-offs from the point of view of the monetary-policy feedback rule: one between short-run stabilisation under a structural monetary-policy shock and transitional growth-maximisation/inflation-minimisation under an R&D-subsidy shock; the other between the latter and transitional growth-maximisation/inflation-minimisation under a manufacturing-subsidy shock. In any case, our results expose a new channel through which monetary policy may support growth and reduce inflation beyond the business-cycle frequency: the cumulative transitional-dynamics effects generated by the monetary-policy feedback rule in face of structural shocks to the economy, and which are due to the overshooting behaviour in response to those shocks.

Our paper is related to different bodies of the literature. First, we underline the literature that studies alternative monetary-policy rules (including feedback rules) in search for equivalence results from the perspective of welfare and, in some cases, of long-run economic growth (e.g., Végh 2001; Lai *et al.* 2005; Yip and Li 2006; Schabert 2009; Chen *et al.* 2008; Lai and Chin 2013). The papers focusing on growth effects typically feature models of the AK type. Some of these papers look into these issues also from the transitional-dynamics perspective. As regards the AK models of economic growth, transitional dynamics typically obtains by positing physical investment convex adjustment costs and/or adjustment effects (lag effects) in the monetary-policy rule itself (from the above, Chen *et al.* 2008, and Lai and Chin 2013). Our paper is closest to the strand of the literature that, in the context of monetary-policy feedback rules, looks into the relationship between the type of monetary policy – active versus passive – and the properties of the long-run equilibrium regarding existence and stability (e.g., Meng and Yip 2004; Yip and Li 2006; Chen *et al.* 2008). As mentioned earlier, we extend the analysis to a setting

of endogenous growth that encompasses both R&D activities and physical capital accumulation.

Second, our paper contributes to the literature that looks into rich transitional dynamics in the context of (usually non-monetary) R&D-driven growth models (e.g., Eicher and Turnovsky 2001; Arnold 2006; Arnold and Kornprobst 2008; Sequeira 2011; Growiec and Schumacher 2013; Gil *et al.* 2017). These papers study how a number of distinct – monotonic or non-monotonic – transition paths of key macroeconomic variables may emerge either by considering alternative initial conditions of the economy or specific configurations of its key structural parameters. To the best of our knowledge, ours is the first paper to combine diverse initial conditions with differences in the monetary-policy feedback rule to generate rich patterns of transition paths.

Finally, our paper also relates to the literature on monetary endogenous-growth models. We follow, in particular, a recent literature that introduces money demand in the models by considering a CIA constraint on R&D investment (e.g., Chu and Cozzi 2014; Chu *et al.* 2015; Huang *et al.* 2017; Chu *et al.* 2017b; Chu *et al.* 2017a; Chu *et al.* 2019a; Gil and Iglésias 2019). From these papers, only Chu and Cozzi (2014) and Gil and Iglésias (2019) also consider a CIA constraint on manufacturing of intermediate goods. In turn, Arawatari *et al.* (2017) combine CIA constraints on consumption and on manufacturing of intermediate goods. Our paper is especially close to Gil and Iglésias (2019) since, in both models, the manufacturing sector uses physical capital as an input and, thus the respective CIA constraint also affects the mechanism of physical capital accumulation. Given the considered complementarity between physical capital accumulation and R&D, this implies a close interrelation between the CIA constraints on R&D and on manufacturing, which differs from the mechanisms previously found in the literature. Our model's joint consideration of a monetary-policy feedback rule and CIA constraints on R&D and on manufacturing is also new to the literature.

The rest of the paper is organised as follows. Section 2 presents the building blocks of the monetary growth model. Section 3 derives the dynamic general equilibrium of the model and qualitatively characterises the local-dynamics properties of the (interior) long-run equilibrium. Section 4 analyses the transitional dynamics of key monetary and real macroeconomic variables under different values of the sensitivity of the nominal interest rate to the inflation gap in the feedback rule and gathers the key qualitative and quantitative results. Section 5 concludes.

2. The model

We consider a version of the model of R&D and physical capital accumulation in Howitt and Aghion (1998) and Gil *et al.* (2017), extended with a monetary sector, as in Chu and Cozzi (2014) and Gil and Iglésias (2019). This is a dynamic general-equilibrium endogenous growth model where a competitively-produced final good can be used in consumption, accumulation of physical capital, and R&D

activities. The economy is populated by infinitely-lived (dynastic) households who consume and inelastically supply labour to final-good firms. The final good is produced using labour and a continuum of varieties of intermediate goods. Potential entrants into the intermediate-good sector devote resources to vertical R&D, by which they increase the quality of an existing variety of intermediate good. We incorporate money demand in the endogenous growth model via cash-in-advance (CIA) constraints on R&D activities and on manufacturing of intermediate goods,¹² whereas the monetary authority determines the money supply.

2.1. Production and price decisions

The final good is produced with a constant-returns-to-scale technology using labour and a continuum of intermediate goods indexed by $\omega \in [0, N]$,

$$Y(t) = A \cdot L^{1-\alpha} \int_0^N \left(\lambda^{j(\omega,t)} \cdot X(\omega, t) \right)^\alpha d\omega, \quad 0 < \alpha < 1, \lambda > 1, \quad (1)$$

where: A is the exogenous component of total factor productivity; L is the labour input (assumed as constant over time, for simplicity); $1 - \alpha$ is the labour share in production; and $\lambda^{j(\omega,t)} \cdot X(\omega, t)$ is the input of intermediate good ω measured in efficiency units, all taken at time t . The quality of the intermediate good ω is indexed by $\lambda^{j(\omega,t)}$, where $j(\omega, t)$ denotes the quality level and λ is a parameter measuring the size of each quality upgrade. Final producers are price-takers in all the markets they participate in. They take wages, $w(t)$, and input prices, $p(\omega, t)$, as given and sell their output at a price also taken as given. All prices and wages are normalised by the price of the final good, so that w and p are defined in real terms. From the profit maximization conditions, the demand of intermediate good ω is

$$X(\omega, t) = L \cdot \left(\frac{A \cdot \lambda^{j(\omega,t) \cdot \alpha} \cdot \alpha}{p(\omega, t)} \right)^{\frac{1}{1-\alpha}}, \quad \omega \in [0, N]. \quad (2)$$

The intermediate good is produced using physical capital, according to $\eta \cdot X(\omega, t) = K(\omega, t)$, where $K(\omega, t)$ is the input of capital in industry ω and $\eta > 0$ is a constant cost factor. We follow the literature and introduce a CIA constraint on manufacturing of intermediate goods by assuming that intermediate-good firms use money, borrowed from households subject to the nominal interest rate $i(t)$,

12. We abstract from the more conventional CIA on consumption, or, more generically, from a money-in-utility or a liquidity/pecuniary-transaction-costs specification in the households' optimization problem (e.g., Feenstra 1986), as we wish to focus on the technology side of the model and its interaction with the monetary sector. Gil and Iglésias (2019) analyse extensions of our baseline model that consider those two specifications: money-in-utility and pecuniary transaction costs on consumption. They show that there is qualitative equivalence of results between the two specifications, but also between the extended model and the baseline model.

to pay for a fraction $\Omega \in [0, 1]$ of the capital input. Consequently, the cost of intermediate good ω has an operational and a financial component, that is, $(1 - \Omega) \cdot r(t) \cdot K(\omega, t) + \Omega \cdot (1 + i(t)) \cdot r(t) \cdot K(\omega, t) = K(\omega, t) + \Omega \cdot i(t) \cdot r(t) \cdot K(\omega, t)$, where $r(t)$ is the equilibrium market real interest rate; thus, the cost of capital is the latter adjusted by the CIA constraint, i.e., $(1 + \Omega \cdot i(t)) \cdot r(t)$.¹³ Thus, the intermediate good ω is produced with a cost function $(1 + \Omega \cdot i(t)) \cdot r(t) \cdot K(\omega, t) = (1 + \Omega \cdot i(t)) \cdot r(t) \cdot \eta \cdot X(\omega, t)$. In other words, Ω controls for the intensity of the CIA constraint on manufacturing of intermediate goods. Later we will compare Ω with the intensity of the CIA constraint on R&D, to be introduced in Section 2.2, below.

The intermediate-good sector consists of a continuum $N(t)$ of industries, characterised by monopolistic competition at the sector level. The monopolist in industry ω chooses the price $p(\omega, t)$ in face of the isoelastic demand curve (2). Profit in industry ω is thus $\Pi(\omega, t) = [p(\omega, t) - (1 + \Omega \cdot i(t)) \cdot r(t) \cdot \eta] \cdot X(\omega, t)$, and the profit maximising price is a markup over marginal cost, $p(\omega, t) \equiv p(t) = (1 + \Omega \cdot i(t)) \cdot \eta \cdot r(t) / \alpha$, which is constant across industries but possibly variable over time. Then, from (2) and the markup, the optimal quantity produced of intermediate good ω is $X(\omega, t) = L \cdot \left(\frac{A \cdot \alpha^2}{(1 + \Omega \cdot i(t)) \cdot \eta \cdot r(t)} \right)^{\frac{1}{1-\alpha}} \cdot q(\omega, t)$, where $q(\omega, t) \equiv \lambda^{j(\omega, t) \frac{\alpha}{1-\alpha}}$ is a monotonic transformation of the quality index.

On the other hand, capital market equilibrium requires $K(t) = \int_0^N K(\omega, t) d\omega = \int_0^N \eta \cdot X(\omega, t) d\omega = \eta \cdot \tilde{X}(t) \cdot Q(t)$, where $\tilde{X}(t) \equiv L \cdot \left(\frac{A \cdot \alpha^2}{(1 + \Omega \cdot i(t)) \cdot \eta \cdot r(t)} \right)^{\frac{1}{1-\alpha}}$ and

$$Q(t) = \int_0^N q(\omega, t) d\omega, \quad (3)$$

which is the aggregate quality index. The latter measures the technological-knowledge stock of the economy, since, by assumption, there are no inter-industry technological spillovers.¹⁴ Then, by using the expression for $\tilde{X}(t)$ in the capital market equilibrium condition and solving with respect to $r(t)$, we get

$$r(t) = \frac{A \cdot \alpha^2 \cdot k(t)^{\alpha-1}}{(1 + \Omega \cdot i(t)) \cdot \eta^\alpha}, \quad (4)$$

where $k(t) \equiv K(t) / (L \cdot Q(t))$ is the physical capital-technological knowledge ratio. Equation (4) expresses the condition that the cost of capital must equal its marginal revenue product, adjusted by the effect of the markup, $1/\alpha$. By using $X(\omega, t)$ and $r(t)$, we get the optimal profit earned by the monopolist in ω

$$\Pi(\omega, t) = \Pi_0 \cdot L \cdot \eta^{-\alpha} \cdot k(t)^\alpha \cdot q(\omega, t), \quad (5)$$

13. For sake of simplicity, we abstract from physical depreciation.

14. See, e.g., Barro and Sala-i-Martin (2004, ch.7); this setting contrasts with the one in, e.g., Howitt and Aghion (1998), where the leading-edge technology is available to the (potential) entrant in every industry.

where $\Pi_0 \equiv A \cdot \alpha \cdot (1 - \alpha)$ is a positive constant. Finally, using all the above, we get total optimal intermediate-good production, total optimal profits, and total optimal final-good production,

$$X(t) = \int_0^N X(\omega, t) d\omega = \frac{1}{\eta} K(t), \quad (6)$$

$$\Pi(t) = \int_0^N \Pi(\omega, t) d\omega = \Pi_0 \cdot L \cdot \eta^{-\alpha} \cdot k(t)^\alpha \cdot Q(t), \quad (7)$$

$$Y(t) = A \cdot L \cdot \eta^{-\alpha} \cdot k(t)^\alpha \cdot Q(t). \quad (8)$$

2.2. R&D decisions and the aggregate quality index dynamics

This section modifies the vertical R&D sector in, e.g., Barro and Sala-i-Martin (2004, ch. 7) and Gil *et al.* (2017) by introducing a CIA constraint on R&D activities. We consider an R&D sector targeting vertical innovation so that a new design pertains to a higher quality intermediate good. Each new design is granted a perpetual patent and thus a successful innovator retains exclusive rights over the use of that good. R&D is performed by (potential) entrants and successful R&D leads to the set-up of a new intermediate-good firm and the replacement of the incumbent. There is free entry in the R&D business and perfect competition among entrants.

To be concrete, by improving on the current top quality level $j(\omega, t)$, a successful innovator earns monopoly profits from selling the leading-edge intermediate-good of $j(\omega, t) + 1$ quality to final-good firms. A successful innovation increases the quality index in ω from $q(\omega, t) = q(j)$ to $q^+(\omega, t) = q(j + 1) = \lambda^{\alpha/(1-\alpha)} q(\omega, t)$. In equilibrium, the lower quality good is priced out of business and the entrant replaces the incumbent, i.e., there is a creative-destruction effect.

Let $I_i(j)$ denote the Poisson arrival rate of vertical innovations (innovation rate) by potential entrant i in industry ω when the highest quality is j . Rate $I_i(j)$ is independently distributed across firms, across industries and over time, and depends on the flow of resources $R_{vi}(j)$ allocated by potential entrant i at time t , measured in units of the final good. Rate $I_i(j)$ features constant returns in R&D expenditures, $I_i(j) = R_{vi}(j) / \Phi(j)$, where $\Phi(j)$ is the unit innovation cost, which is homogeneous across i in industry ω . Aggregating across i in ω , we get $R_v(j) = \sum_i R_{vi}(j)$ and $I(j) = \sum_i I_i(j)$, and thus

$$I(j) = \frac{1}{\Phi(j)} R_v(j), \quad (9)$$

where $\Phi(j) = \zeta \cdot L \cdot q(j + 1)$, and $\zeta > 0$ is a constant flow fixed cost. We also posit that there is an adverse complexity effect, so that the difficulty of introducing new

qualities and replacing old ones is proportional to the market size, which in turn is proportional to L (e.g., Dinopoulos and Thompson 1999; Barro and Sala-i-Martin 2004, ch. 7).¹⁵

As the terminal date of each monopoly arrives as a Poisson process with frequency $I(j)$ per (infinitesimal) increment of time, reflecting the creative-destruction effect, the expected value of an incumbent firm with current quality level $j(\omega, t)$ is

$$V(j) = \Pi_0 \cdot L \cdot \eta^{-\alpha} \cdot q(j) \cdot \int_t^\infty k(s)^\alpha \cdot e^{-\int_t^s (r(v) + I(j)) dv} ds \quad (10)$$

where $\Pi_0 \cdot L \cdot \eta^{-\alpha} \cdot q(j) = \Pi(\omega, t)/k(t)^\alpha$, given by (5), is constant in-between innovations. As physical capital accumulation and R&D investment both represent foregone consumption (see Subsection 2.5, below), the real rate of return to R&D is equal to that for capital, r . We assume that the financing of R&D costs requires money borrowed from households, so that a CIA constraint on R&D activities also exists alongside that on manufacturing of intermediate goods. In this context, the R&D cost has an operational and a financial component, that is, $(1 - \beta) \cdot R_v(j) + \beta \cdot (1 + i(t)) \cdot R_v(j) = R_v(j) + \beta \cdot i(t) \cdot R_v(j)$, where $\beta \in [0, 1]$ is the share of the R&D cost that requires the borrowing of money from households. Free-entry prevails in R&D such that the condition $I(j) \cdot V(j+1) = (1 + \beta \cdot i(t)) \cdot R_v(j)$ holds and, thus, from (9), $V(j+1) = (1 + \beta \cdot i(t)) \cdot \zeta \cdot L \cdot q(j+1)$. Next, we determine $V(j+1)$ analogously to (10) and time-differentiate the resulting expression. By recalling (5), we get the no-arbitrage condition facing an innovator¹⁶

$$r(t) + I(t) = \frac{\Pi_0 \cdot k(t)^\alpha}{(1 + \beta \cdot i(t)) \cdot \zeta \cdot \eta^\alpha}, \quad (11)$$

15. These complexity costs offset the positive effect of scale on the (expected) profits of the successful innovator, thus delivering a long-run equilibrium without strong scale effects on growth, which are known to be counterfactual in modern economies.

16. From (5) and (9), we have $\frac{\dot{\Pi}(\omega, t)}{\Pi(\omega, t)} - \alpha \frac{\dot{k}(t)}{k(t)} = I(\omega, t) \cdot \left[\dot{j}(\omega, t) \cdot \left(\frac{\alpha}{1-\alpha} \right) \cdot \ln \lambda \right]$ and $\frac{\dot{R}_v(\omega, t)}{R_v(\omega, t)} - \frac{\dot{I}(\omega, t)}{I(\omega, t)} = I(\omega, t) \cdot \left[\dot{j}(\omega, t) \cdot \left(\frac{\alpha}{1-\alpha} \right) \cdot \ln \lambda \right]$. Then, if we time-differentiate the free-entry condition considering (10) and the equations above, we get $r(t) = \frac{\Pi(j+1) \cdot I(j)}{(1 + \beta \cdot i) \cdot R_v(j)} - I(j+1)$, which can then be re-written as (11). In this regard, we also notice that the cost of borrowing is given by $R_v(j) \cdot \int_t^{t+\Delta t} i(s) ds \approx R_v(j) \cdot i(t) \cdot \Delta t$, meaning that the CIA constraint applies as the requirement that the amount $R_v(j)$ can only be repaid after a (small) time interval Δt (see, e.g., Chu and Cozzi 2014). Following the literature, and considering Δt as an infinitesimal increment of time, we assume that i is constant over $\Delta t \rightarrow 0$ so that the previous relationship holds exactly and thus the cost of borrowing *per unit of time* is $R_v(j) \cdot i(t)$, as stated in the text. Accordingly, we also consider i constant over $\Delta t \rightarrow 0$ when we time-differentiate the R&D free-entry condition to derive the no-arbitrage condition. It can be shown, however, that the consideration of the (second-order) dynamical effect arising from the time-differentiation of $i(t)$ in the derivation of the no-arbitrage condition does not change the qualitative properties of the dynamical system to be derived in Section 3, below. Quantitatively, the consideration of the time-differentiation of $i(t)$ attenuates (respectively, intensifies) somewhat the dynamics of the macro variables over transition when $\gamma < 1$ ($\gamma > 1$).

The right-hand side of (11) implies that the innovation rates are homogeneous across industries, $I(\omega, t) = I(t)$.

Solving equation (9) for $R_v(\omega, t) = R_v(j)$ and aggregating across industries ω , we determine total resources devoted to R&D, $R_v(t) = \int_0^{N(t)} R_v(\omega, t) d\omega = \int_0^{N(t)} \zeta \cdot L \cdot q^+(\omega, t) \cdot I(\omega, t) d\omega$, which is equivalent to

$$R_v(t) = \zeta \cdot L \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(t) \cdot Q(t), \quad (12)$$

given the homogeneity of the innovation rate across industries.

Since a successful innovation increases the quality index in industry ω from $q(\omega, t)$ to $q^+(\omega, t) = \lambda^{\alpha/(1-\alpha)} q(\omega, t)$ with an expected arrival rate $I(t)$, then, in aggregate terms – and given the continuum of industries in $[0, N]$ – that change can be measured over a small time interval as $\dot{Q}(t) = \int_0^N I(t) \cdot \left(\lambda^{\frac{\alpha}{1-\alpha}} \cdot q(\omega, t) - q(\omega, t) \right) d\omega$. This can be rewritten as

$$\dot{Q}(t) = I(t) \cdot \Xi \cdot Q(t), \quad (13)$$

where $\Xi \equiv \lambda^{\frac{\alpha}{1-\alpha}} - 1$ is the quality shift generated by successful R&D. The innovation rate $I(t)$ is endogenous and will be determined at the aggregate level below.

2.3. Households

The economy is populated by a constant number of dynastic identical families who consume and earn income from labour, L , and from investments in financial assets and money balances. L is inelastically supplied to final-good firms. Households have perfect foresight and choose the path of consumption $\{C(t), t \geq 0\}$ in order to maximise discounted lifetime utility,

$$U = \int_0^\infty \left(\frac{C(t)^{1-\theta} - 1}{1-\theta} \right) \cdot e^{-\rho t} dt, \quad (14)$$

where $\rho > 0$ is the subjective discount rate and $\theta > 0$ is the inverse of the intertemporal elasticity of substitution in consumption. The households' flow budget constraint is

$$\dot{a}(t) + \dot{m}(t) = r(t) \cdot a(t) + w(t) \cdot L - C(t) + \tau(t) - \pi(t) \cdot m(t) + i(t) \cdot b(t), \quad (15)$$

where: $a(t)$ represents the households' real financial assets holdings (equity); $m(t)$ is the households' real money balance; $\tau(t)$ denotes a lump-sum transfer/tax from the monetary authority; $\pi(t)$ is the inflation rate, which determines the cost of holding money; and $b(t)$ is the amount of money lent by households to incumbent intermediate-good firms and to entrants to finance the manufacturing of intermediate-goods and R&D investment, respectively, and which return is $i(t)$. Thus, the CIA constraints imply that $b(t) \leq m(t)$. The initial level of the state

variables, $a(0)$ and $m(0)$, is given. From standard dynamic optimisation,¹⁷ we derive a no-arbitrage condition (this is the well-known Fisher equation and it establishes that $i(t)$ is, indeed, the nominal interest rate) and the optimal path of consumption,

$$i(t) = r(t) + \pi(t), \quad (16)$$

$$\dot{C}(t) = \frac{1}{\theta} \cdot (r(t) - \rho) \cdot C(t), \quad (17)$$

whereas the transversality conditions are

$$\lim_{t \rightarrow +\infty} e^{-\rho t} \cdot C(t)^{-\theta} \cdot a(t) = 0; \quad \lim_{t \rightarrow +\infty} e^{-\rho t} \cdot C(t)^{-\theta} \cdot m(t) = 0. \quad (18)$$

2.4. Monetary authority

The monetary sector is considered as in, e.g., Chu and Cozzi (2014) and Gil and Iglésias (2019), but with a monetary-policy rule in line with Meng and Yip (2004) and Yip and Li (2006) (see, also, Chen *et al.* 2008). The nominal money supply is denoted by $M(t)$ and its growth rate is $\mu(t) \equiv \dot{M}(t)/M(t)$. The real money balance is $m(t) = M(t)/P(t)$, where $P(t)$ is the nominal price of the final good, and, thus, its growth rate is $\dot{m}(t)/m(t) = \mu(t) - \pi(t)$. The monetary authority follows (either implicitly or explicitly) a nominal interest-rate feedback rule as its monetary-policy rule,

$$i(t) = \bar{i} + \gamma \cdot (\pi(t) - \bar{\pi}), \quad \gamma > 0, \gamma \neq 1, \quad (19)$$

where $\bar{\pi}$ is the monetary authority's (exogenous) long-run inflation target, $\bar{i}$ is the nominal interest rate that is compatible with that target given the long-run equilibrium of the real variables in the economy, and γ is a parameter that controls for the sensitivity of the nominal interest rate to the inflation gap, $\pi(t) - \bar{\pi}$.¹⁸ As is well known, if $\gamma > 1$ ($\gamma < 1$), equation (19) expresses an active (passive) monetary policy (see, e.g., Meng and Yip 2004; Chen *et al.* 2008). As explained later, in Section 3, $i(t)$ and $\pi(t)$ are both endogenously determined in transitional dynamics, while converging to $\bar{i}$ and $\bar{\pi}$ in the long-run equilibrium. Given $\pi(t)$, with $\lim_{t \rightarrow \infty} \pi(t) = \bar{\pi}$, the growth rate of the nominal money supply will be

17. Appendix A provides further details on the derivation of the results.

18. Implicitly, the rule in (19) results from assuming that $Y = \bar{Y}$, $\forall t$, in Taylor (1993)'s rule (thus corresponding to $g_Y = g_{\bar{Y}}$, $\forall t$, in a dynamic setting such as ours), i.e., output is at its flexible-price level at all times, as usually considered in the neoclassical growth models. Models that combine R&D-based growth with nominal-price rigidity and use the Taylor (1993)'s rule as a monetary-policy rule can be found in Moran and Queralto (2018) and Bianchi *et al.* (2019). Notice also that the case of a nominal interest rate set exogenously by the monetary authority, $i(t) = \bar{i}$, $\forall t$, as considered by Chu and Cozzi (2014), Gil and Iglésias (2019) and several others, is trivially recovered under $\gamma = 0$.

endogenously determined according to $\mu(t) = \dot{m}(t)/m(t) + \pi(t)$, where $\dot{m}(t)/m(t)$ is determined by the real conditions in the economy.¹⁹ That is, the monetary authority will endogenously adjust the money growth rate to whatever level is needed for the inflation rate $\pi(t)$ (and, thus, the nominal interest rate, $i(t)$) to prevail. As usually assumed in the literature, the monetary authority returns the seigniorage revenues to households as a lump-sum transfer at every time t to balance its budget,, i.e., $\tau(t) = \dot{M}(t)/P(t) = \dot{m}(t) + \pi(t) \cdot m(t)$.

2.5. Macroeconomic aggregation and equilibrium capital accumulation and innovation rates

The aggregate financial wealth held by all households is $a(t) = K(t) + \int_0^N V(\omega, t) d\omega$, which, considering equation (10) together with the free-entry condition in R&D, is equivalent to $a(t) = K(t) + (1 + \beta \cdot i(t)) \cdot \zeta \cdot L \cdot Q(t)$.²⁰ Taking time derivatives and using (13), (15), together with the lump-sum transfer, $\tau = \dot{m}(t) + \pi(t) \cdot m(t)$, and the real wage, $w(t) = (1 - \alpha) \cdot Y(t)/L$ (from the profit maximisation problem of the final-good firms), we get

$$\begin{aligned} \left(K(t) + \int_0^N V(\omega, t) d\omega \right) \cdot r(t) + (1 - \alpha) \cdot Y(t) - C(t) + i(t) \cdot b(t) = \\ = \dot{K}(t) + (1 + \beta \cdot i(t)) \cdot \zeta \cdot L \cdot I(t) \cdot \Xi \cdot Q(t). \end{aligned}$$

Next, consider (4) and (8) to get $r(t) \cdot K(t) = \alpha^2 \cdot Y(t)/(1 + \Omega \cdot i(t))$, and (7) and (11) to get $r(t) \cdot \int_0^N V(\omega, t) d\omega = \alpha \cdot (1 - \alpha) \cdot Y(t) - (1 + \beta \cdot i(t)) \cdot \zeta \cdot L \cdot I(t) \cdot Q(t)$. Then, also recalling equation (12) and $\Xi \equiv \lambda^{\frac{\alpha}{1-\alpha}} - 1$, and considering the amount of money lent by households as $b(t) = \beta \cdot \zeta \cdot L \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(t) \cdot Q(t) + \Omega \cdot r(t) \cdot K(t)$, we obtain

$$Y(t) = C(t) + \dot{K}(t) + R_v(t), \quad (20)$$

which is the aggregate flow budget constraint or, equivalently, the product market equilibrium condition. Solving with respect to $\dot{K}(t)$ and replacing again $Y(t)$ and $R_v(t)$ with (8) and (12), we get the endogenous rate of physical-capital accumulation,

$$\dot{K}(t) = L \cdot Q(t) \cdot \left(A \cdot \eta^{-\alpha} \cdot k(t)^\alpha - \frac{C(t)}{L \cdot Q(t)} - \zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(t) \right). \quad (21)$$

19. To see this, consider the CIA constraint as a binding condition, i.e., $b(t) = m(t)$, which implies that the dynamics of the real money balance, m , is determined by the dynamics of the (real) resources allocated to both capital accumulation and R&D activities (see Section 2.5, below, for a formal derivation). In the long-run equilibrium, the growth rate of m equals the real growth rate of the economy (see Section 3.2, below).

20. To see this, notice that $V(\omega, t) = V(j) = (1 + \beta \cdot i) \cdot \zeta \cdot L \cdot q(j)$ and, thus, $\int_0^N V(\omega, t) d\omega = (1 + \beta \cdot i) \cdot \zeta \cdot L \cdot Q(t)$.

Finally, use (4) and (11) to define $r(t) \equiv r(Q, K)$ and, thereby, determine the endogenous innovation rate

$$I(t) \equiv I(Q, K) = \max \left\{ \frac{\Pi_0 \cdot k(t)^\alpha}{(1 + \beta \cdot i(t)) \cdot \zeta \cdot \eta^\alpha} - r(Q, K), 0 \right\}. \quad (22)$$

The latter underlines the complementarity between the innovation rate and physical-capital accumulation, by showing that when k is too low, R&D shuts down because $I = 0$.

3. General equilibrium

3.1. Dynamic general equilibrium

From the households' optimisation problem, we recall the Fisher equation (16). By considering the latter together with the monetary policy rule (19), we determine $\pi(t)$ as an endogenous variable, for given $\bar{\pi}$ and $\bar{i}$,

$$i(t) = \bar{i} + \gamma \cdot (\pi(t) - \bar{\pi}) = r(t) + \pi(t) \Leftrightarrow$$

$$\Leftrightarrow \pi(t) = \frac{1}{1 - \gamma} \cdot (\bar{i} - r(t) - \gamma \bar{\pi}). \quad (23)$$

Recall the capital market equilibrium condition, given by (4). By replacing $i(t)$ from (16) and, then, replacing $\pi(t)$ from (23), we have:

$$r(t) = \frac{A \cdot \alpha^2 \cdot k(t)^{\alpha-1}}{\left(1 + \Omega \cdot \left[r(t) + \frac{1}{1-\gamma} \cdot (\bar{i} - r(t) - \gamma \bar{\pi})\right]\right) \cdot \eta^\alpha} \Leftrightarrow$$

$$\Leftrightarrow a \cdot r(t)^2 + b \cdot r(t) = c, \quad (24)$$

where

$$a \equiv \Omega \cdot \left(1 - \frac{1}{1-\gamma}\right),$$

$$b \equiv 1 + \Omega \cdot \frac{1}{1-\gamma} \cdot (\bar{i} - \gamma \bar{\pi}),$$

$$c \equiv \frac{A \cdot \alpha^2 \cdot k(t)^{\alpha-1}}{\eta^\alpha},$$

which defines $r = r(k(t))$, for given $\bar{\pi}$ and $\bar{i}$, by considering the positive root of the polynomial in r .²¹

The dynamic general equilibrium is defined by the allocation $\{X(\omega, t), \omega \in [0, N], t \geq 0\}$, the prices $\{p(\omega, t), \omega \in [0, N], t \geq 0\}$, and the aggregate paths $\{C(t), Q(t), K(t), I(t), r(t), t \geq 0\}$, such that: (i) households, final-good firms and intermediate-good firms solve their problems; (ii) the innovation free-entry and no-arbitrage conditions are satisfied; and (iii) markets clear. The dynamical system that describes the behaviour of the economy can be obtained, for $I(Q, K) > 0$, from equations (17), (13), and (21),

$$\dot{C}(t) = \frac{1}{\theta} \cdot (r(Q, K) - \rho) \cdot C(t) \quad (25)$$

$$\dot{Q}(t) = I(Q, K) \cdot \Xi \cdot Q(t) \quad (26)$$

$$\dot{K}(t) = L \cdot Q(t) \cdot \left(A \cdot \eta^{-\alpha} \cdot k(t)^\alpha - \frac{C(t)}{L \cdot Q(t)} - \zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(Q, K) \right), \quad (27)$$

given $K(0)$, $Q(0)$, and the transversality condition (18). The latter may be re-written, for $a(t)$, as

$$\lim_{t \rightarrow +\infty} e^{-\rho t} \cdot C(t)^{-\theta} \cdot [K(t) + (1 + \beta \cdot i(t)) \cdot \zeta \cdot L \cdot Q(t)] = 0. \quad (28)$$

3.2. Balanced-growth path

In the long-run equilibrium, the nominal interest rate feedback rule (19) implies that $\pi = \bar{\pi}$ and $i = \bar{i}$. Then, by applying the households' Fisher equation (16), we get $r = \bar{r}$ so that $\bar{i} = \bar{r} + \bar{\pi}$. Considering that the monetary authority sets $\bar{\pi}$ for a given $\bar{r}$ (i.e., the underlying long-run target pertains to the inflation rate, $\bar{\pi}$, and $\bar{i}$ is adjusted accordingly by the monetary authority), we take $\bar{i} = \bar{r} + \bar{\pi}$ and replace it in the capital market equilibrium condition (4), to get:

$$\begin{aligned} \bar{r} &= \frac{A \cdot \alpha^2 \cdot k^{\alpha-1}}{\left(1 + \Omega \cdot \left[\bar{r} + \frac{1}{1-\gamma} (\bar{\pi} - \gamma \bar{\pi})\right]\right) \cdot \eta^\alpha} \Leftrightarrow \\ &\Leftrightarrow (1 + \Omega \cdot \bar{\pi}) \cdot \bar{r} + \Omega \cdot \bar{r}^2 = \frac{A \cdot \alpha^2 \cdot k^{\alpha-1}}{\eta^\alpha}, \end{aligned} \quad (29)$$

21. Under a feedback rule, equation (4) has two roots. When $\gamma < 1$ (the case of a passive monetary policy), the existence of real roots requires that the condition $\left[1 + \Omega \cdot \frac{1}{1-\gamma} \cdot (\bar{i} - \gamma \bar{\pi})\right]^2 > -4 \cdot \Omega \cdot \left(1 - \frac{1}{1-\gamma}\right) \cdot \left(\frac{A \cdot \alpha^2 \cdot k^{\alpha-1}}{\eta^\alpha}\right)$ is satisfied. In this case, two positive real roots may emerge. However, it can be shown that only one of them is compatible with a balanced growth path as a long-run equilibrium of the model, thus eschewing the case of multiple equilibria (see Section 3.2, below).

which defines $\bar{r} = \bar{r}(k)$, for a given $\bar{\pi}$, by considering the positive root of the polynomial in r .

A balanced-growth path (BGP) as a representation of the long-run equilibrium associated with the dynamical system (25)-(27) is the path $[C(t)^*, Q(t)^*, K(t)^*, t \geq 0]$, along which the growth rates g_C^* , g_Q^* and g_K^* are constant. By considering equations (20) and (12), and the CIA constraint as an equality, i.e., $b(t) = m(t)$, a BGP only exists if: (i) the asymptotic growth rates of consumption, technological knowledge, physical capital, real money balances, and final-good output are constant and equal to the real economic growth rate, $g_C = g_Q = g_K = g_m = g_Y = g$; and (ii) the innovation rate and the real interest rate are asymptotically trendless, $g_I = g_r = 0$. Under these conditions, $g_C = g_C^*$, $g_Q = g_Q^*$, $g_K = g_K^*$, $I(Q^*, K^*) = I^*$, $r(Q^*, K^*) = r^* \equiv \bar{r}$, besides $\pi^* = \bar{\pi}$ and $i^* = \bar{i}$, and, from (13) and (17),

$$g_C^* = g_Q^* = g_K^* = g_m^* = g_Y^* = g^* = \frac{1}{\theta} \cdot (r^* - \rho) = \Xi \cdot I^*. \quad (30)$$

Also bearing the BGP conditions in mind, recall the physical capital-technological knowledge ratio, $k(t) \equiv K(t)/(L \cdot Q(t))$, and let $c(t) \equiv C(t)/(L \cdot Q(t))$ denote the consumption-technological knowledge ratio, with the property that, along the BGP, $\dot{c} = \dot{k} = 0$. Then, the dynamical system (25)-(27) can be recast as an equivalent system in the plane of detrended variables (c, k) ,

$$\dot{c}(t) = \left[\frac{1}{\theta} \cdot (r(k(t)) - \rho) - \Xi \cdot I(k(t)) \right] \cdot c(t) \quad (31)$$

$$\dot{k}(t) = \left[\frac{1}{k(t)} \cdot \left(A \cdot \eta^{-\alpha} \cdot k(t)^\alpha - c(t) - \zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(k(t)) \right) - \Xi \cdot I(k(t)) \right] \cdot k(t) \quad (32)$$

where $r(k) \equiv r(Q, K) > 0$ and $I(k) \equiv I(Q, K) > 0$ (see (4) and (22)). This system of equations has one jump-like variable, c , and one state-like (predetermined) variable, k . This system, plus the transversality condition and the initial condition $k(0)$, describes the transitional dynamics and the BGP, by jointly determining $(c(t), k(t))$. Given the latter, we can then determine the original variables $K(t)$ and $C(t)$ for a given $Q(t)$.

The long-run equilibrium values of the detrended variables $c(t)$ and $k(t)$ (steady-state values, c^* and k^*) are then obtained by setting $\dot{c} = \dot{k} = 0$. The equation of motion for $k(t)$, (32), provides the steady-state value of $c(t)$,

$$c^* = A \cdot \eta^{-\alpha} \cdot (k^*)^\alpha - \left(\zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} + k^* \cdot \Xi \right) \cdot I(k^*), \quad (33)$$

where $I(k^*) = I^*$. However, generically, k^* is defined only implicitly. This value solves equation $f_1(k) = f_2(k)$ (see Figure 1), where $f_1(k)$ and $f_2(k)$ result from considering $\dot{c} = \dot{k} = 0$ in system (31)-(32) and simplifying with (13) and (17), together with (11),

$$f_1(k) = \frac{1}{\theta} \cdot (r(k(t)) - \rho), \quad (34)$$

$$f_2(k) = \Xi \cdot \left(\frac{\Pi_0 \cdot k(t)^\alpha}{(1 + \beta \cdot (r(k(t)) + \bar{\pi})) \cdot \zeta \cdot \eta^\alpha} - r(k(t)) \right), \quad (35)$$

where

$$r(k(t)) = \bar{r}(k) = \frac{-(1 + \Omega \cdot \bar{\pi}) + \sqrt{(1 + \Omega \cdot \bar{\pi})^2 + 4 \cdot \Omega \cdot A \cdot \alpha^2 \cdot \eta^{-\alpha} \cdot k^{\alpha-1}}}{2 \cdot \Omega}$$

is the positive root of the polynomial in r obtained from equation (29). Equation $f_1(k) = f_2(k)$, jointly with (33), defines the pair (c^*, k^*) , which then allows for the derivation of r^* and I^* , where the latter is positive under a sufficiently productive technology (see again (4) and (22)). This geometrical locus represents a steady-state equilibrium with balanced growth in the usual sense (i.e., the steady state and the BGP are equivalent representations of the long-run equilibrium), characterised by a constant and positive endogenous growth rate, as obtained in (30), and with the transversality condition in (28) satisfied with $\rho > (1 - \theta) \cdot g^*$. It is also noteworthy that, in our setting, both $\gamma < 1$ and $\gamma > 1$ are compatible with equilibrium uniqueness.^{22,23}

3.3. Long-run equilibrium stability and transitional dynamics

In this section, we qualitatively characterise the local dynamics properties in a neighbourhood of the (unique) long-run equilibrium, by studying the solution of the linearised system obtained from the system (31)-(32) in the space (c, k) .

Proposition 1. The steady state (c^*, k^*) is saddle-path stable.

Proof. The Jacobian matrix at the steady-state values (c^*, k^*) is given by

$$J = \begin{pmatrix} 0 & J_{12} \\ -1 & J_{22} \end{pmatrix},$$

where

22. As noted above (see fn. 21), with $\gamma > 1$ in the feedback rule (19), one root of the polynomial in (24) is positive and the other is negative. With $\gamma < 1$, it is possible that the two roots are positive; one of the roots must be excluded, however, because either some constraint or some optimality condition is not satisfied.

23. Standard comparative-statics techniques with respect to the structural parameters of the model can be applied to further characterise the steady state. Since our focus in this paper is on the analysis of the transitional dynamics of the model (carried out in Section 4, below), we refer the interested reader to Gil and Iglésias (2019).

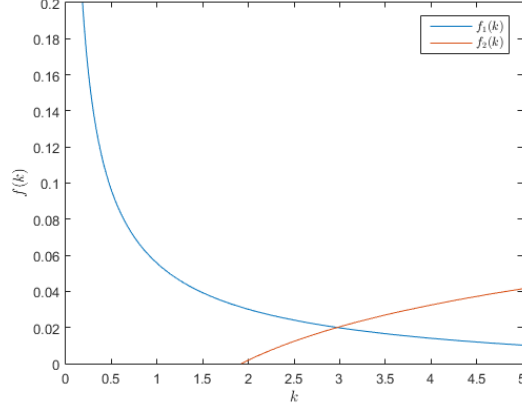


Figure 1: The interior steady state of the physical capital-technological knowledge ratio, k^* , implicitly determined by the intersection of curves $f_1(k)$ and $f_2(k)$ (equations (34) and (35) in the text). The geometrical locus of k^* is obtained, as an illustration, by considering $\alpha = 1/3$, $\theta = 1.5$, $\rho = 0.02$, $\lambda = 3$, $\zeta = 3.8$, $i = 0.075$, $A = 1$, $\eta = 1$, $\beta = 1$ and $\Omega = 1$ (details on the calibration of the model appear in Section 4).

$$\begin{aligned}
 J_{12} &= \frac{1}{\theta} \cdot c^* \cdot \frac{\partial r(t)}{\partial k(t)} \Big|_{c^*, k^*} - \Xi \cdot c^* \cdot \frac{\partial I(t)}{\partial k(t)} \Big|_{c^*, k^*} \\
 J_{22} &= \alpha \cdot A \cdot \eta^{-\alpha} \cdot (k^*)^{\alpha-1} - \zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot \frac{\partial I(t)}{\partial k(t)} \Big|_{c^*, k^*} - \\
 &\quad \Xi \cdot \left(k^* \cdot \frac{\partial I(t)}{\partial k(t)} \Big|_{c^*, k^*} + I(k^*) \right),
 \end{aligned}$$

with

$$\begin{aligned}
 \frac{\partial r(t)}{\partial k(t)} \Big|_{c^*, k^*} &= \frac{(\alpha - 1) \cdot A \cdot \alpha^2 \cdot \eta^{-\alpha}}{\sqrt{(1 + \Omega \cdot \bar{\pi})^2 + 4 \cdot \Omega \cdot A \cdot \alpha^2 \cdot \eta^{-\alpha} \cdot (k^*)^{\alpha-1}}} \cdot (k^*)^{\alpha-2} < 0 \\
 \frac{\partial I(t)}{\partial k(t)} \Big|_{c^*, k^*} &= \frac{\alpha \cdot [1 + \beta \cdot (r^* + \bar{\pi})] \cdot \Pi_0 \cdot (k^*)^{\alpha-1} - \beta \cdot \Pi_0 \cdot (k^*)^{\alpha} \cdot \frac{\partial r(t)}{\partial k(t)} \Big|_{c^*, k^*}}{\zeta \cdot \eta^{\alpha} \cdot [1 + \beta \cdot (r^* + \bar{\pi})]^2} \\
 &\quad - \frac{\partial r(t)}{\partial k(t)} \Big|_{c^*, k^*} > 0.
 \end{aligned}$$

The trace and determinant of J are, respectively, $\text{tr}(J) = J_{22}$ and $\det(J) = J_{12} < 0$. Thus, J has two distinct real eigenvalues with opposite signs, $\mu_1 = \frac{1}{2} \left(\text{tr}(J) - \Delta(J)^{\frac{1}{2}} \right) < 0$ and $\mu_2 = \frac{1}{2} \left(\text{tr}(J) + \Delta(J)^{\frac{1}{2}} \right) > 0$, where $\Delta(J) \equiv (\text{tr}(J))^2 - 4 \cdot \det(J)$. Therefore, the long-run (steady state) equilibrium (c^*, k^*) is saddle-path stable, where μ_1 determines the dynamics for the

transversality condition to hold. Since the eigenspace associated to the negative eigenvalue (the linearised saddle path) has dimension one and its slope is $-(J_{22} - \mu_1)/J_{21} > 0$,²⁴ then, c and k will follow monotonic trajectories with a positive correlation along the transition towards the steady state. $\square$

Importantly, we notice that, besides equilibrium uniqueness (as shown in Section 3.2), saddle-path stability emerges irrespective of the values taken by γ , the parameter in the feedback rule (19). In particular, this result does not depend on whether γ is larger or smaller than unity (i.e., on whether an active or a passive monetary policy is being implemented). This echoes the findings in the literature that show that with endogenous investment and decreasing marginal returns to physical capital, and under general assumptions about preferences and technology, equilibrium uniqueness and local determinacy arise under both active and passive monetary policies (see Meng and Yip 2004 and references therein).

Yet, the magnitude of γ in the feedback rule (19) – i.e., whether it is close to unity or not and whether it is above or below unity – plays a key role regarding both the intensity and the direction of the change of the endogenous variables along the transition path. The following proposition summarises the results concerning the transitional dynamics of the real interest rate, $r(t)$, the inflation rate, $\pi(t)$, and the nominal interest rate, $i(t)$.

Proposition 2. **A.** The transition path of $\pi(t)$ relates positively to that of $i(t)$ whatever $\gamma > 0$. **B.** The transition paths of $\pi(t)$ and $i(t)$ relate positively (respectively, negatively) to that of $r(t)$ when $\gamma > 1$ ($\gamma < 1$). **C.** Values of γ close to (respectively, far from) unity amplify (dampen) the shifts in $\pi(t)$ and $i(t)$ along the respective transition path, for a given shift in $r(t)$. **D.** Values of γ below (respectively, above) but close to unity amplify (dampen) the shift in $r(t)$ along the transition path.

Proof. **A.** This result can be immediately verified by inspecting the feedback rule (19). **B.** Using equation (16), we can rewrite (19) as $r(t) - \bar{r} = (\gamma - 1) \cdot (\pi(t) - \bar{\pi})$. Together with the result in part A, it is immediate to see that $\pi(t)$ and $i(t)$ relate positively (respectively, negatively) to $r(t)$ when $\gamma > 1$ ($\gamma < 1$). **C.** Using equation (23), it is clear that, given $r(t)$, values of γ close to unity exacerbate the movements in $\pi(t)$ and, thus, in $i(t)$. The opposite occurs with values of γ far from unity. **D.** From the numerator on the right-hand side of equation (24), we see that a given shift in $k(t)$ induces a shift in $r(t)$ with the opposite sign, which is the usual manifestation of the decreasing marginal returns to physical capital due to $\alpha < 1$. From the results in parts B and C, together with the denominator on the right-hand side of (24), we find that, under values of γ below but close to unity, a given shift in $r(t)$, in turn, implies a large shift in $i(t)$ in the *opposite* direction. The consequent impact on the CIA-related costs of capital accumulation implies that, in equilibrium, a given

24. To see this, just recall $J_{21} = -1$ and the expression for μ_1 , above.

shift in $k(t)$ is matched by a large shift in $r(t)$. Following the same reasoning, under values of γ above but close to unity, a given shift in $r(t)$ implies a large shift in $i(t)$ in the *same* direction. The latter implies that, in equilibrium, a given shift in $k(t)$ is matched by a small shift in $r(t)$. *Ad contrario*, under values of γ far from unity, a given shift in $k(t)$ induces shifts in $r(t)$ of intermediate magnitude. $\square$

4. Real and Nominal Variables Dynamics

In what follows, we are interested in analysing both the long-run effect (shift in the steady-state/BGP values) and its decomposition into short-run and transitional-dynamics effects of a unanticipated one-off change (i) in the monetary authority's target (i.e., a change of the structural stance of the monetary policy, given by $\bar{\pi}$) and (ii) in a real industrial-policy parameter (reflecting, e.g., a subsidy to R&D or to intermediate-good manufacturing). We are also interested in looking into the transition paths that emerge from given initial conditions off the steady-state/BGP.

Besides the dynamics of the endogenous variables in the system (31)-(32), $c(t)$ and $k(t)$, we will focus on other key variables of interest, such as: the nominal interest rate, $i(t)$, the inflation rate, $\pi(t)$, the real interest rate, $r(t)$, the innovation rate, $I(t)$, the growth rate of the technological-knowledge stock, $g_Q(t) = \Xi \cdot I(t)$ (see (13)), the R&D intensity, $R_v(t)/Y(t) = \zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(t)/(A \cdot \eta^{-\alpha} \cdot k(t)^\alpha)$ (see (8) and (12)), the economic growth rate, $g_Y(t) = \Xi \cdot I(t) + \alpha \cdot g_k(t)$ (see again (8)); and the velocity of money, $v(t) \equiv Y(t)/m(t) = A \cdot \eta^{-\alpha} \cdot k(t)^\alpha / \left(\beta \cdot \zeta \cdot \lambda^{\frac{\alpha}{1-\alpha}} \cdot I(t) + \Omega \cdot r(t) \cdot k(t) \right)$ (recall $m = b$ in Section 2.5).

In order to analyse the transitional dynamics, we perform a numerical illustration considering the following set of baseline values for the parameters and the exogenous monetary-policy variable (the reference period is the year): $\rho = 0.02$; $\theta = 1.5$; $\alpha = 1/3$; $A = 0.99$; $\eta = 1$; $\lambda = 3$; $\zeta = 3.85$; $\beta = 1$; $\Omega = 0.5$; and $\bar{\pi} = 0.025$. The values of ρ , θ , α and λ are standard in the growth literature (e.g., Barro and Sala-i-Martin 2004), while we determine the values of A , ζ , η , and $\bar{\pi}$ in order to approximate the empirical yearly data for the US in the last two decades regarding the long-run economic growth rate, real interest rate, inflation rate and nominal interest rate, that is, $g^* = 0.02$, $\bar{r} = r^* = 0.05$, $\bar{\pi} = \pi^* = 0.025$, and $\bar{i} = i^* = 0.075$ (see, e.g., Chu *et al.* 2017a). In turn, we let β and Ω take different values across some of the numerical exercises. The empirical evidence suggests that R&D investment is more severely affected by liquidity requirements than physical capital (e.g., Brown and Petersen 2015), which implies, in our model, a higher degree of the CIA constraint on R&D than on manufacturing, i.e., $\beta > \Omega$. Yet, given the lack of direct evidence on the relative magnitude of β and Ω , we consider alternative scenarios in some of our numerical exercises. Finally, we consider four different scenarios for γ , the parameter that controls for the sensitivity of the nominal interest rate to the inflation gap in the feedback rule (19). The literature points to a large range of (estimated) values across advanced

and developing countries and also over time (see, e.g., Clarida *et al.* 2000; Mehra and Sawhney 2010; Hofmann and Bogdanova 2012), while some authors underline the difficulty in estimating the parameters of the monetary policy rules, which lends considerable uncertainty concerning their magnitude (e.g., Carare and Tchaidze 2005, and references therein; Hofmann and Bogdanova 2012; Haque *et al.* 2019).²⁵ Thus, for the purpose of numerical illustration, we let $\gamma \in \{0.75, 0.95; 1.05, 1.97\}$; as a reference, we draw the upper and lower values for γ from Clarida *et al.* (2000) (Table III, pre-Volker and Volker-Greenspan periods, respectively), whereas 1.05 is about the estimate obtained by Bianchi *et al.* (2019), and 0.95 is considered to maintain symmetry around unity.

4.1. Transition paths under distinct initial conditions

In this section, we build on the solution of the linearised system obtained from (31)-(32) to study the transition paths that emerge from given initial conditions off the steady-state/BGP, combined with different values of the parameter of the feedback rule, γ .

In order to relate our results with the typical empirical evidence on transition economies, we focus on the case of the economies that exhibit an initial per capita output, $Y(0)/L = Q(0)^{1-\alpha} (K(0)/L)^\alpha$, below that of the frontier countries.²⁶ Notice, however, that the economies may feature distinct combinations of $K(0)$ and $Q(0)$, and hence distinct values of the initial physical capital-technological knowledge ratio, $k(0) \equiv K(0)/(L \cdot Q(0))$, so that two cases are possible: $k(0) < k^*$ and $k(0) > k^*$. The initial conditions considered are such that the innovation rate, $I(t)$, is positive throughout the transition, given equation (22). For each $k(0)$, we carry out the analysis of the transitional dynamics for the four values of γ indicated earlier. We consider the baseline values for β and Ω (i.e., $\beta = 1$ and $\Omega = 0.5$) throughout the analysis in this section since the results are qualitatively robust to changes in those parameters. Figure 2 depicts our results. In what follows, we lay out the economic interpretation of the mechanism underlying the transitional paths.

Let us first consider the case of $k(0) > k^*$ (*high* initial k). The fall in k over the transition path towards the steady-state level reduces the incumbents' profits (see equation (5)) and thus the resources allocated by potential entrants to R&D; therefore, the innovation rate, I , and, hence, the R&D intensity, R_v/Y , and the growth rate of technological knowledge, g_Q , also fall (equations (11)-(13)),

25. Challenges to the estimation of monetary policy rules arise from, e.g., the existence of major structural breaks, the implementation of "stop-and-go" policies by the monetary authorities, the lack of consistent data, the incorrect specification of the fundamentals in the feedback rule, and the omission of serially correlated policy shocks and of supply-side shocks (e.g., Carare and Tchaidze 2005, and Haque *et al.* 2019). In particular in advanced countries, it is also noteworthy the increasing difficulty in estimating parameter γ in a context where major movements in inflation have been absent for a long period.

26. We also assume that both $Q(0)$ and $K(0)/L$ are below the frontier levels.

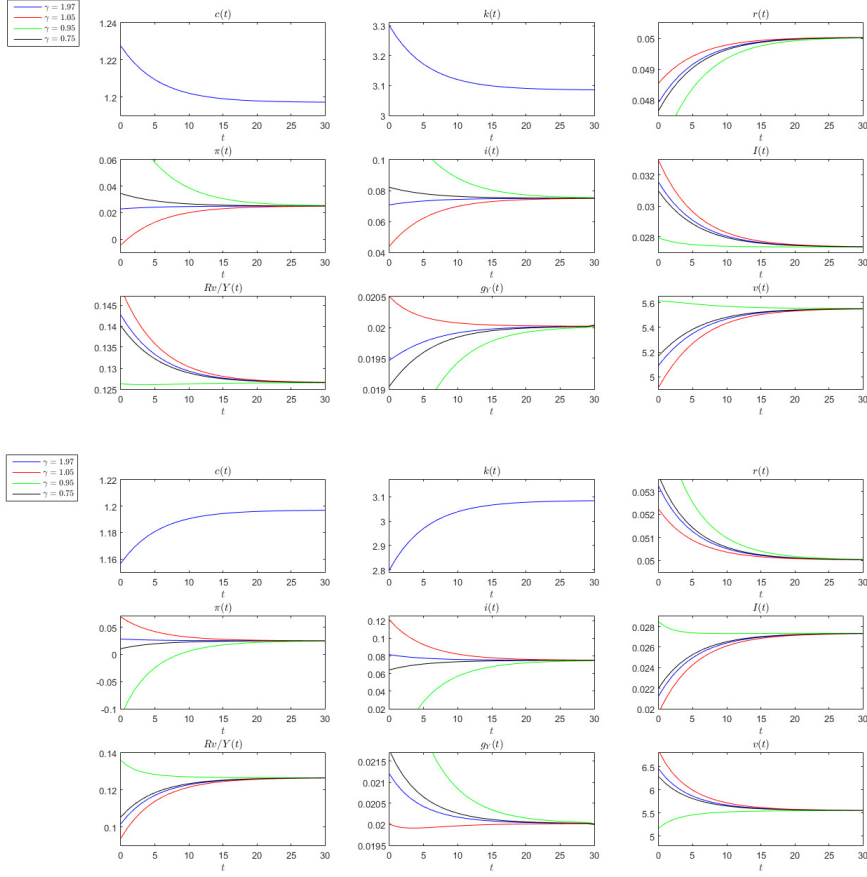


Figure 2: Transitional dynamics of selected nominal and real macroeconomic variables, for different values of the parameter in the feedback rule (19), γ , and distinct initial conditions: $k(0) > k^*$ (upper panel) and $k(0) < k^*$ (lower panel). $\rho = 0.02$; $\theta = 1.5$; $\alpha = 1/3$; $\eta = 1$; $\lambda = 3$; $\zeta = 3.85$; $\beta = 1$; $\Omega = 0.5$; $\bar{\pi} = 0.025$.

hindering economic growth, g_Y . As k falls, however, the increasing marginal returns to capital accelerate g_k and, thereby, g_Y . Under γ sufficiently far from unity (in our numerical exercise, either $\gamma = 0.75$ or $\gamma = 1.97$), the inflation rate, π , and the nominal interest rate, i , – and thus the financial costs arising from the CIA constraints – start off from a level quite close the steady state (Proposition 2). This implies that their shift over transition is quite muted (although displaying opposite signs for $\gamma < 1$ versus $\gamma > 1$; recall again Proposition 2), barely impacting the dynamics of I and g_Q . In this context, the effect from the increasing marginal returns to capital prevails and g_Y increases towards the steady-state equilibrium.

Under $\gamma = 1.05$, the two effects of opposite sign are the same as before. But since, in this case, π and i start the transition from a significantly low level (and thus the financial costs arising from the CIA constraints are also significantly low)

and increase by a large amount afterwards (Proposition 2), then I , R_v/Y , and g_Q start off from a high level and fall by a large amount over transition. As this effect now prevails, g_Y also starts off from a high level and then significantly *decreases* over transition.

Under $\gamma = 0.95$, however, π and i start the transition from a significantly high level (again, Proposition 2), which depresses the initial levels of I , R_v/Y , and g_Q . Then, as π and i fall by a large amount over transition, the negative impact of the decrease in k on the dynamics of I , R_v/Y , and g_Q is largely attenuated or even overturned. This, together with the already referred to positive effect of the increasing marginal returns to capital on growth, implies that g_Y also starts off from a low level and then significantly *increases* over transition.

The case of $k(0) < k^*$ (*low* initial k) generically reverts the sign of the trajectories observed in the case of $k(0) > k^*$. One notable exception is g_Y , which may observe a non-monotonic behaviour over transition. Indeed, the lower panel in Figure 2 shows that when $k(0) < k^*$ and $\gamma = 1.05$, g_Y first decreases and then increases towards the steady-state level. This behaviour reflects the fact that, although π and i start off from a significantly high level, which depresses the initial levels of I , R_v/Y , and g_Q more intensively than under the other values of γ , this is not enough to prevent g_Y from falling over the first periods of the transition reflecting the decreasing returns to capital due to the rapid increase in k . Only after the latter effect fades out does g_Y start increasing as it benefits from the increase in I and, thus, in R_v/Y and g_Q .²⁷

As for the velocity of money, $v \equiv Y/m$, it mainly reflects (the inverse of) the trajectory of I , whatever γ and $k(0)$. This occurs because the movements in aggregate output Y , which are driven by k , tend to cancel with the movements in the real monetary balance, m , that are determined by shifts in r and k (i.e., the demand of money due to the CIA constraint on manufacturing). As a result, the movements in m that are determined by shifts in I (i.e., the demand of money due to the CIA constraint on R&D) tend to prevail as the main driver of v .

Remark 1. The slope of the transition paths displays a different sign: for π and i , when γ is above versus below unity (as indicated by Proposition 2); for v and (in general) for I and R_v/Y , when $\gamma = 0.95$ versus otherwise; and for g_Y , when $\gamma = 1.05$ versus otherwise. In the latter case, a non-monotonic trajectory may even arise.

A recent strand of the growth literature emphasises the diverse convergence behaviour observed in the empirical data on modern growth experiences (i.e., in the postwar period); see, e.g., Fiaschi and Lavezzi (2007) and Gil *et al.* (2017). Our model shows how otherwise similar economies featuring initial below-the-frontier per capita output may experience contrasting convergence paths of key

27. The behaviour of I is also distinct from the overall pattern under $\gamma = 0.95$, since it features a (slight) downward path both when $k(0) < k^*$ and $k(0) > k^*$.

economic variables – most notably the economic growth rate. We find that distinct initial physical capital-technological knowledge ratios, combined with differences in the sensitivity of the nominal interest rate to the inflation gap in the feedback rule followed (either implicitly or explicitly) by the monetary authorities, are able to generate positive monotonic, negative monotonic or even non-monotonic convergence paths (see Remark 1). In particular, it is interesting to observe that a value of γ below but sufficiently close to unity – corresponding to a *mildly passive* monetary policy – strongly exacerbates the typical negative relationship over transition between k and g_Y ; yet, when the value of γ is above but sufficiently close to unity – corresponding to a *mildly active* monetary policy –, the model is able to overturn the slope of the transition path of g_Y so that the latter eventually *increases* (respectively, *decreases*) towards the steady state when the economy features a physical capital-technological knowledge ratio that is initially *low* (*high*) and *increases* (*decreases*) over transition. The typical result in a neoclassical growth model with decreasing marginal returns to capital – and with either exogenous (e.g., Barro and Sala-i-Martin 2004, ch. 2) or endogenous technological progress (e.g., Howitt and Aghion 1998; Gil *et al.* 2017) – is a negative relationship over transition between the physical capital-technological knowledge ratio and the economic growth rate.

Overall, our results nicely complement the rich patterns of transitional dynamics that obtain in Gil *et al.* (2017)'s setting of physical capital accumulation with vertical and horizontal R&D, but where no monetary sector is considered.²⁸

Another finding of the literature is that the economies may experience disparate relationships between inflation, money growth, and key real macro variables along their transition paths. Table 1 depicts the sign of the cross-correlation of selected nominal and real variables under transitional dynamics in our model.

Remark 2. The cross-correlation of the variables of interest, namely π , i , r , I , R_v/Y , g_Y , and v , may feature a different sign for different values of γ . The way γ impacts the sign of the correlation depends on the considered pair of variables.

Importantly, these results generically apply to both scenarios for $k(0)$ (i.e., high and low initial k). Two exceptions occur: for I , when $\gamma = 0.95$, and for g_Y , when $\gamma = 1.05$. In the latter case, if $k(0) < k^*$, the sign of the correlation versus the other variables changes over the transition path, due to the already mentioned non-monotonic behaviour of g_Y . As one can see, except for the correlation between R&D intensity and velocity of money, which always appears as negative, in all cases

28. By exploring a model characterized by a multi-dimensional saddle path, Gil *et al.* (2017) show how contrasting patterns of transitional dynamics – either monotonic or non-monotonic – may emerge depending on the economy's initial conditions, namely the initial endowment of physical versus immaterial inputs (e.g., physical capital versus technological knowledge). Yet, that model still generates the standard negative relationship between the physical capital-technological knowledge ratio and the economic growth rate over transition.

	g_Y	r	I	R_v/Y	v
π, i	- - - +	- - + +	+ ± - -	+ - - -	- + + +
g_Y		+ + - +	- ± + -	- + + -	+ - - +
r			- ± - -	- + - -	+ - + +
I				+ ± + +	- ± - -
R_v/Y					- - - -

Table 1. Cross-correlation (sign) of selected nominal and real macroeconomic variables over transition, for different values of the parameter in the feedback rule (19), γ , respectively, 0.75, 0.95, 1.05, and 1.97. The sign of the correlations pertaining to I , when $\gamma = 0.95$, depends on whether $k(0) < k^*$ or $k(0) > k^*$, respectively. All the corresponding transition paths are depicted by Figure 2.

we observe mixed results (see Remark 2). Bearing in mind the apparent range of values of γ across countries and also over time referred to above, our theoretical results speak to the ambiguity or non-significance of several empirical relationships suggested by the literature that looks into short- to medium-run movements in time-series or panel data, most notably: R&D intensity versus economic growth (e.g., Pintea and Thompson 2007; Gil *et al.* 2013), R&D intensity versus inflation (Chu *et al.* 2015), economic growth versus inflation (Gillman *et al.* 2004; Omay and Kan 2010; López-Villavicencio and Mignon 2011), and velocity of money versus economic growth (Palivos and Wang 1995; Benk *et al.* 2010).

On the theoretical side, Gillman *et al.* (2004) and Rodríguez Mendizábal (2006) suggest that the empirically observed differences across countries and over time regarding the correlation between inflation, money growth, and key real macro variables (namely, economic growth and the velocity of money) may be interpreted in light of the differences in, respectively, the credit production technology and the transaction technologies. In our model, the differences in those relationships arise due to differences in the sensitivity of the nominal interest rate to the inflation gap in the feedback rule and its interaction with the (homogeneous) CIA mechanism.

4.2. Effects of monetary-policy shocks

In this section and the next, we focus on the (short- to long-run) effects originated by structural monetary-policy and real industrial-policy one-off unanticipated shocks. To facilitate the comparison of results among shocks in terms of both short- and long-run effects later in this section, Table 2 summarises the initial (pre-shock) and final (post-shock) steady-state levels of each selected variable, for the three shocks to be considered: a monetary-policy shock implemented as a change in the monetary authority's target (an increase in the inflation target, $\bar{\pi}$, from 0.025 to 0.05); an industrial-policy shock implemented as an R&D subsidy (equivalent to a 10% decrease in the R&D cost factor, ζ); and an industrial-policy

	c	k	r	π	i	I	R_v/Y	g_Y	v
Initial steady state	1.1970	3.0848	0.050	0.025	0.0750	0.0273	0.1265	0.020	5.5530
Final steady state:									
Mon.-policy shock, $\beta = 1$, $\Omega = 0.5$	1.2064	3.1060	0.0492	0.050	0.0992	0.0266	0.1229	0.0195	5.6880
Mon.-policy shock, $\beta = 0.5$, $\Omega = 1$	1.1966	3.0424	0.0493	0.050	0.0993	0.0267	0.1243	0.0195	5.6678
Indust.-policy shock: R&D subsidy	1.1554	2.8177	0.0531	0.025	0.0781	0.0301	0.1293	0.022	5.4728
Indust.-policy shock: manuf. subsidy	1.1880	3.1080	0.0515	0.025	0.0765	0.0287	0.1279	0.021	5.5116

Table 2. The initial (pre-shock) and final (post-shock) steady-state levels of each variable of interest, for three separated one-off shocks: a monetary-policy shock (an increase in $\bar{\pi}$ from 0.025 to 0.05), an industrial-policy shock under the form of an R&D subsidy (a 10% decrease in ζ) and an industrial-policy shock under the form of a subsidy to intermediate-good manufacturing (a 10% decrease in η). $\rho = 0.02$; $\theta = 1.5$; $\alpha = 1/3$; $\eta = 1$; $\lambda = 3$; $\zeta = 3.85$; $\bar{\pi} = 0.025$ (in the case of the monetary-policy shock, this refers to the pre-shock value); $\beta = 1$ and $\Omega = 0.5$ (in the case of the industrial-policy shocks).

shock implemented as a subsidy to intermediate-good manufacturing (equivalent to a 10% decrease in the intermediate-good cost factor, η).²⁹

We first consider a structural monetary-policy shock, implemented as a change in the structural stance of the monetary policy (i.e., an increase in $\bar{\pi}$). We again carry out the analysis for the four values of the parameter of the feedback rule, γ . We start by focusing on the baseline case of $\beta = 1$ and $\Omega = 0.5$, but later we will also consider the alternative scenario of $\beta = 0.5$ and $\Omega = 1$. In addition to the long-run effects depicted by Table 2, Figure 3 shows the short-run and transitional-dynamics results.

Conditional on the transitional behaviour of the physical capital-technological knowledge ratio, k , the pattern of transition paths of the other endogenous variables implied by the different values of γ under a monetary-policy shock is similar to the pattern in the case of transitional dynamics under given initial conditions, as analysed in Section 4.1. Therefore, it is convenient to start our analysis by focusing on the transitional behaviour of k induced by an increase in $\bar{\pi}$. From Table 2, we find that a higher $\bar{\pi}$ implies a higher nominal interest rate, i , in the long-run equilibrium,³⁰ and, thus, an increase in the financial costs arising from the CIA constraints. The sign of the long-run relationship between k and i depends, however, on the strength of the CIA constraint on R&D activities, measured by β , vis-à-vis that on manufacturing of intermediate goods, measured by Ω . When $\beta > \Omega$, an increase in i raises the cost of R&D by more than the cost of intermediate-good production, hence incentivising a diversion of resources from

29. Notice that, in the case of $\beta = 0.5$, $\Omega = 1$, and given our baseline calibration of the remaining parameters, the initial steady-state values of c , k , and R_v/Y are different from those displayed in this table (row "Initial steady state"). Therefore, for the sake of comparison, we normalised the respective initial steady-state values by the values displayed in this table and, then, applied a proportional adjustment to the post-shock steady-state levels of these variables (row " $\beta = 0.5$, $\Omega = 1$ ").

30. This is an outcome of equation (16) combined with the fact that the real interest rate is lower for a higher $\bar{\pi}$ in long-run equilibrium. For an explicit analytical result, see Gil and Iglésias (2019), Lemma 1.

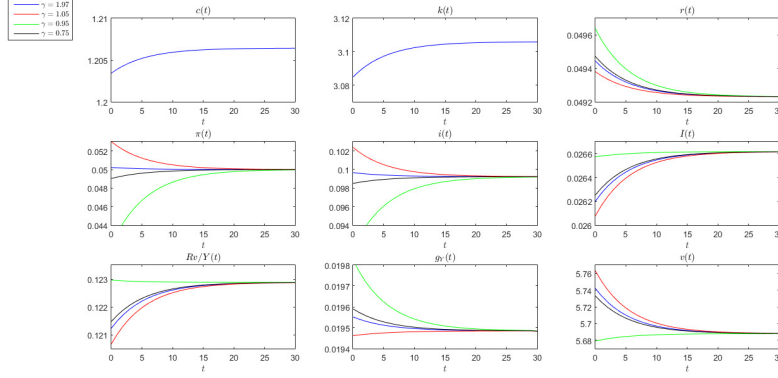


Figure 3: Transitional dynamics of selected nominal and real macroeconomic variables given a monetary-policy shock (an increase in $\bar{\pi}$ from 0.025 to 0.05), for different values of the parameter in the feedback rule (19), γ . $\rho = 0.02$; $\theta = 1.5$; $\alpha = 1/3$; $A = 0.99$; $\eta = 1$; $\lambda = 3$; $\zeta = 3.85$; $\beta = 1$; $\Omega = 0.5$; $\bar{\pi} = 0.025$ (pre-shock value). The pre- and post-shock steady-state levels of each variable are depicted in Table 2.

the former to the latter. Since intermediate-good production uses physical capital as an input, k is higher in the long-run equilibrium when i is higher. This, in turn, implies that k must follow an *upward* path over transition towards the new steady state after the shock. When $\beta < \Omega$, of course, the sign of the long-run relationship between k and i switches, which implies that k must follow a *downward* path towards the new steady state. We note, however, that the ambiguous long-run relationship between k and i (and $\bar{\pi}$) does not extend to the other endogenous variables: the real interest rate, r , economic growth rate, g_Y , innovation rate, I , and R&D intensity, R_v/Y , always decrease with $\bar{\pi}$, whereas the velocity of money, v , always increases with $\bar{\pi}$ (see, again, Table 2).³¹

Focusing on the baseline case of $\beta > \Omega$, Figure 3 illustrates the transitional-dynamics results with $\beta = 1$ and $\Omega = 0.5$. The pattern of the transition paths under the monetary-policy shock is identical to that in the case of a low initial physical capital-technological knowledge ratio, $k(0) < k^*$, as depicted by the lower panel of Figure 2. There is only a small difference with respect to the transition path of the innovation rate, I , when $\gamma = 0.95$ – in the case of the monetary-policy shock, there is a slight increase instead of decrease (but, in both cases, there is a very muted shift of I over transition). There is also a slight difference regarding the transition path of the economic growth rate, g_Y , when $\gamma = 1.05$ – in the case of the shock, g_Y follows a monotonic increasing path instead of a non-monotonic path (but, again, in both cases, the shift of g_Y over transition is very muted). Overall, the

31. For an explicit analytical result concerning the long-run a monetary-policy shock on these variables, see Gil and Iglésias (2019), Propositions 1 and 2. This paper also looks into how the effects relate to the patterns found by the empirical literature.

economic mechanisms underlying the transition of the (other) variables of interest are identical to those detailed in Section 4.1.

Yet, as is well known, in the case of the shock, the transition paths may be preceded by an initial jump in the variables of interest when these are prices or flow variables. That is, there is an immediate (or *short-run*) effect that adds to the transitional-dynamics effect that was previously analysed. All the variables considered in Figure 3 other than k observe a jump as a short-run response to the monetary-policy shock. By looking at the starting levels of the transition paths of those variables in Figure 3 and comparing with the respective initial (pre-shock) and final (post-shock) steady-state values in Table 2, we devise the following results.

Remark 3. Given the considered monetary-policy shock: (i) π and i observe *positive* short- and long-run effects, with some overshooting in the short-run under $\gamma > 1$; (ii) r observes *negative* short- and long-run effects; (iii) I observes *negative* short- and long-run effects, with overshooting in the short-run whatever γ (but very mildly for $\gamma = 0.95$); (iv) R_v/Y observes *negative* short- and long-run effects, with (significant) overshooting under all but $\gamma = 0.95$; (v) g_Y observes *negative* short- and long-run effects, with some overshooting if $\gamma = 1.05$; (vi) v observes *positive* short- and long-run effects, with (significant) overshooting under all but $\gamma = 0.95$.

In light of the results above, and recalling the debate on *active* versus *passive* monetary policies (i.e., when the feedback rules feature $\gamma > 1$ versus $\gamma < 1$) and the way they may induce different reactions of the macroeconomic variables to shocks, we emphasise the following predictions of our model in face of a positive monetary-policy shock:

- Under an *active* monetary policy, there will be an (upward) *over-reaction* (i.e., overshooting) of π and i in the short-run, and, consequently, a *decrease* of these variables over transition towards the new (higher) steady state.
- There will be a (downward) *over-reaction* of g_Y to the shock in the short-run – and, subsequently, an *increase* towards the new (lower) steady state – only under a *mildly active* monetary policy (i.e., γ is above but close to unity).
- In contrast, a *mildly passive* monetary policy (i.e., γ is below but close to unity) *dampens* the short-run response of π , i , and g_Y to the shock (i.e., the instantaneous jump from the initial steady-state level is attenuated).³²

It is also noteworthy that, in all cases described above, the short-run and the long-run effects display the same sign. Given that, in general, as shown in Figure 3, either upward or downward trajectories may occur over transition depending on the value of γ , this means that, overall, the short-run effects either reinforce or dominate the

32. This dampening of the short-run response occurs because, as shown in Section 4.1, a value of γ below but close to unity ($\gamma = 0.95$) either exacerbates the transition path (i.e., the medium-run response) or shifts the sign of the slope of the transition path. Either way, this reduces the need for a sizable instantaneous adjustment to the shock.

	g_Y	r	I	R_v/Y	v
π, i	- -	- -	- -	- -	+ +
g_Y		+ +	+ +	+ +	- -
r			+ +	+ +	- -
I				+ +	- -
R_v/Y					- -

Table 3. Cross-correlation (sign) of selected nominal and real macroeconomic variables considering, respectively, the *short-run* and the *long-run* (steady-state) effects under a monetary-policy shock.

transitional-dynamics effects. A comparison between Table 1 and Table 3 makes clear the discrepancy as regards the cross-correlation of the variables of interest in transitional dynamics versus the short-run/long-run.

However, as explained above, the results of a monetary-policy shock are sensitive to the relative magnitude of the CIA parameters, β and Ω . We will now consider a scenario where the degree of the CIA constraint on R&D is *lower* than on manufacturing, that is $\beta < \Omega$. For concreteness, Figure B.1, in Appendix B, shows the short-run and transitional-dynamics results under $\beta = 0.5$ and $\Omega = 1$, as well as under $\beta = 1$ and $\Omega = 0.5$ (as in Figure 3), both for the case of $\gamma = 1.97$. The key difference in the mechanism underlying the two scenarios pertains to the transitional behaviour of k . As explained earlier, when $\beta < \Omega$, an increase in $\bar{\pi}$ induces a decrease in k over transition towards the new steady state. Thus, in this case, the pattern of transition paths under a monetary-policy shock is similar to the pattern in the case of a high initial physical capital-technological knowledge ratio, $k(0) > k^*$, as depicted by the upper panel of Figure 2. As can be seen, a given monetary-policy shock can originate quite different short-run and transitional responses of the variables of interest, depending on whether $\beta < \Omega$ or $\beta > \Omega$. The transition paths of all variables exhibit slopes of opposite sign for the two scenarios, while I and R_v/Y also exhibit short-run effects (jumps) of opposite direction under the two scenarios.

4.3. Effects of real industrial-policy shocks

Now, we investigate the effects of shocks to the technological parameters ζ and η , for the four different scenarios of γ . We interpret ζ and η as industrial-policy parameters. A decrease in these technological parameters may be seen as equivalent to a proportional government subsidy to, respectively, R&D activities and intermediate-good manufacturing.³³ We consider again the baseline values for β and Ω ($\beta = 1$ and $\Omega = 0.5$) throughout the analysis since the results in this

33. The usual simplifying assumption underlying this type of exercise is that the government balances its budget every period by levying the necessary amount of lump-sum taxes.

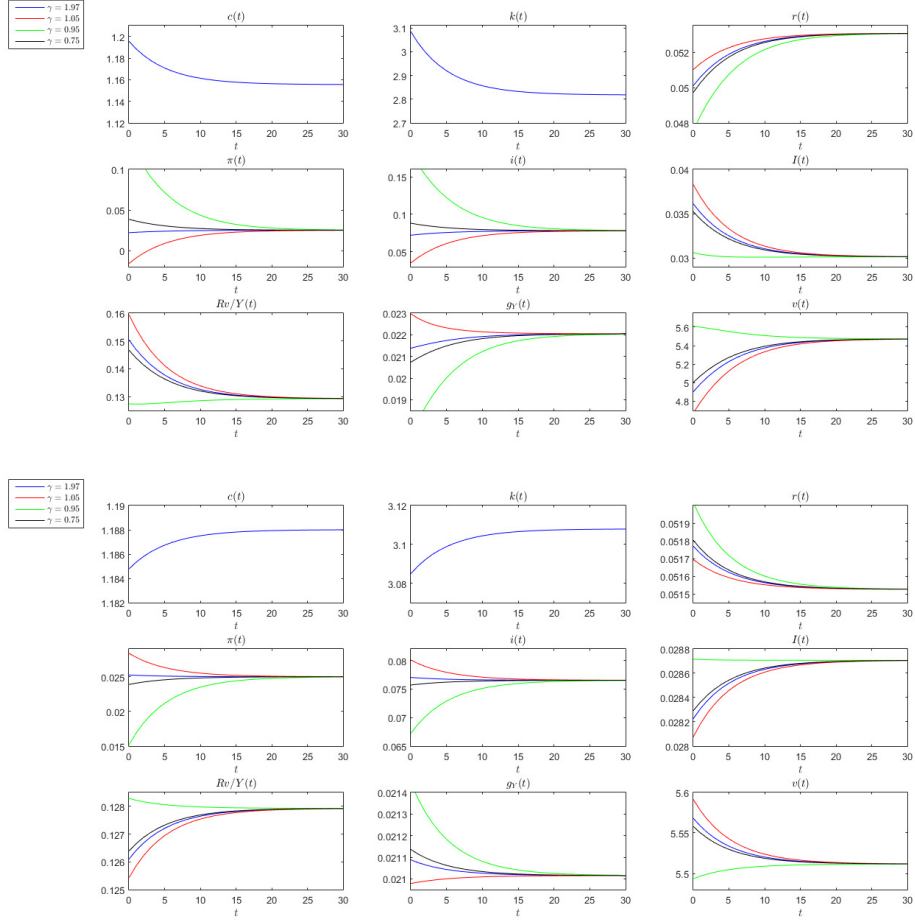


Figure 4: Transitional dynamics of selected nominal and real macroeconomic variables given a real industrial-policy shock, for different values of the parameter in the feedback rule (19), γ . A decrease in ζ in 10% (upper panel) and a decrease in η in 10% (lower panel) are interpreted as the result of a proportional government subsidy to, respectively, R&D activities and intermediate-good manufacturing. $\rho = 0.02$; $\theta = 1.5$; $\alpha = 1/3$; $\eta = 1$; $\lambda = 3$; $\zeta = 3.85$; $\beta = 1$; $\Omega = 0.5$; $\bar{\pi} = 0.025$. The pre- and post-shock steady-state levels of each variable are depicted in Table 2.

section are qualitatively robust to changes in those parameters.³⁴ In addition to the long-run effects depicted by Table 2, above, Figure 4 shows the short-run and transitional-dynamics results.

34. That is, differently from $\bar{\pi}$, the effects of changes in ζ and η on the endogenous variables do not depend on the relative magnitude of β and Ω .

The transitional-dynamics effects of these two types of subsidies are quite distinct, as illustrated in Figure 4. This happens chiefly because the two have opposing implications concerning the transition path followed by the physical capital-technological knowledge ratio, k . An R&D subsidy (equivalent to a decrease in ζ) reduces the cost of R&D activities without directly impacting the cost of intermediate-good production, thereby diverting resources from the latter to the former. Since intermediate-good production uses physical capital as an input, k is lower in the long-run equilibrium when ζ is lower. This, in turn, implies that k must follow a *downward* path over transition towards the new steady state after the shock. The opposite happens under an intermediate-good manufacturing subsidy (decrease in η). Thus, the pattern of the transition paths under the R&D subsidy (respectively, manufacturing subsidy) shock is identical to that in the case of a high (low) initial k , as depicted by the (upper) lower panel of Figure 2.

Moreover, all the variables considered in Figure 4 other than k observe a jump as a short-run response to each industrial-policy shock. That is, there is a short-run effect that adds to the transitional-dynamics effect. By looking at the starting levels of the transition paths of those variables in Figure 4 and comparing with the respective initial (pre-shock) and final (post-shock) steady-state values in Table 2, we find that the pattern of short-run versus long-run effects is richer than under the monetary-policy shock. The following remarks summarise the main results.

Remark 4. Given the considered R&D-subsidy shock: (i) the inflation rate, π , and the nominal interest rate, i , observe a *positive* (respectively *negative*) short-run effect under $\gamma < 1$ ($\gamma > 1$) but a *null* long-run effect; (ii) the real interest rate, r , observes a *positive* (respectively, *negative*) short-run effect under $\gamma > 1$ ($\gamma < 1$) and a *positive* long-run effect; (iii) the innovation rate, I , observes *positive* short- and long-run effects, with overshooting in the short-run for all γ ; (iv) the R&D intensity, R_v/Y , observes *positive* short- and long-run effects, with (significant) overshooting in the short-run under all but $\gamma = 0.95$; (v) the economic growth rate, g_Y , observes a *negative* (respectively, *positive*) short-run effect if $\gamma = 0.95$ (remaining values of γ) and a *positive* long-run effect, with some overshooting in the short-run if $\gamma = 1.05$; (vi) the velocity of money, v , observes a *positive* (respectively, *negative*) short-run effect if $\gamma = 0.95$ (remaining values of γ) and a *negative* long-run effect, with (significant) overshooting in the short-run under all but $\gamma = 0.95$.

Remark 5. Given the considered manufacturing-subsidy shock: (i) π and i observe a *negative* (respectively *positive*) short-run effect under $\gamma < 1$ ($\gamma > 1$) but a *null* long-run effect; (ii) r observes *positive* short- and long-run effects, with an overshooting in the short run whatever γ ; (iii) I observes *positive* short- and long-run effects, with an overshooting in the short-run under $\gamma = 0.95$; (iv) R_v/Y observes a *positive* (respectively, *negative*) short-run effect if $\gamma = 0.95$ (remaining values of γ) and a *positive* long-run effect, with an overshooting in the short-run under $\gamma = 0.95$; (v) the economic growth rate, g_Y , observes *positive* short- and long-run effects, with some overshooting in the short-run

under all but $\gamma = 1.05$; (vi) v observes a *negative* (respectively, *positive*) short-run effect if $\gamma = 0.95$ (remaining values of γ) and a *negative* long-run effect, with overshooting in the short-run if $\gamma = 0.95$.

Recalling again the debate on *active* versus *passive* monetary policies (respectively, $\gamma > 1$ versus $\gamma < 1$), and in light of the results above, we emphasise the following predictions of our model:

- Under an *active* monetary policy, there will be a *downward* jump of π and i upon the R&D-subsidy shock – and, subsequently, an *increase* towards the unchanged steady state –,³⁵ but there will be an *upward* jump – and, subsequently, a *decrease* towards the unchanged steady state – in the case of a manufacturing-subsidy shock. The opposite will occur under a *passive* monetary policy.
- In the case of an R&D subsidy, there will be an (upward) *over-reaction* of g_Y to the shock in the short-run – and, consequently, a *decrease* towards the new (higher) steady state – only under a *mildly active* monetary policy (i.e., γ is above but close to unity). Under a *mildly passive* monetary policy (i.e., γ is below but close to unity), there will be, instead, a significant *downward* jump of g_Y upon the shock – and, subsequently, a significant *increase* towards the new (higher) steady state.
- In the case of a manufacturing subsidy, there will be an (upward) *over-reaction* of g_Y to the shock in the short-run – and, subsequently, a *decrease* towards the new (higher) steady state – under either a *passive* monetary policy or a *strongly active* monetary policy (i.e., γ is above and distant from unity).

The results above make it clear that the accomplishment of qualitatively similar transitional-dynamics effects from R&D-subsidy and manufacturing-subsidy shocks requires distinct types of monetary policy. The same conclusion applies when one confronts the transitional-dynamics effects from industrial-policy and monetary-policy shocks, in particular if policy authorities seek to enhance growth effects under the former but moderate them under the latter.

4.4. Quantitative differences in transitional-dynamics effects

In this section, we focus on the quantitative differences in transitional-dynamics effects that arise from a given policy shock under alternative values of γ , the degree of the sensitivity of the nominal interest rate to the inflation gap in the feedback rule. Based on the results depicted by Figures 3 and 4, Table 4 illustrates the cumulative difference over the first 10 years after a policy shock for the inflation

35. It is interesting that, in our illustration, under a *mildly active* monetary policy with $\gamma = 1.05$, π is pushed below zero as an immediate reaction to the R&D-subsidy shock, that is, the economy temporarily enters a deflationary context. However, it should be clear that, in our model, this is not driven by an aggregate-demand effect but, instead, by the arbitrage between nominal and real assets conducted by the households as a reaction to the R&D-subsidy shock.

	π	R_v/Y	g_Y	v
Monetary-policy shock				
$\gamma = 1.05$ versus $\gamma = 0.95$	0.056	-0.023	0.0019	0.417
$\gamma = 1.97$ versus $\gamma = 0.75$	0.005	-0.001	-0.0002	0.042
Indust.-policy shock: R&D subsidy				
$\gamma = 1.05$ versus $\gamma = 0.95$	-0.885	0.194	0.0312	-3.646
$\gamma = 1.97$ versus $\gamma = 0.75$	-0.073	0.016	0.0031	-0.365
Indust.-policy shock: manuf. subsidy				
$\gamma = 1.05$ versus $\gamma = 0.95$	0.065	-0.015	-0.0033	0.352
$\gamma = 1.97$ versus $\gamma = 0.75$	0.002	-0.002	-0.0002	0.012

Table 4. Cumulative differences in transitional-dynamics effects over the first 10 years after a given policy shock, under two distinct values for the parameter in the feedback rule, γ (1.05 versus 0.95 and 1.97 versus 0.75). The cumulative differences are computed based on the transition paths of a given variable for $t \in (0, 10]$, as depicted by Figures 3 and 4.

rate, π , R&D intensity, R_v/Y , economic growth rate, g_Y , and velocity of money, v , for two pairs of values of γ : 1.05 versus 0.95 and 1.97 versus 0.75.³⁶ These pairings allow us to contrast the largest and the smallest differences in transitional-dynamics effects that result from distinct values of γ , as is visible from Figures 3 and 4: the former pair of values (corresponding, respectively, to a *mildly active* and a *mildly passive* monetary policy) generates the largest differences; the latter pair (corresponding to a *strongly active* and a *strongly passive* monetary policy) generates the smallest differences.

The magnitude of the cumulative differences in transitional-dynamics effects depends on the type and on the size of the shock. Considering industrial-policy shocks of comparable size (the implementation of a 10% subsidy over a constant fixed cost), an R&D subsidy generates cumulative differences of more quantitative significance – one order of magnitude higher – than a manufacturing subsidy. In turn, the cumulative differences generated by a manufacturing-subsidy shock are of the same order of magnitude of those due to a monetary-policy shock implemented as an increase in $\bar{\pi}$ from 0.025 to 0.05.

The results also confirm that the comparison between a *mildly active* and a *mildly passive* monetary policy produces the largest cumulative differences in transitional-dynamics effects – one order of magnitude higher than the comparison between a *strongly active* and a *strongly passive* monetary policy – for all considered variables and all three types of policy shocks.

Finally, among the selected macroeconomic variables, and using as a reference the respective (post-shock) steady-state levels, the cumulative differences are the

36. We choose a 10-year interval only for the purpose of illustration. In our exercise, the cumulative difference in transitional-dynamics effects over 10 years amounts to 87% of the cumulative difference over 30 years, the time period over which the variables roughly attain the respective (post-shock) steady-state levels.

highest for the inflation rate, π , and the lowest for the velocity of money, v , under all three types of policy shocks and both pairings of γ considered.

5. Conclusion

This paper looks into the diverse real and nominal transitional behaviour generated by the differences in the nominal interest-rate feedback rules followed (either implicitly or explicitly) by the monetary authorities. The literature features a large range of (estimated) values of the sensitivity of the nominal interest rate to the inflation gap in the feedback rule both across countries and over time, telling, in particular, between active and passive monetary policies in this regard. The difficulty in estimating the parameters of the monetary-policy rules pointed out by the literature adds to the uncertainty concerning the magnitude of the sensitivity of the nominal interest rate to the inflation gap. These facts gain relevance in a context where interest-rate feedback rules have become pervasive among modern economies as benchmarks for the assessment of the stance of monetary policy.

We develop a growth model of R&D and physical capital accumulation, extended with a monetary sector where monetary authorities follow an interest-rate feedback rule, while money demand is incorporated via CIA constraints on R&D activities and physical investment. Well-behaved (saddle-path) transitional dynamics arises due to the interaction between the process of knowledge accumulation (via vertical R&D) and the process of physical capital accumulation characterised by decreasing marginal returns. We take advantage of this setting, where both active and passive monetary policies ensure uniqueness and local determinacy of the long-run equilibrium, to explore the rich pattern of transitional dynamics that originates from distinct values of the sensitivity of the nominal interest rate to the inflation gap in the feedback rule.

The first instance of the mechanism at play in our model emerges from the interaction between the interest-rate feedback rule and the Fisher equation. This interaction determines whether the transition paths of the nominal variables (inflation and the nominal interest rate) start from low levels and move upwards or the reverse, depending on the type of monetary policy in place (active versus passive). This, in turn, determines the evolution of the financial costs arising from the CIA constraints. The other instance of the mechanism pertains to the dynamics of the physical capital-technological knowledge ratio, which impacts the remaining real variables both directly and through the determination of the real interest rate in the capital market. The two instances of the mechanism jointly set the dynamics of the real variables, namely, the economic growth rate, R&D intensity, and velocity of money.

The results from the literature on monetary growth models suggest that the role of the central banks in supporting growth beyond the business-cycle frequency is not restricted to the appraised focus on the stabilisation of the macroeconomy

over the business cycle.³⁷ This literature has devised a number of real effects of monetary policy from the perspective of the long-run (steady-state) equilibrium of the economy (see, e.g., Gillman and Kejak 2005, and Gil and Iglésias 2019, for overviews of the literature). The results in our paper show, in addition, that the feedback rule implemented by the monetary authorities is able to generate relevant cumulative transitional-dynamics effects in face of structural shocks to the economy. This happens by triggering an overshooting behaviour in response to those shocks and, thus, amplifying the steady-state real effects. Depending on the type of the shock and on the macroeconomic variable under analysis, this amplification may be quite significant quantitatively. Also given the slow transitional dynamics typically observed in the data, this stresses the importance of the debate on how active versus passive monetary policies may induce different reactions of the macroeconomic variables to shocks.

In light of the above, we emphasise some notable results pertaining to the shocks under each type of monetary policy in our model. Under an *active* monetary policy: (i) a positive R&D-subsidy shock induces a *downward* jump of inflation and the nominal interest rate in the short run and, subsequently, an *increase* towards the unchanged steady state; the same shock induces an (upward) *over-reaction* of the economic growth rate in the short-run and, subsequently, a *decrease* towards the new (higher) steady state (only under a *mildly active* monetary policy); (ii) a positive manufacturing-subsidy shock induces an (upward) *over-reaction* of the economic growth rate in the short-run and, subsequently, a *decrease* towards the new (higher) steady state (under a *strongly active* monetary policy). Under a *passive* monetary policy: (i) a positive structural monetary-policy shock induces a *dampened* short-run response of inflation, the nominal interest rate, and the economic growth rate (only under a *mildly passive* monetary policy); (ii) a positive manufacturing-subsidy shock induces a *downward* jump of inflation and the nominal interest rate in the short run and, subsequently, an *increase* towards the unchanged steady state; the same shock induces an (upward) *over-reaction* of the economic growth rate in the short-run and, subsequently, a *decrease* towards the new (higher) steady state. As pointed out before, these results indicate possible relevant policy trade-offs, namely, between short-run stabilisation under a structural monetary-policy shock and transitional growth-maximisation/inflation-minimisation under an R&D-subsidy shock, and between the latter and transitional growth-maximisation/inflation-minimisation under a manufacturing-subsidy shock.

Finally, regarding the convergence behaviour of catching-up economies, the results in our paper suggest that the characteristics of the monetary-policy feedback

37. For instance, the European Central Bank points out that, over time, “price stability contributes to achieving high levels of economic activity and employment” (text on the “Benefits of price stability”, at <https://www.ecb.europa.eu/mopo/intro/benefits/html/index.en.html>). The Bank of England’s objectives in relation to monetary policy are “to maintain price stability, and, subject to that, to support (...) growth and employment.” (text of the Bank of England Act 1998, <http://www.legislation.gov.uk/ukpga/1998/11/section/11>).

rule add to the set of institutional factors already identified by the literature as determinants of the shape of transitions (see, e.g., Jones and Romer 2010, and Gil *et al.* 2017). Our model uncovers a rich interaction between those characteristics and the initial conditions of the economy off the steady state (e.g., the initial endowment of physical capital versus immaterial inputs, such as the technological-knowledge stock), which may either reinforce or overturn the standard transitional-dynamics implications of initial conditions (e.g., generating a *positive* correlation between physical capital and economic growth over transition).

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Appendix A: Household's dynamic optimisation problem

Following the standard Optimal Control Theory, the maximisation of intertemporal utility (14) requires the consideration of the Hamiltonian function³⁸

$$\begin{aligned} \mathcal{H} = & \left(\frac{C(t)^{1-\theta} - 1}{1-\theta} \right) \cdot e^{-\rho t} + \\ & \nu(t) \cdot (r(t) \cdot a(t) + w(t) \cdot L - C(t) + \tau(t) - \pi(t) \cdot m(t) + i(t) \cdot b(t)) + \\ & \lambda(t) \cdot (b(t) - m(t)) \end{aligned}$$

where a and m are the state variables, ν and λ are the costate variables, and C and b are the control variables. The necessary conditions under the Maximum Principle are:

- a) $\partial \mathcal{H} / \partial C(t) = 0 \Leftrightarrow e^{-\rho t} \cdot C(t)^{-\theta} = \nu(t)$
- b) $\partial \mathcal{H} / \partial b(t) = 0 \Leftrightarrow \nu(t) \cdot i(t) + \lambda(t) = 0$
- c) $\partial \mathcal{H} / \partial a(t) = -\dot{\nu}(t) \Leftrightarrow \nu(t) \cdot r(t) = -\dot{\nu}(t)$
- d) $\partial \mathcal{H} / \partial m(t) = -\dot{\nu}(t) \Leftrightarrow -\nu(t) \cdot \pi(t) - \lambda(t) = -\dot{\nu}(t)$
- e) $\partial \mathcal{H} / \partial v(t) = \dot{a}(t) + \dot{m}(t)$
- f) $\partial \mathcal{H} / \partial \lambda(t) = 0$
- g) $\lim_{t \rightarrow +\infty} \nu(t) \cdot a(t) = 0$; $\lim_{t \rightarrow +\infty} \nu(t) \cdot m(t) = 0$

Using b), c) and d) yields $\nu(t) \cdot r(t) = -\nu(t) \cdot \pi(t) + \nu(t) \cdot i(t)$. Then, by dividing both sides of the equation by $\nu(t)$ and rearranging terms, we get the non-arbitrage equation (16) in the text. Considering a) and b), applying logarithms and deriving with respect to time gives us the consumption Euler equation (17). Finally, using a) together with g) yields the transversality conditions (18).

Appendix B: Effects of monetary-policy shocks: the case of $\beta < \Omega$

This appendix focus on the scenario where the degree of the CIA constraint on R&D is *lower* than that on manufacturing, i.e., $\beta < \Omega$. Figure B.1 illustrates the case of $\beta = 0.5$ and $\Omega = 1$.

38. We follow the usual approach and consider the (static) CIA constraint is binding, i.e., $b(t) = m(t)$.

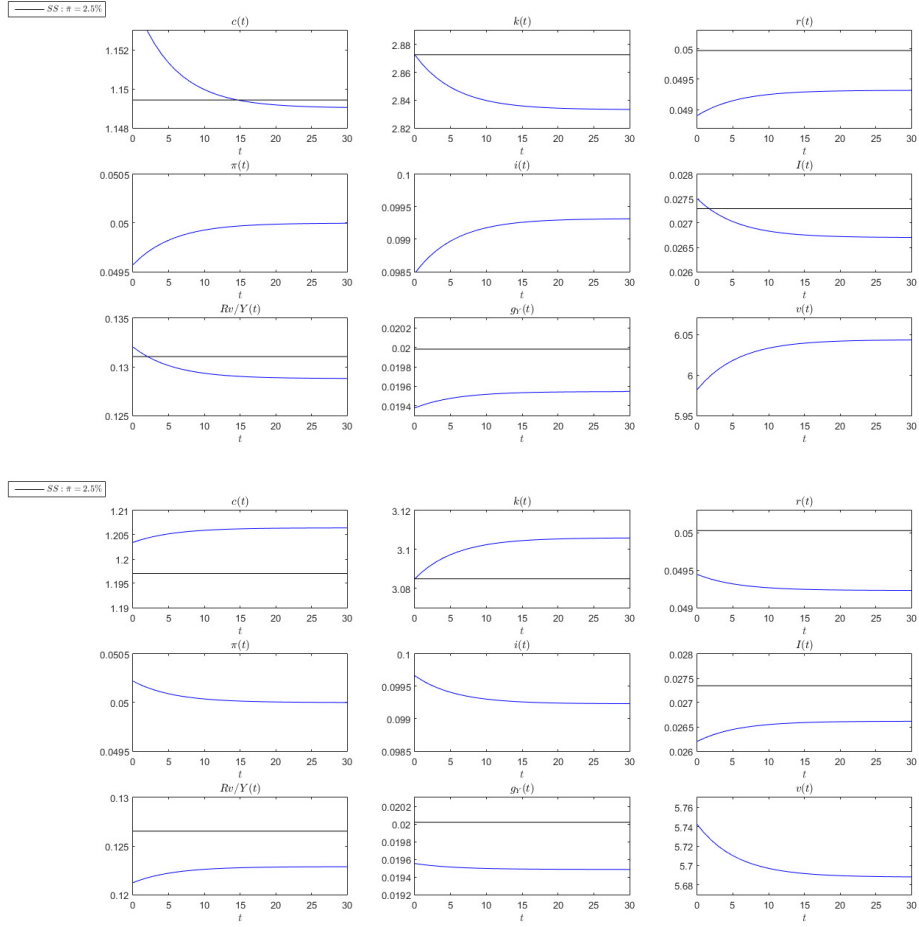


Figure B.1: Transitional dynamics of selected nominal and real macroeconomic variables given a monetary-policy shock (an increase in $\bar{\pi}$ from 0.025 to 0.05) for different scenarios of β and Ω : $\beta = 0.5$ and $\Omega = 1$ (upper panel); $\beta = 1$ and $\Omega = 0.5$ (lower panel). $\gamma = 1.97$, $\rho = 0.02$; $\theta = 1.5$; $\alpha = 1/3$; $\eta = 1$; $\lambda = 3$; $\zeta = 3.85$; $\bar{\pi} = 0.025$ (pre-shock). The horizontal lines represent the pre-shock steady-state level of each variable.

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