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Monetary policy and innovation in Europe: An SVAR approach

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A B S T R A C T

Using quarterly data, we estimate the effects of monetary policy on innovation in the Eurozone over 2000–2021. Variations in the monetary stance may affect how firms and governments allocate resources to innovative investments. The identification of the structural shocks relies on an SVAR framework with a set of exclusion restrictions. Although characterised by the predominance of ZLB periods, conventional monetary policy shocks affect private and public R&D spending in the medium term with some initial inertia. Unconventional monetary shocks affect innovative expenditure in the short to medium term, but their impacts vanish in the longer run.

1. Introduction

Over recent decades, several advanced economies have experienced slowdowns in aggregate growth and productivity, despite the spread of digital technologies (Ciaffi et al., 2022). Such trends have been notably evident in the Euro Area during the post-Global Financial Crisis period. Whilst most of the Eurozone's pre-COVID era was characterised by persistently low interest rates and unconventional monetary policy, the sudden 2021 economic rebounds and the ongoing global geopolitical tensions have led to unprecedented peaks in the inflation rate, which in turn have translated into sharp rises in European Central Bank (ECB) policy rates.

It is largely recognised that the dynamics of innovation activity represent a crucial determinant of productivity trajectories (Guérin, 2023). A recent work by Ma and Zimmermann (2023) relates monetary policy to innovation in the US, finding detrimental effects of monetary contraction on various measures of innovation. However, opposite effects emerge in Moran and Queralto (2018), still in the US. This issue is thus open to further investigation and appears to be relevant, especially in the context of the current global scenario characterised by, among other things, increased financial risks and uncertainties. It seems reasonable to argue that innovation activity represents a relevant channel through which monetary policy transmits its effects on the supply-side of the economy, with possible long-run implications for economic growth.

It is worth recalling that the transmission mechanisms through which monetary policy can affect companies' innovative investment involve the so-called credit channel (Bernanke and Gertler, 1995; Bernanke, 2023), which ultimately refers to the role of the external finance premium. The external finance premium is then explained by the balance sheet channel (or the net worth channel) and the bank-lending channel. The first is mainly linked to the shrinkage of a borrower's collateral value and the co-movement of a firm's coverage ratio and the policy rate. The second, i.e. the bank-lending channel, arises because the disruption of bank loan supplies may lead to additional costs for firms that are highly dependent on bank credit flows. In particular, it could be the case that small and

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medium-sized businesses face relatively higher and more cyclically sensitive external finance premiums (Bernanke et al., 1994). Overall, this mechanism brings about a decrease in profitability and innovative propensity (Huber, 2018). The impact on public R&D investment may result in a deterioration of financial conditions, which can induce a government budget consolidation, thus affecting innovative expenditure.

The quantitative easing transmission mechanism is broadly concerned with the impact of large-scale asset purchases on the medium-to-long-term interest rate and the implicit effect on the decreased financing cost brought about by reduced yields on corporate bonds. Bank lending may also be positively affected, as more cash is available for credit financing. In addition, confidence and anchored expectations may lower uncertainty, thus reducing credit risk and, in general, the external finance premium (Stefański, 2022). It has also been shown that the direct purchase of corporate bonds can stimulate innovation spending through a wealth transfer to more innovative companies (Grimm et al., 2022). In addition, the impact on public innovative expenditure may be encouraged by more favourable financial conditions, which in turn may reduce the burden of interest payments.

Although recent studies have estimated the real effects of monetary policy in the Eurozone (e.g. Burriel and Galesi, 2018; Pellegrino, 2018; Murgia, 2020; Badinger and Schiman, 2023), there is still a gap in the links between monetary policy and innovation. Therefore, we contribute to the existing literature by estimating the effects of monetary policy on both private and government R&D expenditure in the Eurozone. Using quarterly data from 2000 to 2021, we propose a structural VAR (SVAR) framework in which identification is achieved through a parsimonious set of exclusion restrictions. We employ three different monetary instruments to account for the role of expectations and unconventional monetary policy. Our limited set of prior assumptions on the distribution of the true parameters is mainly due to the persistently low interest rates and unconventional policy that have characterised most of the period under analysis and which are likely to imply controversial or even anomalous real effects of monetary policy (Brunnermeier and Koby, 2018; Ahmed et al., 2023¸ Onofri et al., 2023).

2. Measuring the ECB's monetary shocks

In the first stage of our analysis, we separate the systematic and unexpected components of monetary policy, as proposed by Christiano et al. (1996). For this purpose, we follow Romer and Romer (2004) and split the meeting-by-meeting main refinancing operations rate (MRO) change into its predicted and unpredicted components, thus specifying the following function:

$$\Delta MRO_m = \eta + \sum_{k=1}^{2} \alpha_k \widetilde{Q_m^k} + \sum_{k=1}^{2} \beta_k \widetilde{\pi_m^k} + \sum_{k=1}^{2} \lambda_k \widetilde{u_m^k} + \sum_{k=1}^{2} \phi_k \Delta \widetilde{Q_m^k} + \sum_{k=1}^{2} \psi_k \Delta \widetilde{\pi_m^k} + \sum_{k=1}^{2} \theta_k \Delta \widetilde{u_m^k} + \rho MRO_{m-14} + \gamma \log(A)_m + \varepsilon_m \tag{1}$$

where $\widetilde{Q_m^k}$ is the expected k-years-ahead output growth rate at the m-*th* meeting of the ECB Governing Council in which decisions on policy rates are taken. Analogously, the same applies to the inflation rate π and the unemployment rate u. The association of Δ with the predicted variables denotes the revisions of the forecasts with respect to the previous meeting. Compared to the original specification of Romer and Romer (2004), we augment the equation with the ECB's total assets A to control for the unconventional monetary policy, consistent with Burriel and Galesi (2018). The ordinary least squares (OLS) residual $\widehat{\varepsilon}_m$ obtained through the estimation of Eq. (1) is our measure of monetary policy shock. The differences between the variation in the MRO and its unpredicted component can be observed in Fig. 1.

3. Structural VAR

In order to model the structural relationship between the ECB's monetary stance and innovation, as a first step we build the following reduced-form VAR model:

$$\boldsymbol{A}(\mathrm{L})\boldsymbol{y}_\mathrm{t} - \boldsymbol{B}(\mathrm{L})\boldsymbol{x}_\mathrm{t} = \boldsymbol{\varepsilon}_\mathrm{t} \tag{2}$$

where $\boldsymbol{y}$ and $\boldsymbol{x}$ are vectors of endogeneous and exogeneous variables, respectively. The sets of lagged coefficients are $\boldsymbol{A(L)} = (\boldsymbol{I_n} - \boldsymbol{A_1 L^1} - \ldots - \boldsymbol{A_p L^p})$ and $\boldsymbol{B(L)} = (\boldsymbol{I_n} + \boldsymbol{B_1 L^1} + \ldots + \boldsymbol{B_q L^q})$. The forecast errors are such that $E(\varepsilon_t) = E(\varepsilon_t \varepsilon_s{}')\ 0\ \forall\, t \neq s$ and $E(\varepsilon_t \varepsilon_t{}') = \boldsymbol{\Sigma}$. The model specified in Eq. (2) cannot unveil much about the causal relationships between the endogenous variables, as the variance-covariance matrix $\boldsymbol{\Sigma}$ is non-diagonal. Therefore, some extensions are needed.

To identify the effects of monetary policy, we propose the following SVAR model:

$$\boldsymbol{A_0 A}(\mathrm{L})\boldsymbol{y}_\mathrm{t} - \boldsymbol{A_0 B}(\mathrm{L})\boldsymbol{x}_\mathrm{t} = \boldsymbol{A_0 \varepsilon}_\mathrm{t} = \boldsymbol{C v}_\mathrm{t} \tag{3}$$

where $\boldsymbol{A_0}$ is a square matrix of dimension n (with n equal to the number of endogenous variables) containing the contemporaneous effects among the covariates in $\boldsymbol{y}$, $\boldsymbol{C}$ is a diagonal matrix and $\boldsymbol{v_t} = \boldsymbol{A_0 C^{-1} \varepsilon_t}$ is the structural shocks matrix. Since we aim to evaluate how the relationships among the variables in $\boldsymbol{y}$ evolve over time, we need to obtain impulse response functions (IRFs) that are economically meaningful. Thus, assuming the non-singularity of $\boldsymbol{A_0}$ and $\boldsymbol{A(L)}$, we re-parametrise Eq. (3) into its infinite moving-average representation:

$$\boldsymbol{y}_\mathrm{t} = \boldsymbol{A}(\mathrm{L})^{-1}\boldsymbol{B}(\mathrm{L})\boldsymbol{x}_\mathrm{t} + \boldsymbol{D}(\mathrm{L})\boldsymbol{v}_\mathrm{t} \tag{4}$$

where $\boldsymbol{D(L)} = \boldsymbol{A_0}^{-1}\boldsymbol{A(L)}^{-1}\boldsymbol{C}$ represents the structural IRF coefficients. It follows that the s_{th}-ahead response of an endogenous variable in

Fig. 1. ECB monetary policy, 1999q1–2023q3.

the system following a structural shock at time t is given by $\vartheta \boldsymbol{y}_{t+s}/\vartheta \boldsymbol{v}_t = \boldsymbol{D(s)} \forall t,\ s \in T$ – provided that $\boldsymbol{D(L)}$ is differentiable over the entire parameter space.[1]

4. Identifying restrictions

Given $\widehat{\Sigma}$, we must identify $\boldsymbol{A_0}$ and $\boldsymbol{C}$ such that $E(\boldsymbol{v_t}'\boldsymbol{v_t}) = \boldsymbol{I_n}$. Following Sims (1980) and Amisano and Giannini (2012), as well as the application to monetary policy and innovation proposed by Moran and Queralto (2018), we consider as a starting point the Cholesky decomposition of $\boldsymbol{\Sigma}$. Assuming that $\boldsymbol{\Sigma}$ satisfies the full rank conditions, we can find a unique matrix $\boldsymbol{P}$ such that $\boldsymbol{\Sigma} = \boldsymbol{PP}'$. In our case, the identification through the Cholesky decomposition implies imposing *i)* $(n^2 - n)/2$ zero restrictions[2] (exactly identified model), *ii)* lower triangularity on $\boldsymbol{A_0}$ with unit elements on the main diagonal and *iii)* diagonality on $\boldsymbol{C}$. Therefore, our Cholesky factor is given by $\boldsymbol{P}{=}\boldsymbol{A_0^{-1}C}$. We can verify the diagonality of the structural shocks matrix as follows: $E(\boldsymbol{v_t}'\boldsymbol{v_t}) = \boldsymbol{A_0C^{-1}(A_0C^{-1})'\Sigma{=}\Sigma^{-1}\Sigma} = \boldsymbol{I_n}$.

It is worth highlighting that the Cholesky factor $\boldsymbol{P}$ is not invariant to the order of the endogenous variables. Hence, deciding which structural shocks have zero contemporaneous effects in each equation is pivotal for the identification strategy. Considering both the economic and inferential features of the phenomenon, the ordering of the variables is the following: (1) GDP growth; (2) monetary instrument; (3) innovation; (4) inflation rate. Such a recursive-ordering criterion is broadly in line with Sims (1986), at least with regard to the non-innovation observables, and implies that innovation takes at least one quarter to respond to inflation shocks. It is worth pointing out that our prior assumptions on the contemporaneous effects across the endogenous variables do consider the quarterly time frequency of the sample, in the sense that imposing economic or financial stickiness in the very short run is less restrictive and more realistic compared to the case of, say, an annual frequency, in which the exclusion restrictions allow for effects only after one year. Moreover, the choice of imposing stickiness of monetary policy to unexpected changes in growth rates and inflation is made by also carefully assessing the time-frequency of the meetings of the ECB Governing Council where decisions on policy rates are taken. Although we did not find existing works that impose contemporaneous restrictions on innovation in the context of SVAR modelling, it appears reasonable to assume that firm and government innovation projects need at least one quarter to adjust to the unexpected changes in the inflation rate.

As a monetary instrument, we alternatively consider the main refinancing operations rate (MRO), a measure of monetary policy shocks (MPS) that we built following Christiano et al. (1996) and Romer and Romer (2004), and the ECB's total assets as a measure of the unconventional monetary stance. As concerns the vector of exogenous covariates $\boldsymbol{x}$, we include the unemployment rate since it is a relevant explanatory factor for the variables in $\boldsymbol{y}$, especially as concerns monetary policy (e.g. Sims, 1986; Arias et al., 2018; Geiger and Scharler, 2021). Including the unemployment rate in the exogenous vector appears to be a good balance between the willingness to avoid misspecification and the need to maintain an acceptable ratio between the sample size and the number of free parameters.[3]

As a subsequent step, in addition to the set of Cholesky restrictions described above, we assume that the monetary instrument does

[1] Considering how we have defined $\boldsymbol{D(L)}$, it is interesting to note that the reduced-form parameters $\boldsymbol{A(L)}$ play a crucial role in shaping the structural IRFs. For this reason, a good structural VAR model should reflect a careful construction of its reduced-form counterpart.

[2] Where n represents the size of the matrix $\boldsymbol{A_0}$.

[3] In fact, a 5x5 VAR specification when $T < 90$ is unusual in the literature.

not respond to output changes within a quarter, in the spirit of Uhlig (2005). Although other identification schemes are possible, we prefer an agnostic approach with limited restrictions[4] for two main reasons: statistical and economic. Firstly, since T does not diverge, imposing a larger number of identifying restrictions would translate into huge costs in terms of consistency, thus threatening any proper balance of the bias-variance trade-off. Secondly, a large portion of the period under analysis is characterised by unconventional monetary policy and low policy rates. As has emerged in recent empirical applications, the overall macroeconomic effects of monetary policy might be counterintuitive when central banks implement unconventional measures or even within conventional contexts but with policy rates persistently close to zero (Brunnermeier and Koby, 2018; Ahmed et al., 2023; Onofri et al., 2023). Except for the post-COVID period, the ECB's policy rates were persistently close to zero most of the time. In that case, imposing further prior restrictions based on standard economic theory might not capture the plausible 'anomalies' of the true effects.

It is worth relating the reduced-form errors as a function of the structural shocks in matrix form as follows:

$$\begin{pmatrix} \varepsilon_t^{GDP} \\ \varepsilon_t^{Money} \\ \varepsilon_t^{Innov.} \\ \varepsilon_t^{Infl.} \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_{21} & 1 & 0 & 0 \\ a_{31} & a_{32} & 1 & 0 \\ a_{41} & a_{42} & a_{43} & 1 \end{bmatrix}^{-1} \begin{bmatrix} c_{11} & 0 & 0 & 0 \\ 0 & c_{22} & 0 & 0 \\ 0 & 0 & c_{33} & 0 \\ 0 & 0 & 0 & c_{44} \end{bmatrix} \begin{pmatrix} v_t^{GDP} \\ v_t^{Money} \\ v_t^{Innov.} \\ v_t^{Infl.} \end{pmatrix} \tag{5}$$

where a_{ij} and c_{ij}, for $i = 1, \ldots, 4$ and $j = 1, \ldots, 4$, are free elements to be estimated consistently with the above-discussed strategy. The matrices entering Eq. (5) reflect our just-identified model under the Cholesky identification scheme. Within the over-identification strategy, we impose an additional zero restriction on the element a_{21}.

Although our agnostic identification approach is calibrated to obtain the desirable property of mutually orthogonal shocks through identification schemes based on reasonable prior restrictions, we are aware that it can still suffer inferential limitations and potential endogeneity bias. The risk of omitted variable bias cannot be ruled out, especially as it concerns the growth equation. However, as discussed earlier, employing a 5x5 (or higher) SVAR model when observing fewer than 90 periods, as in the case of this study, would imply considerable costs in terms of consistency, regardless of the identification strategy adopted. The endogeneity risks, especially due to co-movements between the business cycle and expectations regarding monetary policies (e.g. Christiano et al., 1996; Romer and Romer, 2004), are mitigated by the use of the exogenous monetary measure built in Section 2, combined with the imposition of diagonality on the matrix of the structural shocks. The endogeneity issues are strictly linked to our agnostic identification scheme, the appealing advantages of which lie mainly in *i*) an ad hoc calibration to the extensive periods of persistently low policy rates and unconventional monetary policy in the Eurozone (which require flexibility) and *ii*) gains in terms of the asymptotic performance of the model. We recognise that these benefits of our agnostic identification approach are at least partially mitigated by some disadvantages, i.e. ignoring further contemporaneous or even long-run structural relationships that may help achieve full identification.

In sum, given our research question and the econometric setup proposed in this paper, we believe that our identification approach is still more suitable relative to its natural alternatives, although it is subject to potential weaknesses. However, in order to test the sensitivity of the baseline estimates and the robustness of the overall findings, in Section 7 we relax some assumptions and propose alternative modelling strategies.

5. Data and stationarity properties

Table 1 reports the main descriptive statistics and the sources of the actual data employed in the analysis. The sources for the forecasted variables employed in Eq. (1) are the same as the actual variables (any statistic or further information on forecasts can be made available upon reasonable request).

Data on private and government expenditure in R&D, gathered from the Gross Domestic Expenditure on R&D (GERD) database of Eurostat, represent our measure of innovation and are originally observed at the annual level. To maintain the quarterly frequency of our dataset – a crucial condition for our proposed identification strategy – we transform these into quarterly data by applying a local quadratic polynomial with the sum matched to the source data.

As concerns our innovation measures, we consider the detrended logarithm of the expenses in real R&D (at the private and government levels, separately).[5] We also transform the ECB's total assets into a detrended logarithm, which represents the unconventional monetary instrument. The monetary variables are converted in real terms by employing the deflator proposed by Eurostat. As a further step, we assess the stationarity properties of our innovation measures and the ECB's total assets, as they represent a crucial statistical feature to propose a causal interpretation within our empirical framework. Since both the dynamics of innovation and the monetary stance are likely to exhibit significant persistence – as reflected in our modelling strategy – we implement the KPSS test developed by Kwiatkowski et al. (1992) as it weights the serial dependence of the residuals. Moreover, the KPSS test is characterised by asymptotic properties and finite-sample power, which are particularly suitable for our series. The outcomes reported in Table 2 suggest that all series considered are non-stationary in levels and become stationary once they are converted into detrended logarithms.

[4] In relation to the Eurozone, the use of a limited number of identifying restrictions is proposed in the recent work of Badinger and Schiman (2023).

[5] The use of the detrended logarithm of the variable follows the approach proposed by Blanchard and Quah (1988).

Table 1
Summary statistics and variable sources.

Variable	Source	T	Mean	SD	Min.	Max.
MRO	ECB economic bulletin	86	1.486	1.523	0.000	4.750
Monetary policy shock	Authors' construction	86	-0.003	0.066	-0.291	0.136
ECB's total assets (logarithm, detrended)	Federal reserve economic data (FRED)	86	-0.026	0.152	-0.389	0.272
GDP growth rate	ECB survey of professional forecasters	86	-0.295	3.042	-15.203	13.495
Inflation rate (HICP)	ECB survey of professional forecasters	86	1.662	1.006	-0.367	4.550
Unemployment rate	ECB survey of professional forecasters	86	9.367	1.417	7.125	12.230
Private R&D expenditure (logarithm, detrended)	EUROSTAT- GERD by sector of performance	86	0.00074	0.023	-0.0398	0.0554
Government R&D expenditure (logarithm, detrended)	EUROSTAT- GERD by sector of performance	86	0.00033	0.022	-0.0328	0.0598

Table 2
KPSS test for stationarity.

	Levels		Detrended logarithm	
	Test statistic	*P*-value	Test statistic	*P*-value
Priv. R&D Exp., Lag(1)	12.560	0.0000	1.923	0.0361
Priv. R&D Exp., Lag(2)	8.415	0.0000	1.300	0.0876
Priv. R&D Exp., Lag(3)	6.341	0.0000	0.991	0.1416
Priv. R&D Exp., Lag(4)	5.095	0.0006	0.807	0.1911
Gov. R&D Exp., Lag(1)	13.780	0.0000	2.421	0.0180
Gov. R&D Exp., Lag(2)	9.231	0.0000	1.718	0.0471
Gov. R&D Exp., Lag(3)	6.954	0.0000	1.389	0.0757
Gov. R&D Exp., Lag(4)	5.587	0.0003	1.213	0.0994
ECB Assets., Lag(1)	4.729	0.0008	0.365	0.4298
ECB Assets., Lag(2)	3.183	0.0076	0.253	0.5545
ECB Assets., Lag(3)	2.410	0.0183	0.198	0.6374
ECB Assets., Lag(4)	1.948	0.0347	0.167	0.6945

Notes. The test is built under the null hypothesis of stationarity.

6. Results

We estimate separate models according to the monetary instrument employed. We report the conventional confidence intervals associated with each IRF at the 68 % level. The lengths of p and q are chosen according to the values that minimise the AIC statistic. For the sake of space, this section only shows the IRFs where monetary impulses exert their effects on innovation. The full results are reported in the Online Appendix.

The IRF estimates reported in Fig. 2 suggest that private and government innovation activities react differently in the wake of a monetary impulse. An MRO impulse exerts contractionary effects on private innovation from the second to the fourteenth quarters (partially aligning with Ma and Zimmermann, 2023), with the greatest negative impact being reached after roughly two years. More specifically, a one hundred basis point shock in the MRO implies an approximate 0.1 % reduction in private R&D expenditure after around eight quarters. However, once the systematic component of monetary policy is excluded, private innovation contracts only after one year and reverts faster to its long-run equilibrium, with magnitude effects that align with the model in which the MRO is employed as an impulse variable. The effects exerted by our measure of monetary shocks maintain a temporary nature and do not contrast with the previous overall findings. The similarity between the red and blue IRFs in Fig. 2 is likely because our over-identification strategy can be seen as an extended Cholesky structure with an additional restriction set that, as we can observe, does not lead to different findings over the entire time horizon considered.

As for government innovations, the effects of monetary contraction in the first two years appear to be characterised by more complex nonlinearities. However, a clear decline in innovative spending emerges two years after the monetary impulse, reaching a minimum in the twelfth quarter when both measures of monetary shocks are employed. Such a negative effect associated with the lowest point reached by the IRF signals that a one hundred basis point shock in the impulse variable generates a decline in government R&D expenditure of approximately 0.2 % in the MRO case and 0.1 % in the MPS alternative.[6] Unlike the case of private R&D, the effects of monetary policy are persistent when government R&D is the response variable, provided that the monetary shock measure includes the systematic component. This pattern might signal that the expectations regarding the ECB's policy rate exert different effects on private and government innovation, perhaps largely due to the role of expected returns on R&D investments, borrowing costs and fiscal constraints.

The monetary impulse in Fig. 3 is given by the detrended logarithm of the ECB's total assets, whose positive shocks reflect expansionary monetary policies within the unconventional regime. Unlike the cases reported in Fig. 2, we can observe a positive effect of expansionary (unconventional) monetary policy on impact, with the peak being reached faster, and the effects are offset after three

[6] Recall that the values on the vertical axes of the IRF graphs should be multiplied by 100 to obtain the percentage variation.

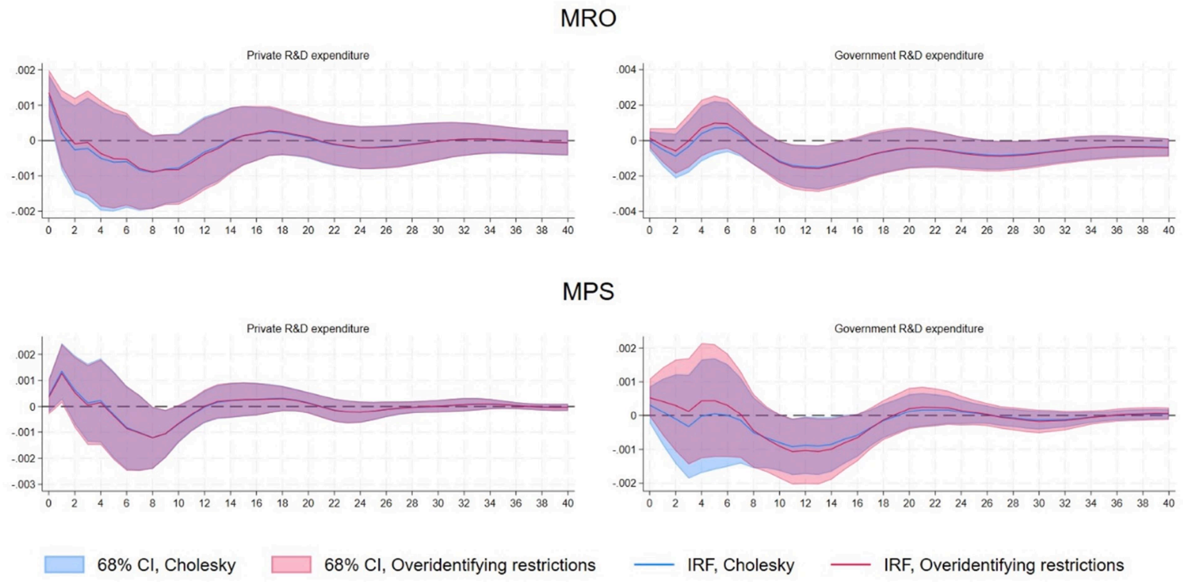

Fig. 2. IRFs, monetary policy and innovation.

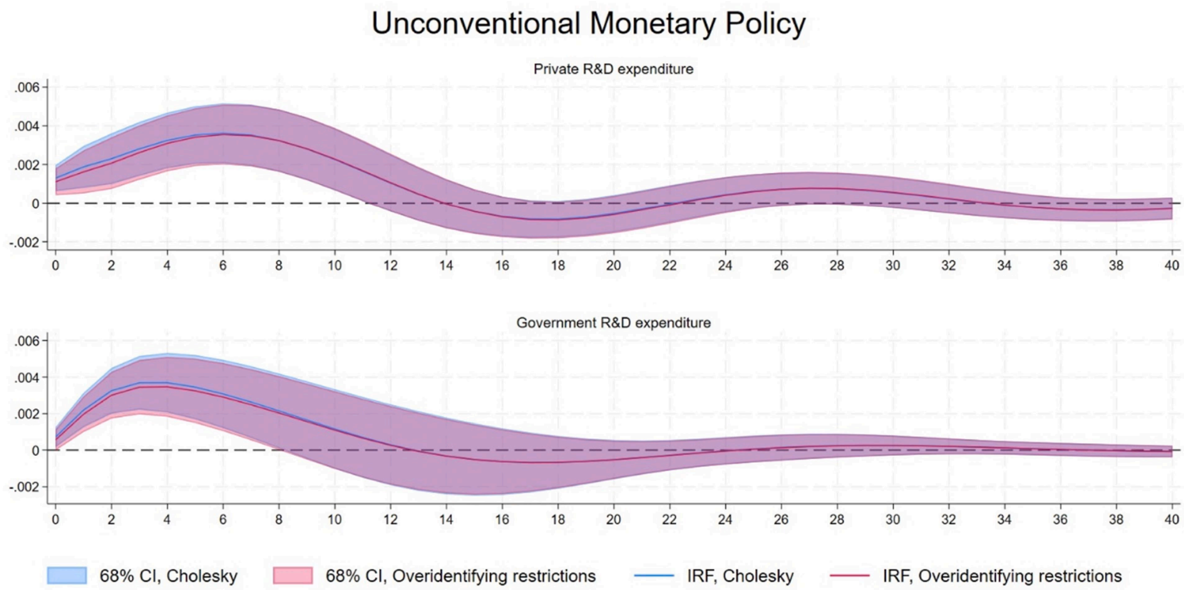

Fig. 3. IRFs, unconventional monetary policy and innovation.

years. In other words, relative to the case in which conventional monetary shocks are employed in the model, the IRFs are smoother and lean towards neutral in the medium and long run. Moreover, it is worth highlighting that the impacts of unconventional monetary policy on both private and government innovation are stronger relative to the conventional scenario. Indeed, the effects exerted by expansionary unconventional policies lead to a nearly 0.2 % rise in both private and government R&D expenditure. Similarly to the previous case, the IRF associated with the over-identification strategy almost overlaps with that related to the Cholesky scheme over the whole period.

The lack of persistence in the innovation effects of unconventional monetary policy – despite the stronger short-run impacts – can be explained by the fact that variations in the long-run dynamics of innovative expenditure are more likely affected when the actual policy rate changes, since a mere injection of liquidity into the economy when interest rates are persistently null may not significantly alter the expected return or the borrowing costs. This is broadly consistent with the theoretical mechanisms behind the monetary–innovation relationship associated with the credit channel, as discussed in Section 1, especially considering that the supply-side effects are likely stickier and more dependent on the interest rates. Consistently, the mere increases in the ECB's assets when policy rates are characterised either by negligible changes or persistently low values might instead exert a prevalence of demand-side effects, which translates into increased R&D spending, thus explaining the faster and greater rises in the IRFs presented in Fig. 3. Such interpretations regarding the potential neutrality of the long-run innovation effects of the ECB's policy are consistent with recent empirical evidence, according to which prolonged periods of unconventional monetary policy may weaken the transmission channels (Ahmed et al., 2023) and could even imply contractionary effects of expansive monetary policy due to the phenomenon of the so-called *reversal interest rate* (Brunnermeier and Koby, 2018), which in the case of the present analysis is likely to offset any long-run beneficial effect on government and private innovation activities.

7. Robustness checks

While our measure of monetary policy shocks à la Romer and Romer (2004) can be considered as a good robustness exercise regarding endogeneity – assuming that the unexpected variations in monetary policy are orthogonal to the simultaneous variations of the variables in the system – there are nevertheless inferential issues worth investigating in order to assess the sensitivity of our baseline results. At the same time, the empirical setup proposed in this paper, as well as the nature and size of our dataset, represent a constraint with regard to the alternative robustness exercises. Considering such issues, we attempt to propose a valid balance between the need to assess the sensitivity of the baseline results and the necessity of avoiding extensive changes in the econometric strategy. Therefore, we propose two additional empirical exercises for all model versions.

Firstly, we exclude the inflation rate from the system. Such a reduction in the size of our system of equations translates into substantial efficiency gains, mainly because our time dimension does not diverge. Consistently, we try to parsimoniously balance the bias-variance trade-off. Moreover, the inclusion of the inflation rate in the system may result in non-trivial collinearity issues with the endogenous variables converted in real terms.

Secondly, we employ an alternative identification scheme. While we believe that our baseline prior assumptions may have a net advantage compared to plausible alternatives, we are aware that allowing a response of growth and monetary policy to inflation shocks only after three months may result in a strict imposition, at least as concerns some periods of the time horizon considered. It is worth remarking that since our identification strategy is based on the construction of a diagonal variance-covariance matrix of the shocks, imposing at least an $(n^2 - n)/2$ restriction is essential in order to obtain orthogonal IRFs, even when we consider the most parsimonious identification scheme (i.e. Cholesky identification). We therefore propose an alternative identification scheme that relaxes the above-mentioned exclusion restrictions and which, in turn, restricts other contemporaneous relationships. More specifically, we change the recursive ordering of the variables while maintaining the same mathematical structure of the matrices $\boldsymbol{A_0}$ and $\boldsymbol{C}$. The alternative ordering is the following: (1) inflation; (2) GDP growth; (3) monetary instrument; (4) innovation. Such an ordering criterion, within the Cholesky structure (just-identified models), allows for the following contemporaneous effects: (*i*) output growth to inflation; (*ii*) policy rate to inflation and output growth; (*iii*) innovation to all variables in the system. The overidentified model maintains the Cholesky structure and imposes a further set of exclusion restrictions on the contemporaneous parameters associated with our measure of innovation.

The IRFs associated with the models that exclude the inflation rate (reported in Figs. A1 and A2) closely align with their baseline counterparts, except for some slight differences. For instance, the effects of MRO expansions on private innovation are positive on impact and quickly become negative, with a milder but more persistent behaviour compared to the baseline counterpart. The gains in terms of efficiency clearly arise when considering the IRFs associated with the unconventional monetary policy, as the bandwidths are narrower compared to the baseline case. Similarly, the results associated with the alternative identification scheme (reported in Figs. A3 and A4) highlight only negligible differences compared to the baseline IRFs, as well as more marked contrasts between the results associated with the exactly- and over-identified models. In sum, it appears reasonable to claim that despite some slight differences in terms of IRF trajectories and confidence intervals, the robustness exercises proposed in this section are broadly consistent with the baseline results as they do not lead to different conclusions.

8. Conclusions

The post-COVID era has been characterised by drastic changes in ECB policy, as unusual global economic scenarios and financial dynamics pose new concerns for the monetary authority. While average productivity and growth in the Eurozone have been stagnating over the last decades, recent empirical evidence for the US suggests that innovation could be a key channel through which monetary policy transmits its effects into the real economy (Moran and Queralto, 2018; Ma and Zimmermann, 2023).

We contribute to the literature by identifying the effects of ECB policy on private and government innovation dynamics in the Euro Area over the 2000–2021 period. To this aim, we propose an SVAR framework where the identification of the structural parameters relies on a parsimonious set of exclusion restrictions calibrated to the Eurozone's characteristics and the quarterly time-frequency of the data. The estimates support the following findings. Firstly, monetary contractions negatively affect private R&D, with a time lag between two and four quarters depending on whether the systematic monetary policy component is included (MRO vs MPS). Secondly, the negative and non-monotonic effect of monetary restrictions on government R&D tends to wear off after five years. Thirdly, unconventional monetary policy impacts public R&D faster than private spending, with a peak after four quarters; conversely, the positive effects fade away more quickly (twelve quarters) compared to private R&D.

We can argue that the ECB's monetary policy transmission mechanism additionally depends on, among other things, how private and government innovation activities relate and on expected returns to R&D, which ultimately depend on aggregate demand factors.

However, our findings should be interpreted parsimoniously, as they reflect the links between a common monetary policy and the aggregate innovation activity in the Euro Area. Indeed, we cannot rule out that the responses of private and government innovation within each Eurozone member are heterogeneous. As a result, the estimated dynamic effects can be seen as average country-specific responses whose weight is given by the individual innovation efforts.

Two major policy implications arise as a direct consequence of the findings proposed in this study. Firstly, the long-run effects of monetary policy on innovation working through the supply-side channels could be significantly dependent on the conventional or unconventional regimes that characterise the behaviour of the ECB, in addition to their persistence across time. Secondly, cross-country heterogeneity could significantly affect aggregate effects at the Eurozone level. Accordingly, any calibration of the monetary stance should also consider the internal macroeconomic dynamics of Eurozone members, to more effectively address innovation and productivity targets at both the country and aggregate level. Accounting for cross-country heterogeneity within the Eurozone, as well as how innovation shocks within a Eurozone country propagate across borders, appear to be relevant issues to address in future research.

CRediT authorship contribution statement

Gianni Carvelli: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Eleonora Bartoloni:** Investigation, Data curation. **Maurizio Baussola:** Writing – review & editing, Supervision, Investigation, Data curation, Conceptualization.

Declaration of competing interest

None.

Data availability

We have attached the dataset in the submission stage.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.frl.2024.105730.

Appendix

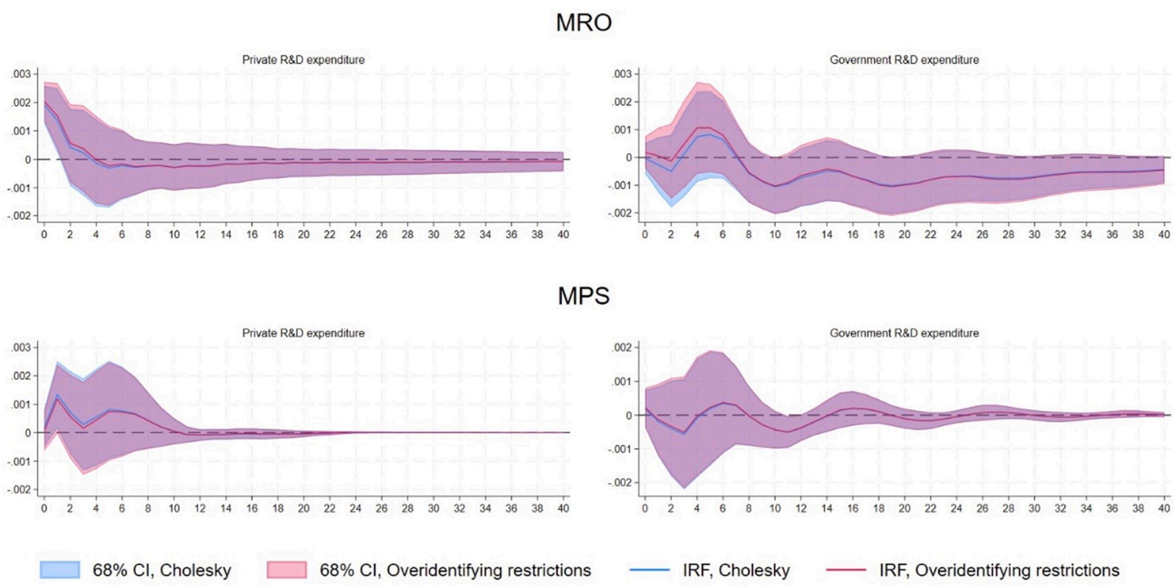

Fig. A1. IRFs, monetary policy and innovation. Alternative model specification.

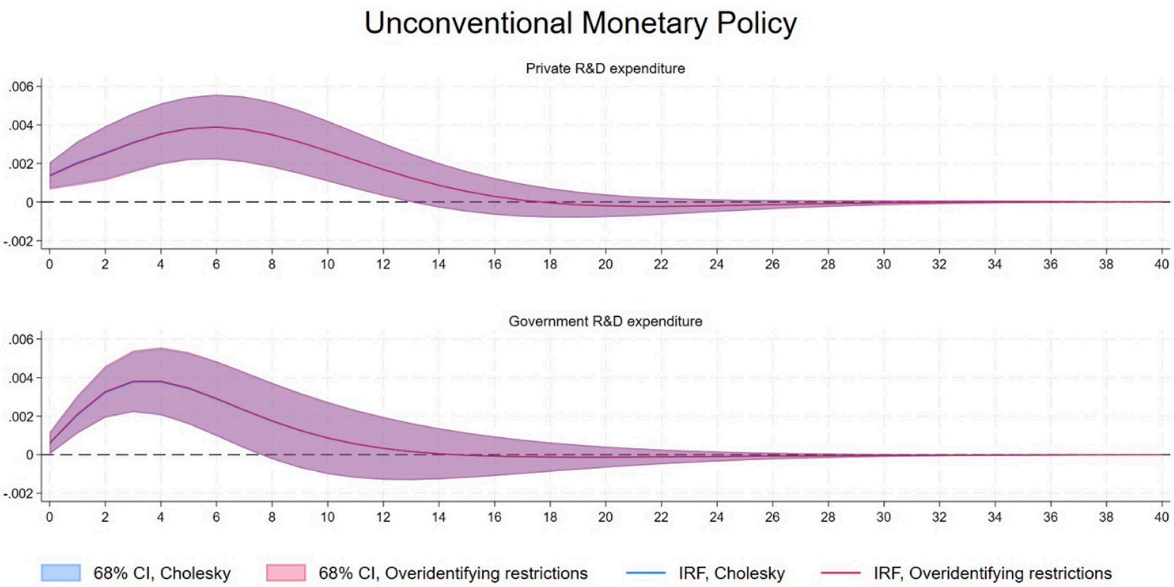

Fig. A2. IRFs, unconventional monetary policy and innovation. Alternative model specification.

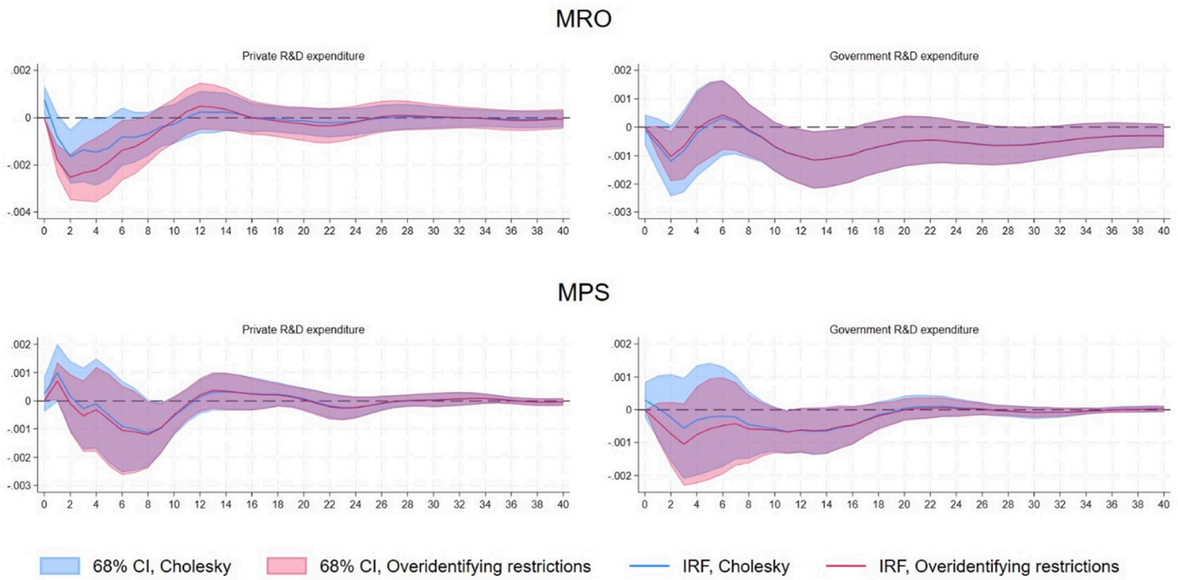

Fig. A3. IRFs, monetary policy and innovation. Alternative identification scheme.

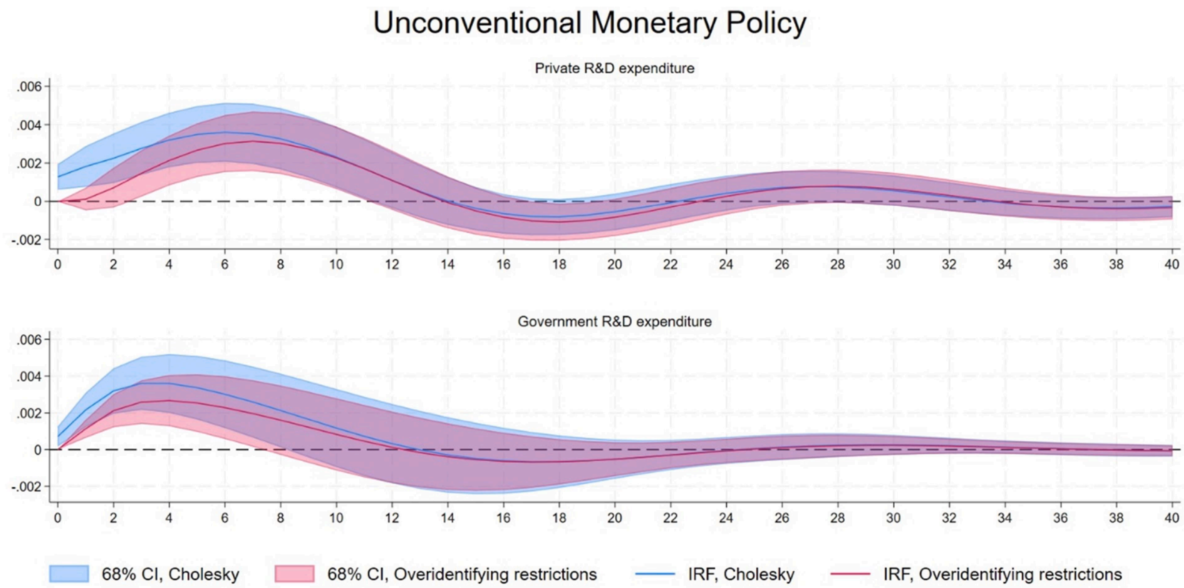

Fig. A4. IRFs, unconventional monetary policy and innovation. Alternative identification scheme.

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