Central Banks' Behavior in the Aftermath of the Great Recession

Aymeric Ortmans *

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Abstract

I estimate a Taylor-type monetary policy rule using a time-varying parameter vector autoregressive model to assess changes in central banks' behavior during and after the Great Recession. The results show large increases in responses to inflation and output for both the Federal Reserve and the European Central Bank after the 2008 crisis. Both weights on current inflation and output decrease with the monetary policy normalization started in the US, whereas the contemporaneous coefficients stay at their highest level at the end of the sample period in the Euro Area. Counterfactual analysis bring evidence to the macroeconomic effect of behavior changes in unconventional times. In the Euro Area, inflation rate would have been negative from 2014 to 2017 without any change in the coefficients of the monetary policy rule in the aftermath of the Great Recession.

Keywords: Central banks, Taylor rule, Time-varying parameter VAR, Shadow rate, Zero lower bound

JEL Codes: C32, E31, E32, E37, E43, E44, E52, E58

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*EPEE, Université Paris-Saclay, Université d'Évry-Val-d'Essonne. Comments are appreciated.

Contact: aymeric.ortmans@univ-evry.fr

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1 Introduction

Central banks are in the spotlight since the 2008 financial crisis and the 'Great Recession'. The global economic downturn spured the main central banks to take drastic decisions, as cutting short-term interest rates to zero and adopting unconventional measures by implementing new monetary policy tools. Despite their exceptional nature, these policies have been launched in order to pursue the standard objectives of stabilizing inflation or promoting economic growth. But in which extent do central banks have changed the weights of these objectives in the aftermath of the Great Recession?

To answer these questions, I draw on the seminal work of Taylor (1993) and the so-called 'Taylor rule', in which the central bank sets its interest rate according to an inflation target and the economic growth. Since then, a huge literature has emerged to give further insights of central banks' behavior. Referring to the standard Taylor rule, the central bank behavior can be interpreted as the respective weights the central bank puts on stabilizing inflation and output when it sets the policy rate according to the Taylor rule. For instance, several studies focus on the US monetary policy in the 1970s and the 1980s and try to explain the role of changes in Fed's behavior in the 'Great Moderation' episode (see Clarida et al., 2000).[1] It is widely accepted that the Fed was particularly careful concerning inflationary pressures after Paul Volcker's appointment. In this paper, I investigate in which extent changes in central banks' behavior may explain monetary policy decisions since the Great Recession. Based on the methodology employed in Belongia and Ireland (2016), I use a time-varying parameters vector autoregression (TVP-VAR) model with stochastic volatility to estimate a Taylor-type rule. I extend their work by considering the post-2008 crisis period, including the Great Recession, and by comparing the Federal Reserve and the European Central Bank (Fed and ECB hereafter, respectively). To get rid of flat rates challenging Taylor rule estimations in the Zero Lower Bound (ZLB) era, I use shadow rates constructed by Krippner (2013, 2019) as a proxy for unconventional monetary policies.[2]

My results show that central banks have changed their behavior since the Great Recession. Contemporaneous responses to inflation and output gap in the US have a different path than in the Euro Area. Fed's short-term

[1] Lots of methodologies have been developped to disentangle shifts in the conduct of monetary policy across regimes (Bernanke and Mihov 1998, Judd et al. 1998, Orphanides 2002, Lubik and Schorfheide 2004, Primiceri 2005, Cogley and Sargent 2005, Sims and Zha 2006, Mavroeidis 2010, Coibion and Gorodnichenko 2011 and Fernández-Villaverde et al. 2015 for instance). See Section 2 on related literature for further details.

[2] See pioneering papers using the shadow rate in VAR models (Wu and Xia, 2016) or in DSGE models (Wu and Zhang, 2019) (cf. Section 4.b for more references).

responses to macroeconomic fluctuations have been characterized by a peak around the year 2013, before falling back to their pre-crisis level. The story is not the same in the Euro Area: ECB's responses to current inflation and output gap have continuously increased since the Great Recession before reaching highest levels at the end of 2018. These shifts in Fed's and ECB's behavior reflect the different timing of the monetary policy normalization process. The Fed raised its main policy rate at the end-2015, whereas the ECB is still dealing with unconventional measures and negative rates. Counterfactuals analysis give some empirical evidence about the effect of changing behavior of central banks. Without change in monetary policy rule at the ZLB, the Euro Area would have suffered a deflationary episode from 2014 to 2017. Moreover, estimated unconventional monetary policy rule led to higher output gaps in the US and in the Euro Area, reducing output losses at the end of the period of estimation.

The rest of the paper is organized as follows. Section 2 is dedicated to the literature review on monetary policy rules and central banks' preferences. Section 3 describes the methodology used for the modelling framework. Section 4 presents the data. Section 5 and 6 are devoted to the results of my estimations, including the counterfactual analysis based on the empirical model. Finally, the last section is for the conclusion.

2 Related literature

The question of optimal monetary policy and central banks' preferences has been wiedely discussed in the literature. Since the benchmark work of John B. Taylor (Taylor, 1993), lots of papers have proposed discussions on optimal monetary policy and improvements in Taylor-type rules (see Clarida et al., 1999 and Woodford, 2001, 2003, among others). At the same time, a growing literature has emerged and found support to the use of Taylor rules as a practical tool to capture central banks' behavior across different monetary policy regimes.

Monetary policy rules have been used to identify changes in the Fed's behavior across different monetary policy regimes in the US, by disentangling pre-Volcker and post-Volcker periods. Clarida et al. (2000) advocate that a shift in the systematic component of monetary policy has been the main source of macroeconomic stability during the post-Volcker period. Favero and Rovelli (2003), Ozlale (2003), Dennis (2006), and Surico (2007a) provide additional support for these findings, with a specific attention on interest rate smoothing in the reaction function.[3]Using Bayesian methods to estimate a basic New Keynesian model, Ilbas (2012) also finds a

[3]Higher persistence of lagged interest rate in the conduct of monetary policy can be justified by misspecifications of the

break in the conduct of US monetary policy during the post-Volcker period. Based on similar methods, other studies deal with indeterminacy issue of US monetary policy during the Volcker-Greenspan era, and give further insights that allow for useful interpretations of the conduct of monetary policy at this time, including Lubik and Schorfheide (2004), and Mavroeidis (2010).

Since all of the papers cited above focus on Fed's behavior, other studies focus on the ECB (Taylor, 1999, Gerlach and Schnabel, 2000).[4] Relying on estimates of reaction functions, Gerdesmeier and Roffia (2003), Garcia-Iglesias (2007) and Surico (2007b) find similar results with a stronger interest rate response to inflation than to output fluctuations. However, other studies find a relatively high contemporaneous coefficient on output stabilization in a Taylor rule applied to the Eurozone, that is consistent with my results (see Fourçans and Vranceanu 2007, Sauer and Sturm 2007 for estimations on ex-post data, and Castelnuovo 2007 and Gorter et al. 2008 for forward-looking estimations of monetary policy rules). More recently, Rühl (2015) finds that the ECB seems to have used interest rate smoothing and strong significant output stabilization in its interest rate decisions. Other papers do the same exercise including the ZLB and the financial crisis, as Gorter et al. (2010), Gerlach (2011), and more recently Gerlach and Lewis (2014).

A strand of the literature proposes a comparative analysis of the conduct of monetary policy between the US and the Euro Area. Ullrich (2003) finds significant differences in the reactions functions between the Fed and the ECB. Belke and Polleit (2007) find that the standard Taylor rule is a better tool for modelling the behavior of the Fed rather than that of the ECB. They also find a lower weight on inflation relative to the output gap. Another interesting result comes from the cautious Fed's behavior comparing to the ECB, illustrated by a higher interest rate smoothing in the US. Belke and Klose (2013) propose the same exercise during the Great Recession, and find that both central banks became less cautious and put less weight on inflation when the crisis occured. Chen et al. (2017a) compare the US and Euro Area monetary policies at the ZLB. As a result, they find that the conduct of monetary policy has been more efficient in the US than in the Euro Area.

Previous papers mostly lay the emphasis on the systematic component of monetary policy. They show how the conduct of monetary policy has evolved on a given period of time by investigating the central banks' behavior. Also, the evolution of monetary policy shocks volatility is essential to understand changes in the

macroeconomic dynamics, as highlighted by Rudebusch (2001), Castelnuovo and Surico (2004), Castelnuovo (2006) and Givens (2012).

[4]More recently, Hartmann and Smets (2018) looked at the evolution of ECB's behavior during its first twenty years.

conduct of monetary policy, because it concerns the non-systematic part of the interest rate setting process in a time-varying dimension.[5] Hence, it is reasonable to assume that central banks' reaction to inflation and output growth can also vary over a period of time (see Fernández-Villaverde et al., 2015). To capture changes in central banks' behavior, the parameters of the Taylor-type monetary policy rule are allowed to change overtime.

For this purpose, two techniques are commonly used in the empirical literature on VAR analysis for monetary policy: the regime switching and the time-varying parameter approaches. Concerning the first one, several studies assume discrete changes in the parameters which are governed by a Markov switching variable. Therefore, they use a VAR model to investigate monetary policy regime shifts over a given period of time. Benchmark works using regime switching methodology include Sims and Zha (2006), Canova and Ferroni (2012), Debortoli and Nunes (2014) for the US, and Assenmacher-Wesche (2006), Drakos and Kouretas (2015) or Chen et al. (2017b) for the Eurozone. The second approach concerns time varying parameter models. It allows for gradual changes in the parameters of the monetary policy rule, and hence a nonlinear dynamics of central banks' behavior over the entire sample period. In a seminal paper, Primiceri (2005) (see Del Negro and Primiceri, 2015 for a corrigendum) wonders if monetary policy in the US has been less active against inflationnary pressure during the Martin-Burns period than during the Volcker-Greenspan era. He finds that the non-systematic part of US monetary policy was higher in the 1960s and 1970s, although monetary policy was more systematic under Greenspan in the US. Other influential studies such as Cogley and Sargent (2005), Boivin (2006), Kim and Nelson (2006), Benati and Mumtaz (2007) use a VAR with drifting coefficients and stochastic volatilities to analyse the Fed's behavior during the post-WWII period in the US. All these papers agree on the improvement in the systematic component of monetary policy after Volcker's appointment. As a whole, time-varying parameters VAR methodolgy has been widely employed in monetary policy analyses, including Benati and Surico (2008), Koop et al. (2009), Canova and Gambetti (2009), Mumtaz and Surico (2009), Ikeda (2010), Trecroci and Vassalli (2010), Benati (2011), Kapetanios et al. (2012), Baxa et al. (2014), and more recently Creel and Hubert (2015),

[5] Further analyses on the non-systematic component have been proposed to better understand changes in the conduct of monetary policy. In that case, the residual of Taylor-type rules - known as monetary policy shocks - could reflect changes in central banks' behavior as well. It could be seen as the willingness of the central bank to adopt a different behavior than the one based on the monetary policy rule. Following on from Boivin and Giannoni (2006), Justiniano and Primiceri (2008), Benati and Surico (2009), and using both a structural VAR and a Bayesian estimation of DSGE models, more recent papers investigate the impact of time-varying volatility of monetary policy shocks on the economy (Fernández-Villaverde et al., 2011 and Mumtaz and Zanetti, 2013).

Lakdawala (2016). As an extension, the present paper gives the same results than Belongia and Ireland (2016) on the common sample period of estimation: the Fed decreased the weight it placed on stabilizing inflation from 2000 to 2007, and deviated persistently from the estimated policy rule that had important implications for output and inflation. However, one of the main contribution of this paper is to bring some evidence on the evolution of monetary policy in the US and the Euro Area after the 2008 financial crisis.

3 Methodology

The model

The methodology used in this paper is similar to Belongia and Ireland (2016). It is reproduced in this section. Indeed, a vector autoregressive model with time-varying parameters and stochastic volatility (TVP-VAR) is used to study changes in central banks' behavior on the period of estimation. [6] The main difference come from the extension of the sample, that henceforth covers unconventional times. The model is based on Primiceri (2005) and Cogley and Sargent (2005), and its baseline version can be written as follows:

$$y_t = [\Pi_t \quad G_t \quad R_t^s]' \tag{1}$$

where Π_t is the inflation rate, G_t is the output gap and R_t^s is the shadow rate at period t. The three variables are collected in the 3×1 vector named y_t. The model is assumed to follow a second-order time-varying parameters vector autoregressive model with time-varying coefficients in the reduced form:

$$y_t = b_t + B_{1,t} y_{t-1} + B_{2,t} y_{t-2} + u_t \tag{2}$$

where b_t is a 3×1 vector of time-varying intercepts, $B_{i,t}$ for $i = 1, 2$ are 3×3 matrices of time-varying autoregressive coefficients, and u_t is a 3×1 vector of heteroskedastic shocks with time-varying covariance matrix Ω_t. From Equation (2), I can obtain both intercepts and autoregressive coefficients in the 21×1 vectorized form

$$B_t = vec\left(\begin{bmatrix} b_t' \\ B_{1,t}' \\ B_{2,t}' \end{bmatrix}\right)$$

[6] Stability of the simple VAR model is checked in the Appendix.

and decompose the covariance matrix Ω_t by applying a Cholesky factorization as

$\Omega_t = A_t^{-1}\mathbf{\Sigma}_t\mathbf{\Sigma}_t'(A_t')^{-1}$

where the 3×3 matrix is lower triangular with ones along its diagonal

$$A_t = \begin{bmatrix} 1 & 0 & 0 \\ \alpha_{g\pi,t} & 1 & 0 \\ \alpha_{r\pi,t} & \alpha_{rg,t} & 1 \end{bmatrix}$$

and the 3×3 matrix is diagonal

$$\mathbf{\Sigma}_t = \begin{bmatrix} \sigma_{\pi,t} & 0 & 0 \\ 0 & \sigma_{g,t} & 0 \\ 0 & 0 & \sigma_{r,t} \end{bmatrix}$$

Hence, the reduced form of Equation (2) can be rewritten in a matrix form as:

$$y_t = X_t'B_t + A_t^{-1}\mathbf{\Sigma}_t\varepsilon_t$$

where $X_t = I \otimes \begin{bmatrix} \mathbf{1} & \Pi_{t-1} & G_{t-1} & R_{t-1}^s & \Pi_{t-2} & G_{t-2} & R_{t-2}^s \end{bmatrix}$,

$\mathbb{E}\varepsilon_t\varepsilon_t' = I$, and I is a 3×3 identity matrix.

Let $\alpha_t = \begin{bmatrix} \alpha_{g\pi,t} & \alpha_{r\pi,t} & \alpha_{rg,t} \end{bmatrix}'$ be 3×1 vector containing the elements of A_t different from zero or one, and $\sigma_t = \begin{bmatrix} \sigma_{\pi,t} & \sigma_{g,t} & \sigma_{r,t} \end{bmatrix}'$ be 3×1 vector collecting diagonal elements of $\mathbf{\Sigma}_t$. The dynamics of the time-varying parameters are governed by the following process:

$B_t = B_{t-1} + \nu_t$

$\alpha_t = \alpha_{t-1} + \zeta_t$

and

$log\ \sigma_t = log\ \sigma_{t-1} + \eta_t,$

where all the uncorrelated innovations are assumed to be jointly normally distributed, with

$$V = \begin{bmatrix} \varepsilon_t \\ \nu_t \\ \zeta_t \\ \eta_t \end{bmatrix} \begin{bmatrix} \varepsilon_t' & \nu_t' & \zeta_t' & \eta_t' \end{bmatrix} = \begin{bmatrix} I & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & Q & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & S & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & W \end{bmatrix}$$

where $\mathbf{0}$ denotes matrices of zeros, Q is 21×21, S is 3×3, and W is 3×3 and diagonal. Following Primiceri (2005), it is assumed that S is block-diagonal in the following form:

$$S = \begin{bmatrix} s_{1,1} & 0 & 0 \\ 0 & s_{2,2} & s_{2,3} \\ 0 & s_{3,2} & s_{3,3} \end{bmatrix}$$

where $s_{i,j}$ are non-zero elements on line-i and row-j of matrix S. Hence, the two diagonal blocks are given by the following matrices:

$S_1 = s_{1,1}$ and $S_2 = \begin{bmatrix} s_{2,2} & s_{2,3} \\ s_{3,2} & s_{3,3} \end{bmatrix}$, where $s_{2,3} = s_{3,2}$

Moreover, W is diagonal with elements $w_{i,i}$ for $i = 1, 2, 3$.

As a whole, Q has 231 distinct elements, S has four distinct non-zero elements, and W has three distinct non-zero elements.

Estimation strategy

Bayesian methods are often used to estimate large numbers of parameters in classical VAR models because of their strong explanatory and predictive powers. In this paper, I follow the same approach than in Primiceri (2005) and Cogley and Sargent (2005) to be able to deal with autoregressive models with time-varying coefficients. The aim of the estimation strategy is to assess the posterior distribution of the parameters, based on prior distributions calibrated with simple estimates on a training sample period consisting of the first ten years of data (equivalent to the first fourty quarters) to a time-invariant coefficients version of the reduced form model presented above. The, posterior distributions of parameters can be simulated by Markov Chain Monte Carlo algorithm, as detailed in Primiceri (2005) and Cogley and Sargent (2005). Following the same approach, prior distributions of parameters are obtained by running a fixed-coefficient system in the form:

$$y_t = X_t'B + A^{-1}\mathbf{\Sigma}\varepsilon_t$$

Applying OLS methodology to each equation in this system, I obtain an estimate $\hat{B}$ of the parameter vector B, and I use the same Cholesky decomposition shown previously to the covariance matrix of least-squares residuals to obtain estimates $\hat{\alpha}$ and $\hat{\sigma}$ of the parameter vectors α and σ.

Then, normal priors for the initial values of the coefficients are given by:

$B_0 \sim N(\hat{B}, 4\hat{V}_B)$

$\alpha_0 \sim N(\hat{\alpha}, 4\hat{V}_\alpha)$

and

$log\ \sigma_0 \sim N(log\ \hat{\sigma}, I)$

based on those used by Primiceri (2005).

For the block elements of the variance-covariance matrix of innovations V, inverse Wishart priors are defined as follows:

$Q \sim IW(22k_Q^2\hat{V}_B, 22)$

$S_1 \sim IW(2k_S^2\hat{V}_{\alpha,1}, 2)$

$S_2 \sim IW(3k_S^2\hat{V}_{\alpha,2}, 3)$

and

$w_{i,i} \sim IW(2k_w^2, 2)$

for $i = 1, 2, 3$, where $\hat{V}_{\alpha,1}$ and $\hat{V}_{\alpha,2}$ are the diagonal blocks of $\hat{V}_\alpha$. Also, the settings are given taken from Belongia and Ireland (2016), where $k_Q^2 = 0.00035$, $k_S^2 = 0.01$ and $k_W^2 = 0.0001$. Then, a "Metropolis-within-Gibbs" sampling algorithm is used on the remaining sample period starting from the priors given previously to compute blocks of parameters from their conditional posterior distribution. Again, the subsequent steps to obtain estimations for each parameters are well-described in Belongia and Ireland (2016). Draws for the parameters in Q, S and W are taken from their inverse Wishart conditional posterior distribution.

The model is estimated with 50,000 draws of each parameters for the Gibbs sampling. To assess the convergence of the Markov Chain, draws' inefficiency factors are computed across the four blocks of parameters in the sequences B^T, A^T, Σ^T, and in the elements from V. For each individual parameter θ, the ineffciency stastistic is defined as the inverse of the measure of relative numerical efficiency (Geweke, 1991):

$$IF(\theta) = 2\pi \frac{1}{\int_{-\pi}^{\pi} S_\theta(\omega) d\omega} S_\theta(0)$$

where $S_\theta(\omega)$ is the spectral density of θ at frequency ω. According to Primiceri (2005) and Benati (2011), inefficiency factors are said acceptable at or below 20. The statistics for hyperparameters in V are slightly higher than that upper bound, but those for the paramaters and shock covariances and volatilities are largely below it. Table 3 and table 4 containing the results are given in the Appendix.

Structural shocks identification

An approach based on sign restrictions on impulse responses is applied to identify structural disturbances. The technique is based on Rubio-Ramirez et al. (2010), Arias et al. (2018, 2019), and has been applied to VAR models with time-varying coefficients in Benati (2011). Sign restrictions on the impact of structural disturbances are directly given in Table 1.

Table 1: Sign restrictions on the impact effects of structural shocks:

Impact effect on	Structural shocks		
	Aggregate supply	Aggregate demand	Monetary policy
Inflation	+	+	-
Output gap	-	+	-
Shadow rate	?	+	+

Note: the symbol ? indicates that the response is left unconstrained

As a result, the reduced form covariance matrix is factored as :

$\Omega_t = C_t^{-1} D_t D_t' (C_t')^{-1}$

where the 3×3 matrix is no more lower triangular, but still with ones along its diagonal

$$C_t = \begin{bmatrix} 1 & -c_{\pi g,t} & -c_{\pi r,t} \\ -c_{g\pi,t} & 1 & -c_{gr,t} \\ -c_{r\pi,t} & -c_{rg,t} & 1 \end{bmatrix}$$

and the 3×3 matrix is still diagonal

$$D_t = \begin{bmatrix} \delta_{\pi,t} & 0 & 0 \\ 0 & \delta_{g,t} & 0 \\ 0 & 0 & \delta_{r,t} \end{bmatrix}$$

the three structural shocks now have an effect on inflation, output gap and the shadow rate.

Consequently, the structural model can be written is as:

$C_t y_t = \gamma_t + \Gamma_{1,t} y_{t-1} + \Gamma_{2,t} y_{t-2} + D_t \xi_t$

where $\gamma_t = C_t b_t$, $\Gamma_{i,t} = C_t B_{i,t}$, for $i = 1, 2$, and $\xi_t = \begin{bmatrix} \xi_t^{as} & \xi_t^{ad} & \xi_t^{mp} \end{bmatrix}'$ is a 3×1 vector of structural disturbances to aggregate supply, aggregate demand and monetary policy, with $\mathbb{E}\xi_t\xi_t' = I$, and I is a 3×3 identity matrix.

With estimation strategy and sign restrictions based on Belongia and Ireland (2016), the third row of the structural model is presented as a Taylor-type monetary policy rule:

$$\begin{aligned} R_t^s = \gamma_{r,t} + c_{r\pi,t}\Pi_t + \gamma_{1,r\pi,t}\Pi_{t-1} + \gamma_{2,r\pi,t}\Pi_{t-2} \\ + c_{rg,t}G_t + \gamma_{1,rg,t}G_{t-1} + \gamma_{2,rg,t}G_{t-2} \\ + \gamma_{1,rr,t}R_{t-1}^s + \gamma_{2,rr,t}R_{t-2}^s + \delta_{r,t}\xi_t^{mp} \end{aligned} \quad (3)$$

This Taylor-type rule prescribes a setting for the policy rate regarding to changes in inflation and output gap variables. It also includes lagged interest rate terms to capture persistence in the central banks behavior in monetary policy decisions. The time-varying estimation of the intercept $\gamma_{r,t}$ and of the coefficients from matrices $\Gamma_{1,t}$ and $\Gamma_{2,t}$ allows to assess changes to monetary policy that might have occured on the sample period. More precisely, this estimation permits disentangling changes in central bank responses to inflation versus output gap stabilization and the extent to which the central bank depart from its systematic behavior. Concerning the latter point, the deviations in the actual policy rate from the value dictated by the estimated monetary policy rule get picked up as monetary policy shocks in the equation.

Then, this equation is estimated with the data described in the following sections.

4 Data

4.a Monetary policy estimates away from ZLB

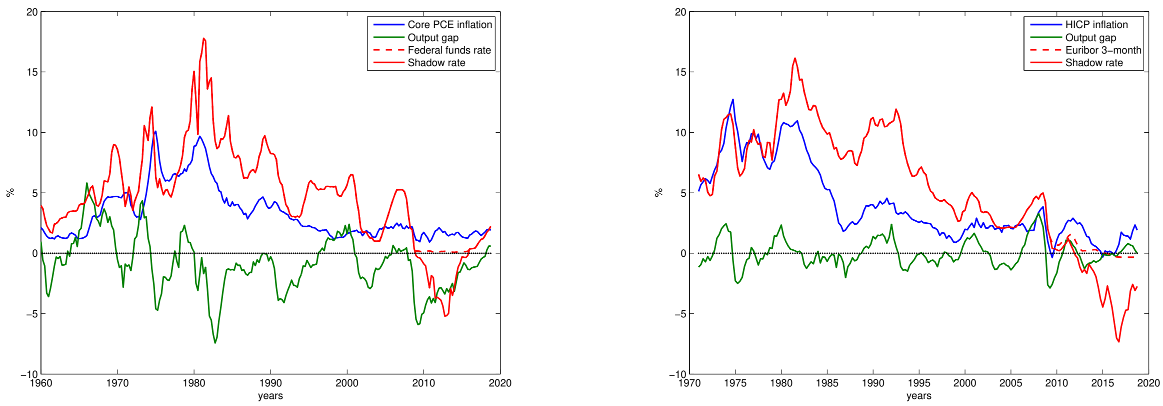
The US data are extracted from the Federal Reserve Economic Data (FRED) database, and run from 1960Q1 to 2018Q4. The interest rate is the federal funds rate. Core PCE inflation is taken as a relevant measure of inflation in the estimation[7], and is given as a percentage annual change. The output gap comes from the

[7] John B. Taylor claims that the Fed has not followed the prescription of the Taylor rule by keeping the interest rate too low from 2003 to 2005 and hence generated the housing bubble in the US. Ben Bernanke disagreed with that by

Congressional Budget Office (CBO).[8] Prior distribution of the coefficients are obtained from the training sample period from 1960Q1 to 1969Q4. Then, the Taylor rule is estimated by the TVP-VAR model with stochastic volatility from 1970Q1 to 2018Q4.

Concerning the Euro Area, interest rate, inflation and output gap data are from two main sources. The first one is the New Area-Wide Model (NAWM, Fagan et al., 2005) to get historical data from 1970Q1 to 2017Q4. Then, the data are uploaded to 2018Q4 with Eurostat. The main policy rate is the Euribor 3-month. Inflation is the Harmonized Index of Consumer Prices (HICP), and the real potential GDP is estimated with the HP filter (Hodrick and Prescott, 1997) to compute the output gap following the basic formula mentioned above. The period 1971Q1 to 1980Q4 is used as the training sample. The model is estimated from 1981Q1 to 2018Q4.

Figure 1: Inflation, output gap and policy rate



(a) US

(b) Euro Area

Figure 1 shows the evolutions of inflation, output gap and policy rates since 1960Q1 in the US and 1971Q1 in the Euro Area, respectively. Both interest rates and inflation lastingly decrease on the sample period in the US and the Euro Area. From a two-digits rate around the 1970s, core PCE deflation substantially decreases in the US to stabilize before the 2000s. Even though it is much more volatile, the federal funds rate followed

justifying that the Fed setted the interest rate according to the Taylor rule by targeting core PCE inflation, and not GDP deflator as in Taylor's estimations. For more details: `https://www.brookings.edu/blog/ben-bernanke/2015/04/28/the-taylor-rule-a-benchmark-for-monetary-policy/`. See also Tchatoka et al. (2017)

[8] The output gap is constructed following the basic formula $gap_t = \frac{Y_t - Y_t^*}{Y_t^*}$ that can be approximated by $gap_t = log(Y_t) - log(Y_t^*)$, where Y_t is the real output and Y_t^* the real potential output at time t.

a similar path on the period before reaching the ZLB at the end of 2008. The interpretation is quite the same concerning the Euro Area: we observe a downward trend in the HICP and Euribor 3-month since the 1980s. However, unlike the Fed, the ECB just managed to stabilize inflation rate around its target level of 'below, but close to, 2% over the medium term' after dealing with deflation in 2015 and 2016. Moreover, the ECB gradually decreased interest rates to their lowest level only in 2012, while the Fed started tapering at this time.

4.b Unconventional monetary policies and shadow rates

Since the data cover the period up to 2018Q4, the estimation results capture both conventional and unconventional aspects of monetary policy. Therefore, a major concern is the constrained policy rate at the zero level during periods of unconventional measures. Because of the 'flat' interest rates at the ZLB, usual policy rate does not entirely reflect central banks' actions during unconventional times, and hence leads to biased monetary policy rule estimation. Unconventional measures have been characterized by the use of 'non-standard' instruments (i.e. other than the policy rate), mainly large scale assets purchases (LSAP) or forward guidance (FG), to fulfill the stated objective given by central banks' mandate. Consequently, and to be able to estimate the Taylor-type rule up to 2018Q4, the policy rate instrument is proxied by the shadow short rate from Krippner (2013)[9], constructed as an extrapolation of the yield curve in the negative territory, and hence taking into account unconventional measures.

Table 2: Outlines of monetary policy since the Great Recession

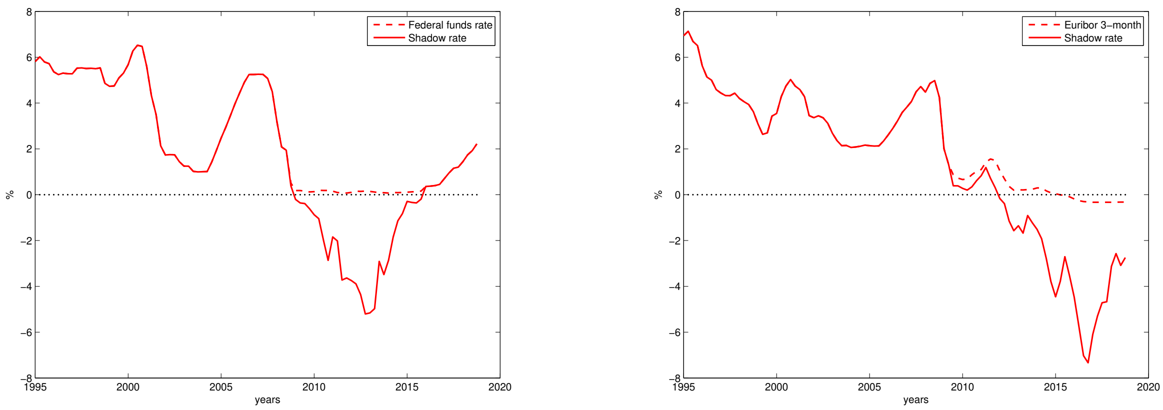
	Fed	ECB
1st LSAP after the financial crisis	Nov. 2008	July 2009
Tapering	Dec. 2012	Dec. 2016
Period of ZLB	Dec. 2008 - Dec. 2015	July 2012 - ?

Sources: Federal Reserve, European Central Bank, Chen et al. (2017a).

[9]Shadow short rates data are available on the Leo Krippner's webpage: https://www.rbnz.govt.nz/research-and-publications/research-programme/additional-research/measures-of-the-stance-of-united-states-monetary-policy/comparison-of-international-monetary-policy-measures

Table 2 gives the outlines of US and Euro Area monetary policies since the 2008-crisis. It shows when the Fed and the ECB launched their main non-standard measures, and when they decided to reduce the magnitude of these mesasures. The Fed reacted quickly to the financial crisis by implementing its first assets purchases programme (QE1, for 'Quantitative easing') of \$600 billion. In the Euro Area, the ECB enhanced credit support in October 2008 and lengthened the maturity of its longer-term refinancing operations (LTROs) in June 2009. However, the ECB only implemented its first assets purchases programme in July 2009 (CBPP1, for 'Covered-bond purchase programme'). Then, the Fed announced slowing down assets purchases in December 2012, before raising its policy rate in December 2015. On the other hand, the ECB announced tapering in end-2016. In 2018, monetary policy in the Euro Area was still at the ZLB.

Figure 2: Policy and shadow rates



(a) US (b) Euro Area

The shadow short rate (SSR) from Krippner (2013) is used as a proxy for unconventional measures of monetary policy in the TVP-VAR specification (Figure 1 and 2).[10] Interest rates used in the model follow the

[10]Several papers highlight the plausibility to use the shadow rate in a VAR model as a measure of the stance of monetary policy under the ZLB. For instance, Wu and Xia (2016), Lombardi and Zhu (2018) and Krippner (2019) show how estimated monetary policy shocks provide a realistic picture of the post-crisis macroeconomic situation. Basu and Bundick (2017) and Caggiano et al. (2017) investigate the macroeconomic effect of uncertainty at the ZLB. Forbes et al. (2018), Rogers et al. (2018) and Pasricha et al. (2018) find empirical evidence of monetary policy effects at the international level. Georgiadis (2016), Horvath and Voslarova (2016), Potjagailo (2017) focus on global spillovers of unconventional monetary policies in the US and the Euro Area. Plante et al. (2017), Caraiani and Călin (2018) and Crespo Cuaresma et al. (2019) incorporate shadow rates in a TVP-VAR model. Similarly,

policy rate in normal times, and are replaced by the shadow rate at the ZLB. In the US, the federal funds rate is replaced by the shadow rate from November 2008 to November 2015. In the Euro Area, the Euribor 3-month is replaced by the shadow rate in July 2009. This dates are consistent with informations contained in Table 2. To fit the rest of the data, quarterly rates are constructed as three-month averages on the whole sample period.

As discussed in Halberstadt and Krippner (2016), Bauer and Rudebusch (2016) and Krippner (2019), shadow rates are very sensitive to the choices made in their estimation. These choices are related to several factors, such as the way to compute the lower bound or the range of rates included in the dataset. Robustness of the estimates to the choice of the shadow rate are checked in the Appendix.

5 Results

5.a Monetary policy in the US

Figure 3 show the evolution of the contemporaneous responses of the shadow rate to movements in inflation (Figure 3a) and output gap (Figure 3b) in the United States, respectively. Figure 3c plots the time-varying standard deviations of the disturbances. Referring to the equation of the monetary policy rule, this figure tracks the volatility of monetary policy shock in the US.

First, the focus is on the magnitude of the short-run coefficients. The contemporaneous response of the Fed to inflation is higher than the response to output gap fluctuations. However, regarding Table 5 (see Appendix), the response to the current output gap has been more stable than the response to inflation before the crisis. Indeed, the probability for the median coefficient in 2009 of being higher than the median coefficient in 2013 is at 19% for inflation and at a lower level of 12% for the output gap. This result is not surprising when the focus is on the median coefficients themselves: the median coefficient on inflation goes from 0.87 in 2009 to 1.50 in 2013, before falling to 0.54 in 2017. This coefficient is 0.52, 0.80 and 0.40 for the output gap, respectively. As a whole, contemporaneous coefficients in the US over the last two decades follow a path that is comparable to the one during the Volcker-Greenspan era in terms of magnitude (see Figure 14 in Appendix).

Concerning monetary policy shock, Figure 3c shows the sharp increase in the volatility of the shock. Table 6 (see Appendix) gives quantitative assessments about this shift: the mean of the coefficient is 0.29 before 2008 and 0.62 between 1995 and 2008.

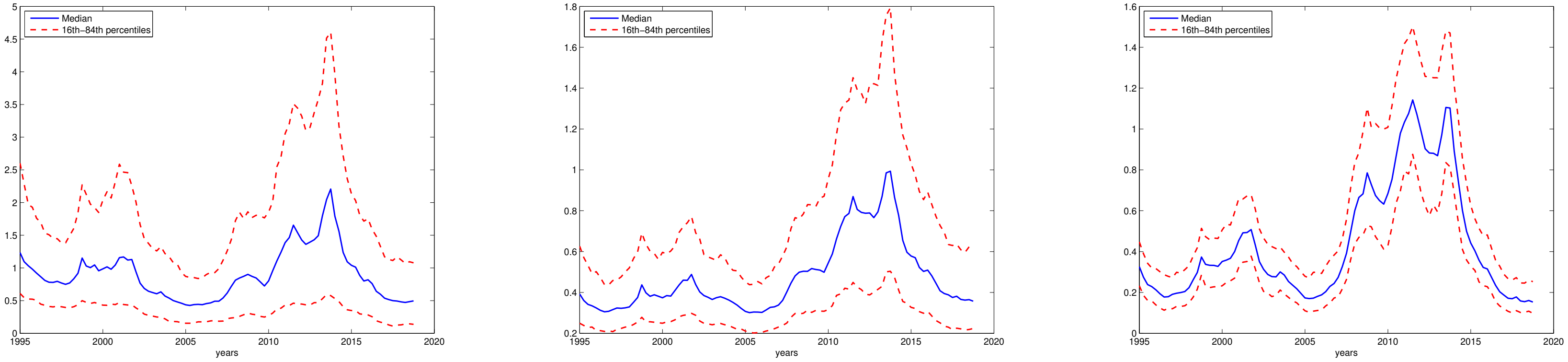
shadow rates can also be used in estimated DSGE models, as in the recent paper of Mouabbi and Sahuc (2019).

Interest rate smoothing (Figure 4a) is given by the sum of the coefficients associated to lagged interest rate terms. The higher the sum, the more the central bank uses gradualism in its decisions. We can observe that the Fed has adopted a more cautious behavior since the start of the Great Recession by setting interest rates in a more gradual way. The median coefficients is equal to 0.91 in 2009, 0.93 in 2013, and around 0.95 in 2017 as given by the Table 5.

The long-run coefficients are presented in Figure 4b for inflation and Figure 4c for the output gap. As for the short-run coefficients, long-run responses of the shadow rate to inflation and the output gap are more agressive in periods of crisis and unconventional monetary policy. Moreover, the response to inflation is still larger than the response to the output gap and the mean of the coefficients is still higher after the Great Recession for both responses, as shown in Table 6. The long-run coefficient on inflation was at 1.57 before the 2008 crisis on average, before reaching 1.95 on the post-crisis subperiod. Note that the mean coefficient of 1.74 over the whole period is consistent with the Taylor principle. Concerning the long-run response to the output gap, the coefficient is a little bit smaller than the one on inflation, but follow the same path. As a whole, the interpretation of long-run coefficients is quite the same as the interpretation of contemporaneous coefficients given above.

Figure 13c (see Appendix) plots the time-varying inflation target fot the core PCE price index, defined by Cogley and Sargent (2005) ans Cogley et al. (2010) as the stochastic trend towards which inflation would gravitate based on draws of parameters for each period. The estimated inflation target has fluctuated around 2% over the period. Table 5 and the figures in Appendix bring some evidence for a stable inflation target on the period, with median inflation rate at 2.11, 2.38 and 2.45 in 2009, 2013 and 2017.

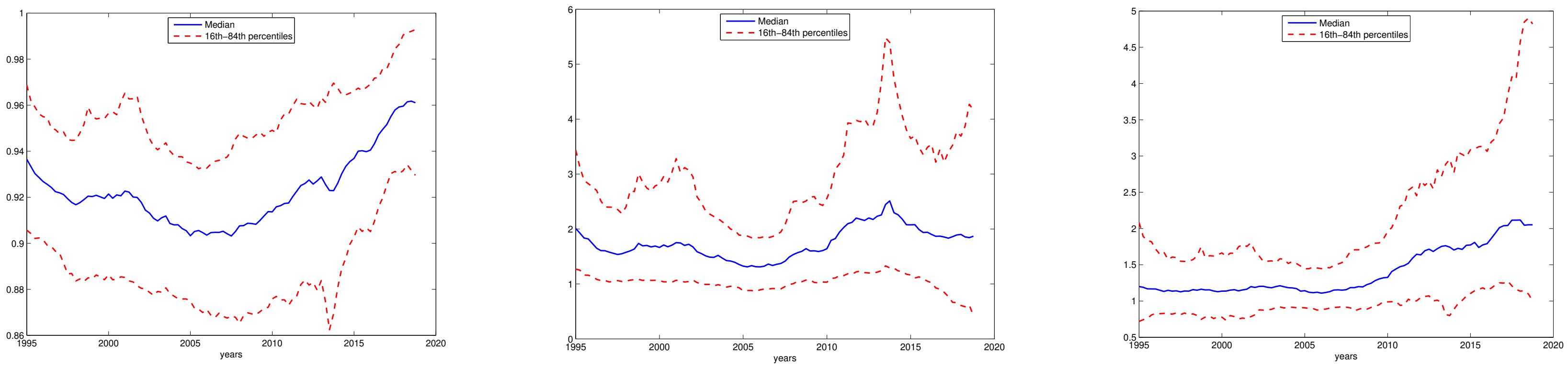
Figure 3: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility in the US since 1995Q1



(a) Contemporaneous coefficient on inflation (b) Contemporaneous coefficient on the output gap (c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

Figure 4: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule in the US since 1995Q1



(a) Interest rate smoothing (b) Long-run coefficient on inflation (c) Long-run coefficient on the output gap

Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

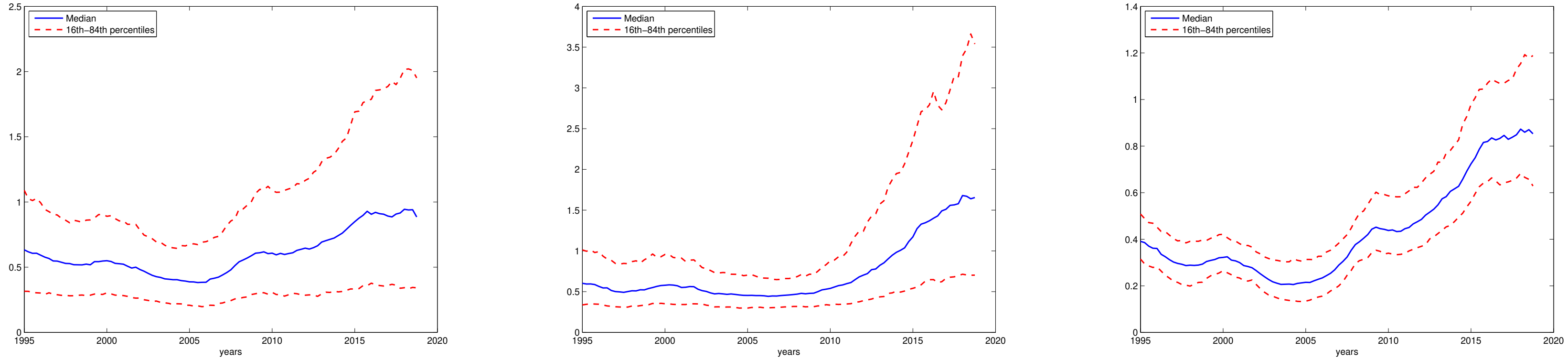
5.b Monetary policy in the Euro Area

Estimated contemporaneous coefficients on inflation and output gap in the Euro Area are plotted on Figure 5a and Figure 5b. They highlight growing ECB's reaction to inflation and output since the Great Recession. Table 7 (see Appendix) shows that short-run coefficients are 0.61 and 0.89 on inflation in 2009 and 2017, where the coefficients are 0.48 and 1.51 on the outptut gap in 2009 and 2017. Graphically, we can see that the latter coefficient sharply increased during the Great Recession, in a greater proportion than the coefficient on inflation. In some sense, this result is consistent with Drakos and Kouretas (2015) in which the ECB shifted its focus on output gap during the post-crisis period. As the ECB is still dealing with unconventional measures, short-run coefficients stay at a high level in the Euro Area. Considering the whole sample period of estimation, the contemporaneous coefficient on inflation in the Euro Area at the end of the period reached a level comparable to the one observed almost fourty years ago. On the other hand, the contemporaneous coefficient on output has been flat since years before reaching an all time high at the end of the sample period (see Figure 16 in Appendix). Monetary policy shock volatility follows a similar path than the short-run coefficients. It has increased continuously since the 2008 crisis, as shown in Table 8 (see Appendix).

However, the interpretation in terms of magnitude of the coefficients is not same when we consider long-run responses to inflation and output. Indeed, although the contemporaneous coefficient is higher for output than for inflation, the long-run coefficient is high for inflation than for output gap especially after the crisis (Table 8). Here again, the Euro Area seems to be in an inertia interest rates situation, where the coefficient on the lagged shadow rate has hugely increased since 2009. The results of a more anti-inflationary and gradual monetary policy in the last decades are consistent with Avouyi-Dovi and Sahuc (2016), in which these changes in monetary policy in the Euro Area have been a major source of the change in the volatility of nominal variables.

Figure 13d (see Appendix) plots the estimated inflation target for the HICP in the Euro Area. The target is "below, but close to 2%" over the sample period (1.70 on average since 1995).

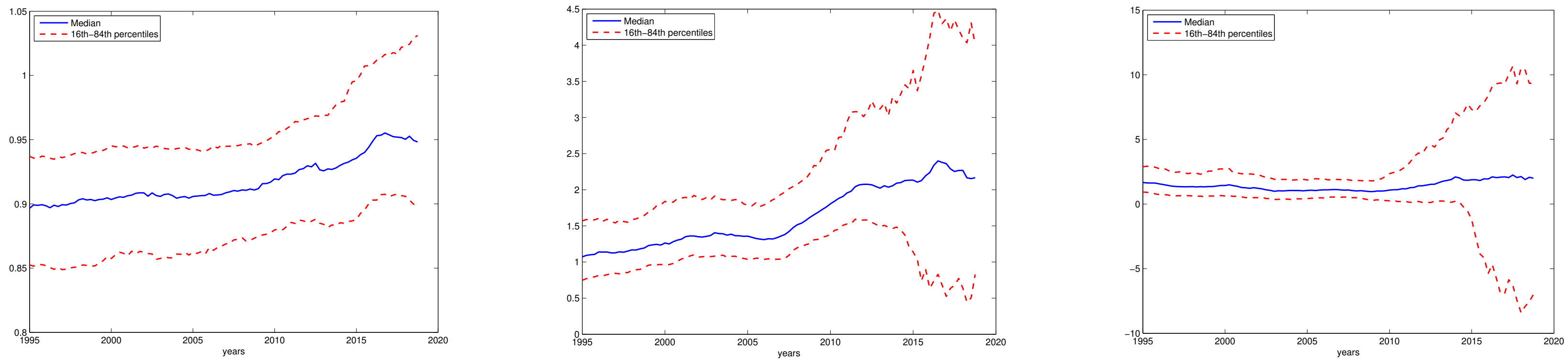
Figure 5: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility in the Euro Area since 1995Q1



(a) Contemporaneous coefficient on inflation (b) Contemporaneous coefficient on the output gap (c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

Figure 6: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule in the Euro Area since 1995Q1



(a) Interest rate smoothing (b) Long-run coefficient on inflation (c) Long-run coefficient on the output gap

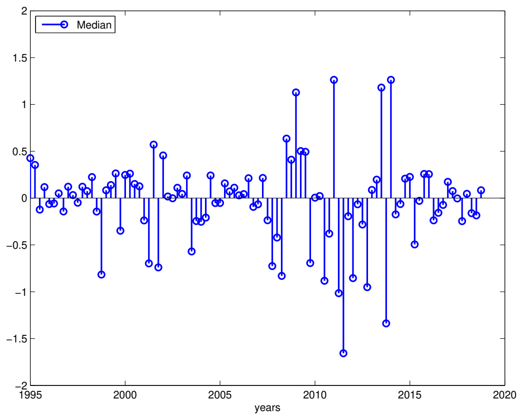
Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

6 A comparison between Fed's and ECB's behavior

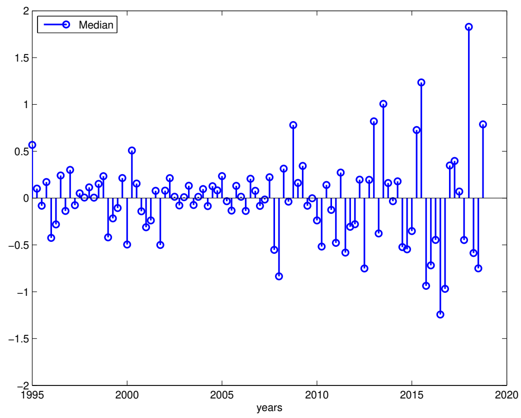
6.a US and Eurozone: how different are the conducts of monetary policy?

Figure 7 shows how monetary policy shocks seem to be more volatile during the ZLB period, that could illustrates the departure of the central bank from the behavior prescribed by the estimated policy rule. Negative monetary policy shock means that the central bank sets interest rate at a level below the rate prescribed by the estimated monetary policy rule. In that case, monetary policy is perceived as too expansionary. Regarding realized monetary policy shocks in the US and the Euro Area, we can graphically deduce that in both cases, monetary policy has been too expansionary for too long in the aftermath of the 2008 crisis. Then, potentially important deviations from the estimated policy rule during the post-crisis period and especially the ZLB.

Figure 7: Monetary policy shocks



(a) US



(b) Euro Area

Figure 8 and 9 compare contemporaneous and long-run coefficients from the estimated Taylor rule, monetary policy shock volatility and interest rate smoothing between the US and the Euro Area.

Focusing on contemporaneous responses to movements in inflation and the gap variables (Figure 8), short-run coefficients in the US follow a more volatile path than in the Euro Area: the Fed seems to response more agressively to inflation and output gap than the ECB, or at least behaves in a more discretionnary way. This interpretation is closely related to the "constrained discretion" raised by Ben Bernanke (Bernanke, 2003).[11]

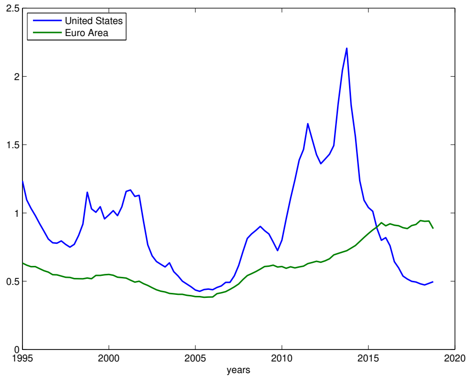
[11] The Fed seems having adopted a flexible behavior such as the inflation targeting objective may be de-emphasized in an output

Also, lagged unconventional monetary policy in the Euro Area comparing to the US leads to a gap between the timing of ECB's responses to inflation and output gap and the Fed's actions. Contemporaneous coefficients from the ECB monetary policy rule reached an all-time high at the end of the period of estimation, whereas they came back to a pre-crisis level in the US. This result is closely related to the timing of policy normalization in the US and in the Euro Area: the Fed began normalizing the stance of monetary policy at a time the ECB had not yet reached the ZLB. The interpretation of the explosive path of contemporaneous coefficients on output gap in the Euro Area is consistent with recent ECB's announcement of the future implementation of new series of targeted longer-term refinancing operations, called TLTRO-III, justified as a way to revive growth in the Euro Area. Even if this recent statement is out-of-sample, it shows that the ECB tends to focus a relatively higher attention on current growth than on contemporaneous inflation in the last quarters. The story is not the same regarding long-run coefficients on inflation and output gap, especially in the US where the they did not fully come back to its pre-crisis level during exit from unconventional monetary policy in the US (Figure 9). This result could be interpreted as the willingness for the Fed to avoid any deflationary episode.

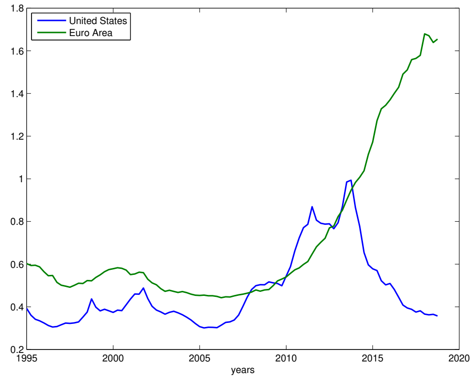
Finally, these results are consistent with a strand of the literature. Comparing the way the Fed and the ECB set their respective interest rates from 1999Q1 to 2005Q2, Belke and Polleit (2007) also find a very strong ECB's reaction to output gap fluctuations relatively to inflation, whereas the response to inflation is higher than to output gap in the US. They argue that the low weight on inflation in the Euro Area lead to interpret ECB's monetary policy as the one that prevailed during the pre-Volcker era of the Fed, characterized by a coefficient on inflation well below one and contrary to the well-known Bundesbank's inflation stabilising policy.

stabilization purpose under some circumstances. As Bernanke mentioned in its speech, "under constrained discretion, the central bank is free to do its best to stabilize output and employment in the face of short-run disturbances, with the appropriate caution born of our imperfect knowledge of the economy and of the effects of policy".

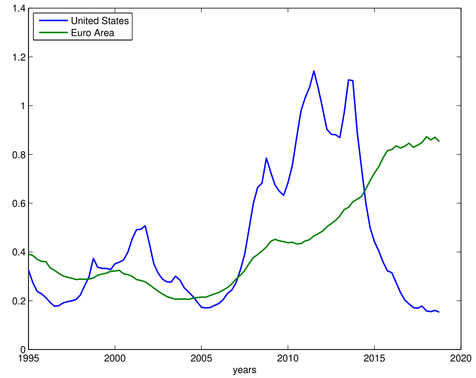
Figure 8: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility since 1995Q1



(a) Contemporaneous coefficient on inflation



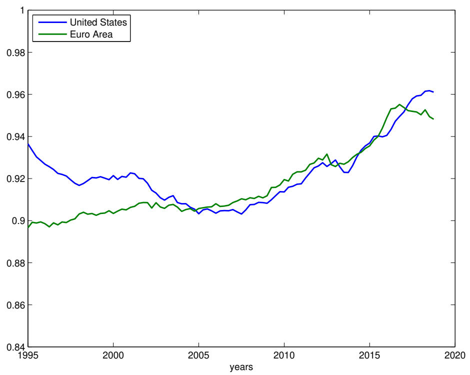
(b) Contemporaneous coefficient on the output gap



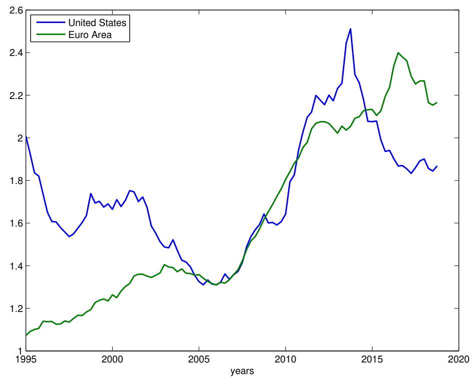
(c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

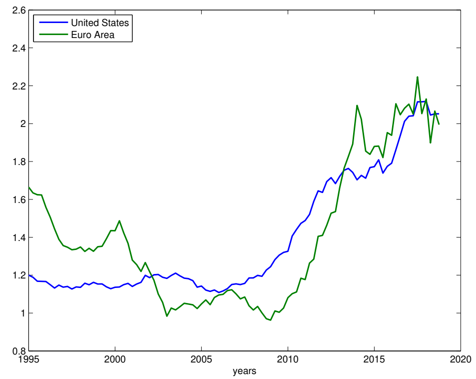
Figure 9: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule since 1995Q1



(a) Interest rate smoothing



(b) Long-run coefficient on inflation



(c) Long-run coefficient on the output gap

Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

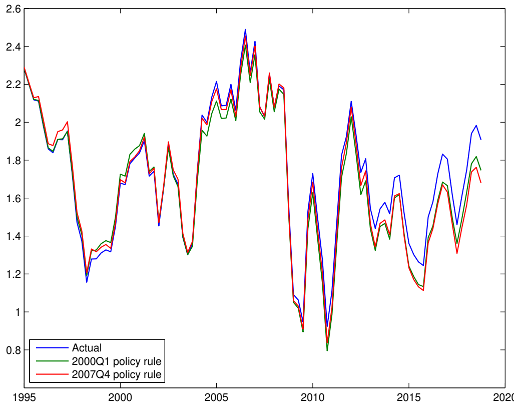
6.b Counterfactual analysis

The model with time-varying coefficients used in this paper allow a counterfactual analysis based on fixed coefficients in the estimated rule at reference date. For this purpose, I give the path that would have followed inflation, output gap and interest rate, in the US and the Euro Area, under two different scenarios. These scenarios explain what would happened if the central bank applied the 2000Q1 and 2007Q4 policy rule over the period, keeping fixed coefficients in the Taylor rule at each dates. The purpose of this exercise is to compare the counterfactual path of inflation, output gap and interest rate with the observed variables. The choice of dates for fixed monetary policy rule can be justified as relatively low coefficients in 2000Q1 and the pre-Great Recession date in 2007Q4.

Figure 10 gives all the counterfactuals for each variable of the model in the US and in the Euro Area. Concerning inflation rates (Figure 10a and 10b), there is no significant difference in the path according to the different scenarios in the US. Core PCE inflation would have been slightly lower than what has been observed after the crisis if the Fed would have kept fixed monetary policy rule in 2007Q4 or even 2000Q1. However, the result is quite impressive in the Euro Area. Changes in ECB's monetary policy had a huge impact on HICP, especially after the Great Recession: unconventional monetary policy rule has strongly reduced the delfationary risk in the Euro Area. More precisely, without any change in the ECB's behavior under unconventional monetary policy, the Euro Area would have suffered a period of deflation from 2014 to 2017. This result is consistent with Mouabbi and Sahuc (2019).

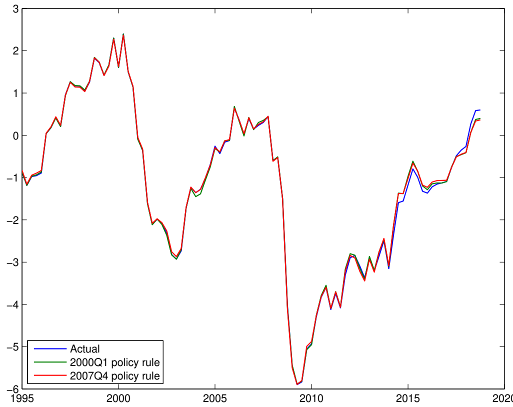
Concerning the output gap (Figure 10c and 10d), aggressive monetary policies implemented at the ZLB by the Fed and the ECB have led to positive output gap at the end of the period of estimation, whereas the Euro Area would have suffered negative output gap if the central banks would have kept the 2000Q1 or 2007Q4 monetary policy rule unchanged.

Figure 10: Counterfactual simulations

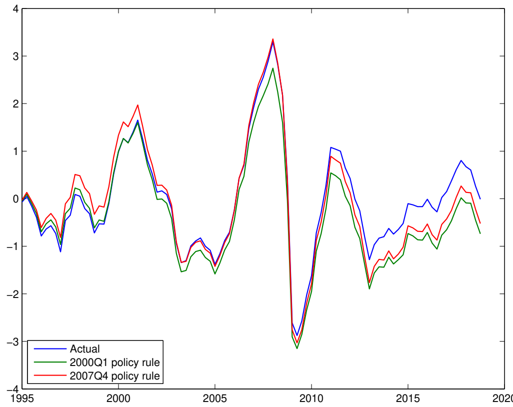


(a) Inflation in the US (Core PCE inflation)

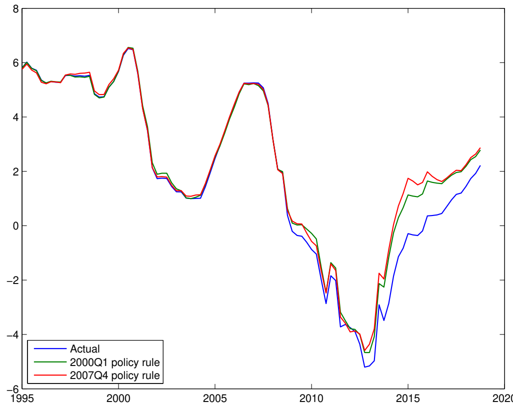
(b) Inflation in the Euro Area (HICP)



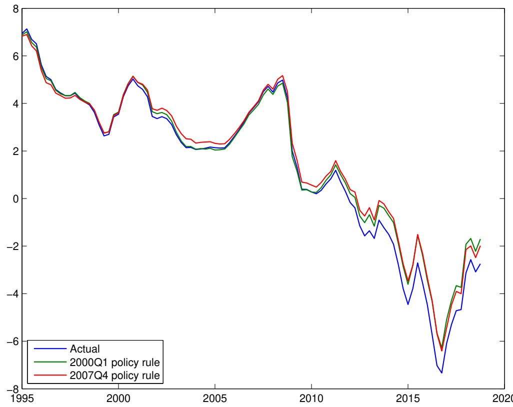
(c) Output gap in the US



(d) Output gap in the Euro Area



(e) Interest rate in the US (shadow rate)



(f) Interest rate in the Euro Area (shadow rate)

7 Conclusion

The issue of changes in central banks behavior can be explored by assuming that the central bank follows a Taylor-type rule to guide monetary policy decisions. According to this framework, the central bank focuses attention on macroeconomic fundamentals, such as inflation and output, to determine its target value for the interest rate. The behavior is characterized as the relative weight the central bank put on inflation or real activity when setting its policy rate. The time-varying paramater vector autoregressive model used in this paper gives some empirical assessments of the Taylor rule in the US and in the Euro Area. It allows a better understanding of monetary policy implementations by capturing changes in Fed's and ECB's behavior in the last decades. Since the period of estimation also covers the ZLB era, I use a shadow rate as a proxy for interest rate in my model. My empirical analyse shows that the Fed has behaved differently than the ECB since the Great Recession. Although the Fed announced starting tapering in end-2012, the ECB has not even reached the ZLB at this time. This shift in the timing of monetary policy normalization between the US and the Euro Area has led to a different path in the coefficients of the monetary policy rules: since the level of Fed's response coefficients went back to their pre-crisis level, the ECB is still in high-coefficients phase. However, counterfactual analysis shows in which extent changes in central banks behavior under unconventional measures have been efficient in the two economies, and especially in the Euro Area.

These results concerning changes in Fed's and ECB's behavior since the Great Recession raise some potential policy implications. First, the concern is about the nature and the efficiency of transmission mechanisms of monetary policy in the US and in the Euro Area. With interest rates close to zero, the main monetary policy instrument has changed with the implementation of unconventional measures, and probably challenged standard transmission mechanisms observed in normal times. Another policy implications is related to the question of international monetary policy coordination (Coeure, 2014). A cooperation between policies of the Fed and the ECB should rely on strong assumptions, such as common aspects in the transmission mechanisms both in the US and the Euro Area, similar mandates and objectives across the central banks or synchronized business cycles. The latter point is probably linked to the results shown previously and could be an explanation for the gap in the timing of monetary policy decisions between the Fed and the ECB. Such implications for the conduct of monetary policy are left for future research.

Appendix

A.1 Stability check with simple VAR analysis

A.1.1 VAR stability

Times series models are usually assumed to be stable over time. Here, the stability of the simple VAR model is checked. First, let's consider a simple VAR(2) model in the form:

$$y_t = b + B_1 y_{t-1} + B_2 y_{t-2} + u_t$$

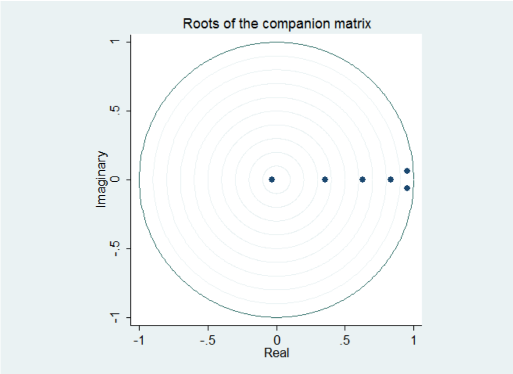
where $y_t = [\Pi_t \quad G_t \quad R_t^s]'$. Then, the companion form of the model can be given as:

$$\Xi_t = \mathbf{A}\Xi_{t-1} + \nu_t$$

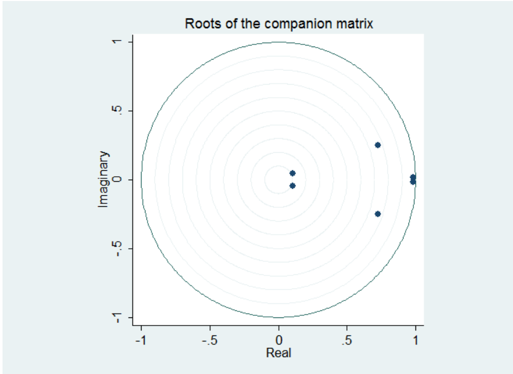
where $\Xi_t = \begin{bmatrix} \tilde{y}_t \\ \tilde{y}_{t-1} \end{bmatrix}$ with $\tilde{y}_t$ the mean corrected element of y_t, $\mathbf{A} = \begin{bmatrix} B_1 & B_2 \\ \mathbf{I} & 0 \end{bmatrix}$ is the companion matrix, and $\nu_t = \begin{bmatrix} u_t \\ 0 \end{bmatrix}$.

The determinant defining the characteristic equation is defined as $\left|\mathbf{A} - \lambda\mathbf{I}\right| = \left|\lambda^2\mathbf{I} - \lambda B_1 - B_2\right| = 0$. Hence, the required condition for the stability of the system is that the roots of the previous equation must lie inside the unit circle. The figures containing the results are given below. The six roots lie inside the unit circle insuring the stability of the VAR.

Figure 11: Roots of VAR(2) models



(a) US data



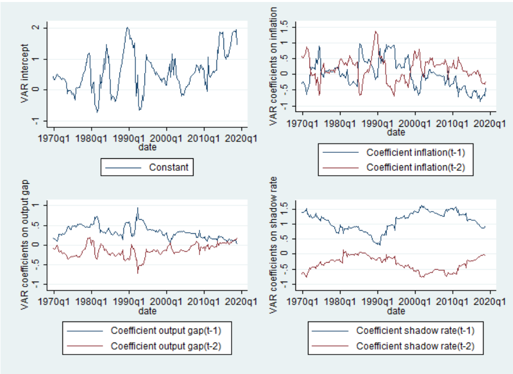
(b) Euro Area data

A.1.2 Rolling-window analysis for parameters stability

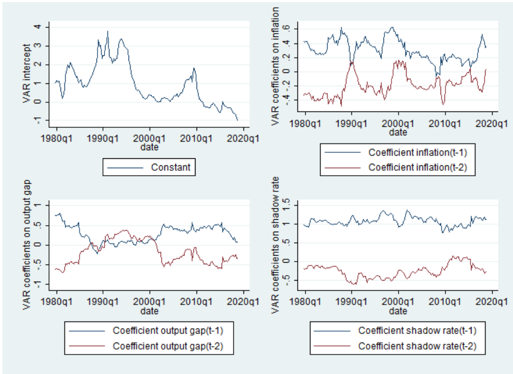
A common assumption in time series analysis is that the coefficients are constant with respect to time. Checking for instability allows to assess whether the coefficients are time-invariant. A rolling-window analysis is used to check the stability of the VAR(2) model described above.

First, the size of the rolling window – the number of consecutive observation per rolling window – is set to $m = 40$, that is consistent with the size of the training sample used in the TVP-VAR (40 quarters, 10 years). Then, the number of increments between successive rolling windows is set to one quarter, in a way that the entire sample is divided into $N = T - m + 1$ subsamples, where T is the sample size such that $t = 1, ..., T$. The results below give some insights on the path of coefficients running the VAR(2) with rolling-windows. The coefficients are subject to a high instability.

Figure 12: Coefficients of VAR(2) model with rolling-windows



(a) US data



(b) Euro Area data

The use of the VAR model with time-varying parameters is justified by the instability of the coefficients from the VAR with rolling windows (fixed windows). Moreover, it seems to be tricky to disentangle regime switches regarding the path of these coefficients on the estimation period. Hence, TVP-VAR estimation is an appropriate tool to investigate changes in the conduct of monetary policy over time. Note that the coefficients are also unstable when the monetary policy rule is estimated with OLS with rolling windows and sequential VAR estimation with recursive windows (increasing windows). The results are not reported here.

A.1.3 Statistical tests for parameters stability

Cogley and Sargent (2005) consider classical tests for variation in the parameters of their model. The purpose of this section is to apply some of those tests to US and Euro Area data used previously to give further insights on the paramaters stability.

Hence, one of the most prominent test that can easily be implemented after fitting a VAR is the Wald test. It allows to compute the Wald lag-exclusion statistics to test the hypothesis that the endogenous variables at a given lag are jointly zero for each equation and for all equations jointly. Testing stability on an equation-by-equation basis, the hypothesis that all three endogenous variables have zero coefficients at the first lag can be rejected at the 1% level for the three equations. Similarly, we strongly reject the hypothesis that the coefficients on the first and second lags of the endogenous variables are zero in all three equations jointly.

A.2 Tables

Table 3: Inefficiency factors (US data)

	Median	Mean	Min.	Max.	10th percentile	90th percentile
3150 Coefficients B^T	3.50	4.29	1.22	5.45	1.99	4.75
450 Covariances A^T	2.92	2.80	0.91	3.43	1.28	3.27
450 Volatilities Σ^T	6.45	6.61	2.85	7.58	4.59	7.18
238 Hyperparameters V	20.14	20.04	13.29	22.92	17.89	22.16

Table 4: Inefficiency factors (Euro Area data)

	Median	Mean	Min.	Max.	10th percentile	90th percentile
3150 Coefficients B^T	3.65	4.08	0.89	11.75	2.00	6.74
450 Covariances A^T	2.35	2.47	0.96	4.49	1.29	3.53
450 Volatilities Σ^T	6.32	6.86	2.10	14.89	4.37	10.78
238 Hyperparameters V	17.57	17.35	10.86	20.85	14.77	19.69

Table 5: Monetary policy rule parameters in the US (median)

	2009:1	2013:1	2017:1	Pr(2009:1 > 2013:1)	Pr(2009:1 > 2017:1)
Contemporaneous coefficient on inflation	0.87	1.50	0.54	0.19	0.69
Contemporaneous coefficient on the output gap	0.52	0.80	0.40	0.12	0.72
Interest rate smoothing	0.91	0.93	0.95	0.33	0.16
Long-run coefficient on inflation	1.60	2.24	1.86	0.21	0.43
Long-run coefficient on the output gap	1.25	1.72	2.04	0.24	0.16
Monetary policy shock volatility	0.73	0.87	0.19	0.35	1.00
Inflation target	2.11	2.38	2.45	0.30	0.28

Table 6: Monetary policy rule parameters in the US (mean)

	1970:1 - 2018:4		1995:1 - 2018:4		
	Sample	$< 2008{:}1$	Sample	$< 2008{:}1$	$\geq 2008{:}1$
Contemporaneous coefficient on inflation	1.04	1.04	0.90	0.78	1.05
Contemporaneous coefficient on the output gap	0.52	0.49	0.47	0.36	0.60
Interest rate smoothing	0.94	0.95	0.92	0.92	0.93
Long-run coefficient on inflation	1.78	1.73	1.74	1.57	1.95
Long-run coefficient on the output gap	1.37	1.28	1.39	1.16	1.68
Monetary policy shock volatility	0.72	0.75	0.44	0.29	0.62
Inflation target	2.44	2.47	2.16	2.02	2.32

Table 7: Monetary policy rule parameters in the Euro Area (median)

	2009:1	2013:1	2017:1	Pr(2009:1 > 2013:1)	Pr(2009:1 > 2017:1)
Contemporaneous coefficient on inflation	0.61	0.69	0.89	0.33	0.18
Contemporaneous coefficient on the output gap	0.48	0.82	1.51	0.08	0.03
Interest rate smoothing	0.91	0.93	0.95	0.31	0.16
Long-run coefficient on inflation	1.65	2.02	2.36	0.21	0.26
Long-run coefficient on the output gap	0.96	1.68	2.12	0.25	0.34
Monetary policy shock volatility	0.44	0.55	0.85	0.19	0.03
Inflation target	1.72	0.87	2.15	0.67	0.36

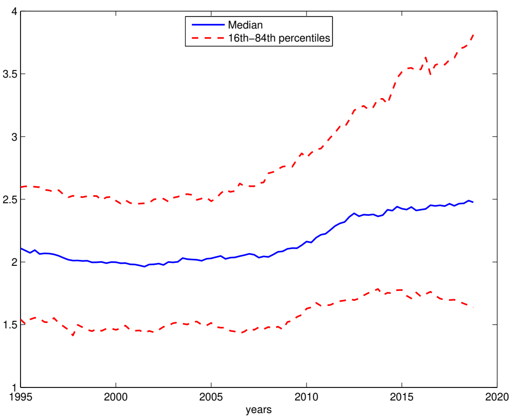
Table 8: Monetary policy rule parameters in the Euro Area (mean)

	1981:1 - 2018:4		1995:1 - 2018:4		
	Sample	< 2008:1	Sample	< 2008:1	≥ 2008:1
Contemporaneous coefficient on inflation	0.69	0.67	0.61	0.49	0.74
Contemporaneous coefficient on the output gap	0.64	0.50	0.73	0.51	0.98
Interest rate smoothing	0.91	0.90	0.92	0.90	0.93
Long-run coefficient on inflation	1.35	1.07	1.62	1.28	2.03
Long-run coefficient on the output gap	1.53	1.50	1.42	1.25	1.61
Monetary policy shock volatility	0.47	0.40	0.43	0.28	0.62
Inflation target	2.15	2.42	1.70	1.87	1.50

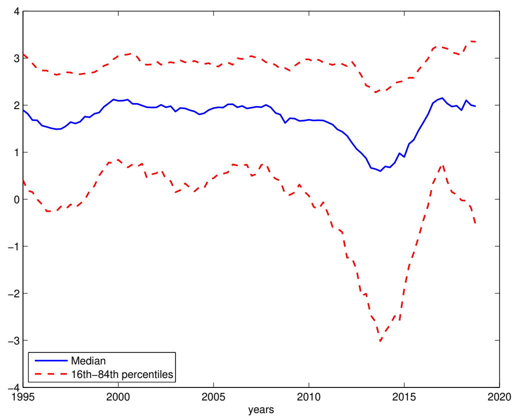
A.3 Figures

Next figures show the path of the estimated inflation target through the respective sample period both in the US and in the Euro Area.

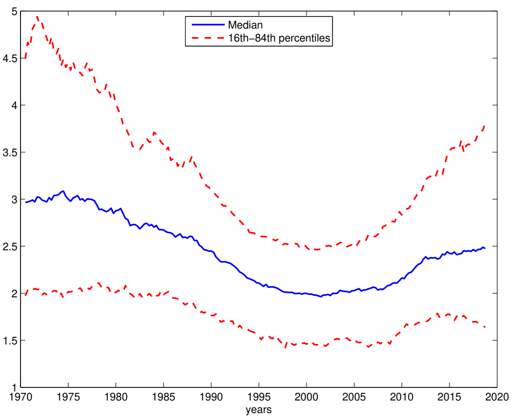
Figure 13: Estimated inflation target



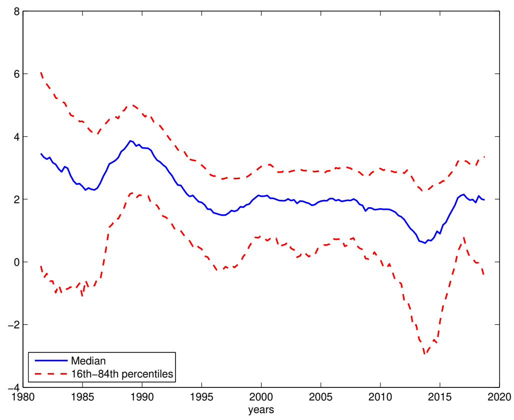
(a) US (since 1995)



(b) Euro Area (since 1995)



(c) US (since 1970)



(d) Euro Area (since 1981)

The estimated inflation target is defined as in Cogley and Sargent (2005) and Cogley et al. (2010). First, we can rewrite the TVP-VAR model in a companion form:

$$\mathbf{z}_{t+1} = \boldsymbol{\mu}_t + \mathbf{A}_t \mathbf{z}_t + \boldsymbol{\varepsilon}_{z,t+1}$$

where the vector $\mathbf{z}_t$ consists of current and lagged values of y_t (remember that y_t is a vector itself that is expressed as $y_t = [\Pi_t \quad G_t \quad R_t^s]'$, where Π_t is the inflation rate, G_t is the output gap and R_t^s is the shadow rate at period t), the vector $\boldsymbol{\mu}_t$ contains the intercepts, and the vector $\mathbf{A}_t$ includes the autoregressive paramaters. Assuming that the parameters will remain constant at their current values over a sufficiently long horizon h, we can define the stochastic trend in $\mathbf{z}_t$ as the value to which the series are expected to converge in the long-run, given by $\bar{\mathbf{z}}_t = \lim_{h\to\infty} E_t \mathbf{z}_{t+h}$.

Then, we estimate inflation target from local linear approximations to mean inflation at time t:

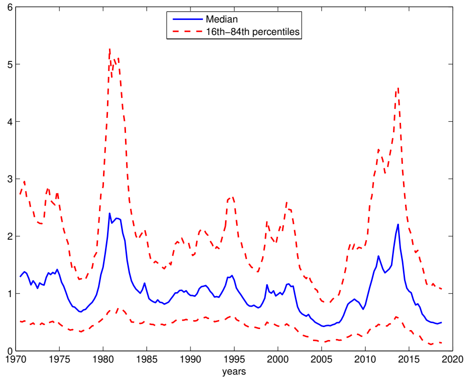
$$\bar{\mathbf{z}}_t \approx (\mathbf{I} - \mathbf{A}_t)^{-1} \boldsymbol{\mu}_t$$

The stochastic trend in inflation is interpreted as the estimated inflation target. Hence:

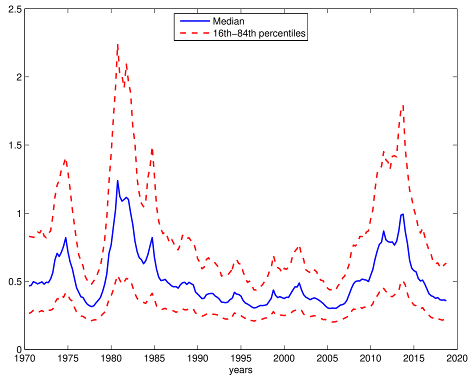
$$\bar{\boldsymbol{\Pi}}_t \approx s_\pi (\mathbf{I} - \mathbf{A}_t)^{-1} \boldsymbol{\mu}_t$$

where s_π is a selector vector that extract inflation from $\boldsymbol{z}_t$.

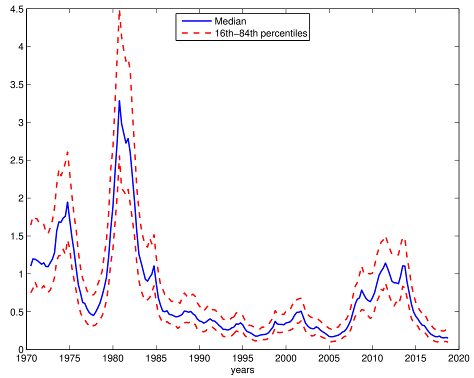
Figure 14: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility in the US since 1970 (whole sample period)



(a) Contemporaneous coefficient on inflation



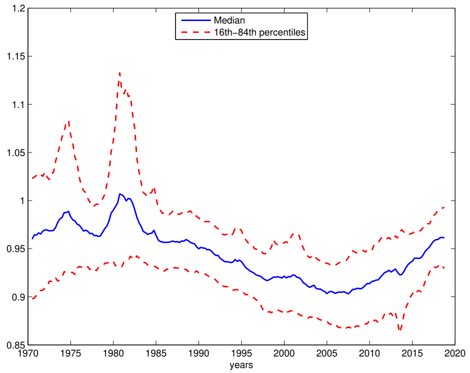
(b) Contemporaneous coefficient on the output gap



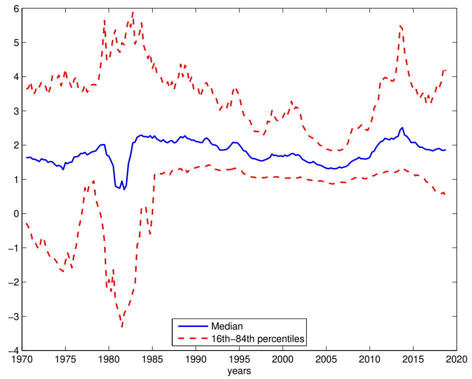
(c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

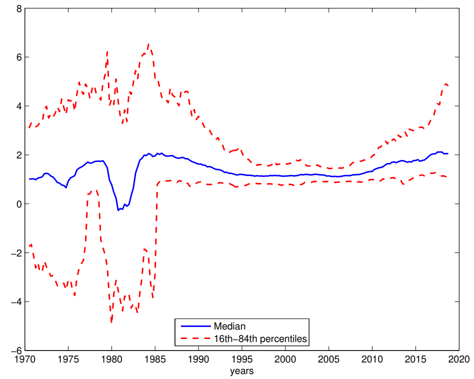
Figure 15: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule in the US since 1970 (whole sample period)



(a) Interest rate smoothing



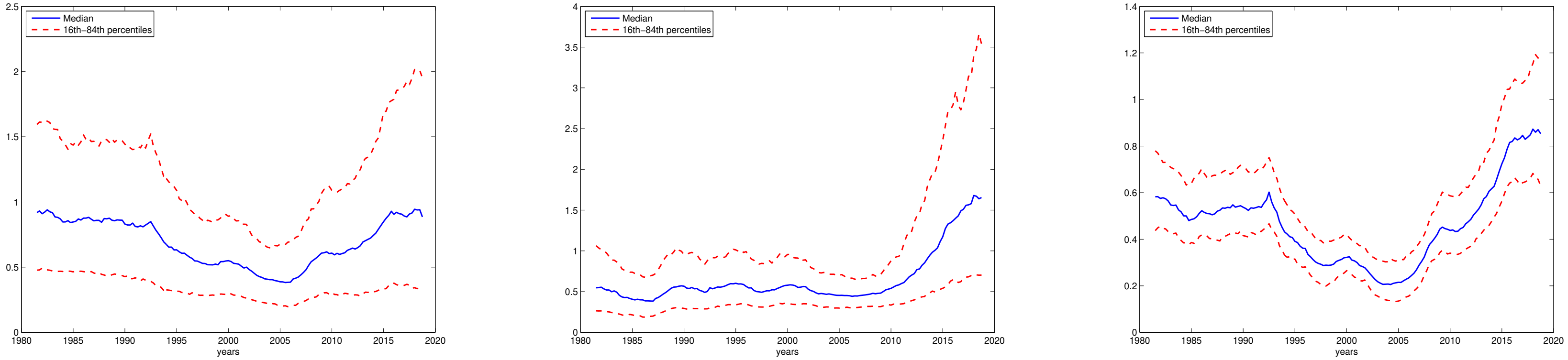
(b) Long-run coefficient on inflation



(c) Long-run coefficient on the output gap

Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

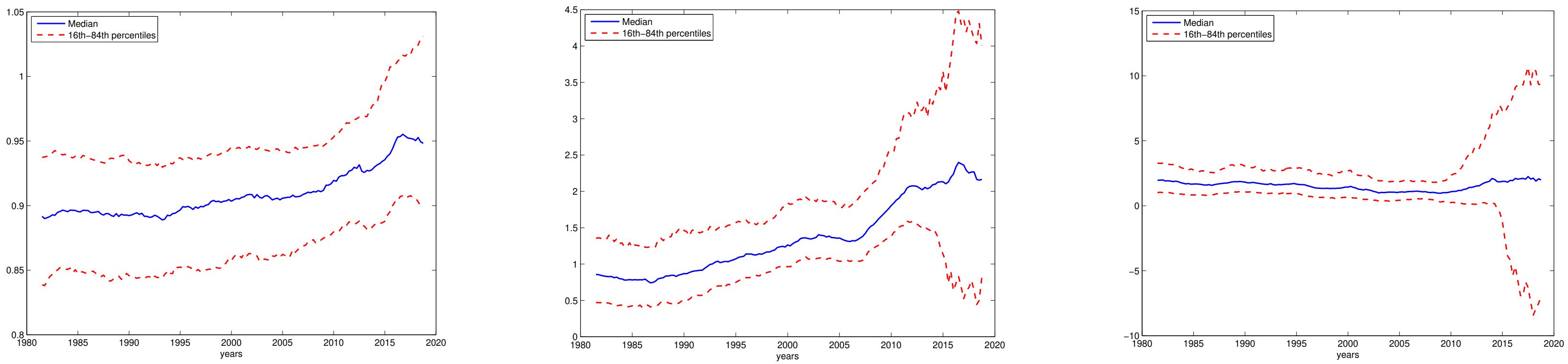
Figure 16: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility in the Euro Area since 1981 (whole sample period)



(a) Contemporaneous coefficient on inflation (b) Contemporaneous coefficient on the output gap (c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

Figure 17: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule in the Euro Area since 1981 (whole sample period)



(a) Interest rate smoothing (b) Long-run coefficient on inflation (c) Long-run coefficient on the output gap

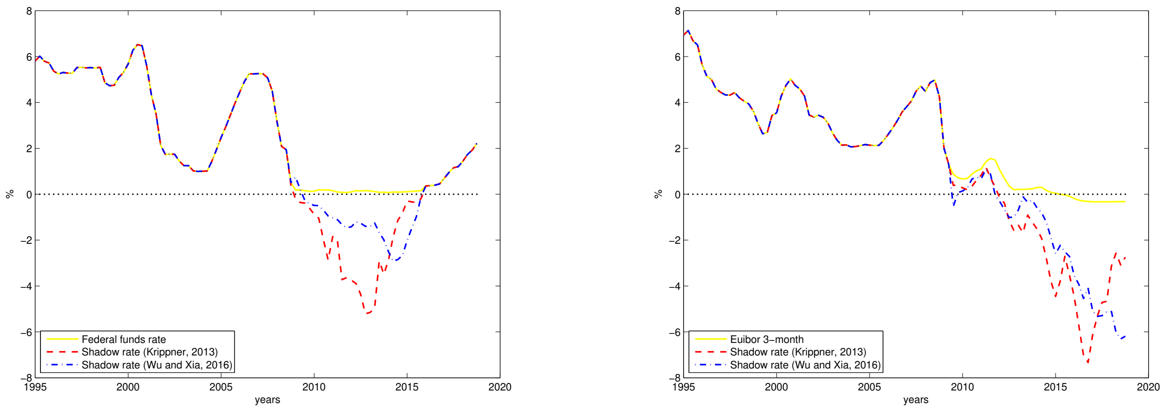
Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

B Robustness checks

B.1 Shadow rate (Wu and Xia, 2016)

The model is re-estimated with the shadow rate extracted from Wu and Xia (2016).[12] As discussed previously in this paper, this shadow rate follows a different path than the one used in the previous estimation (Figure 18)

Figure 18: Shadow rates

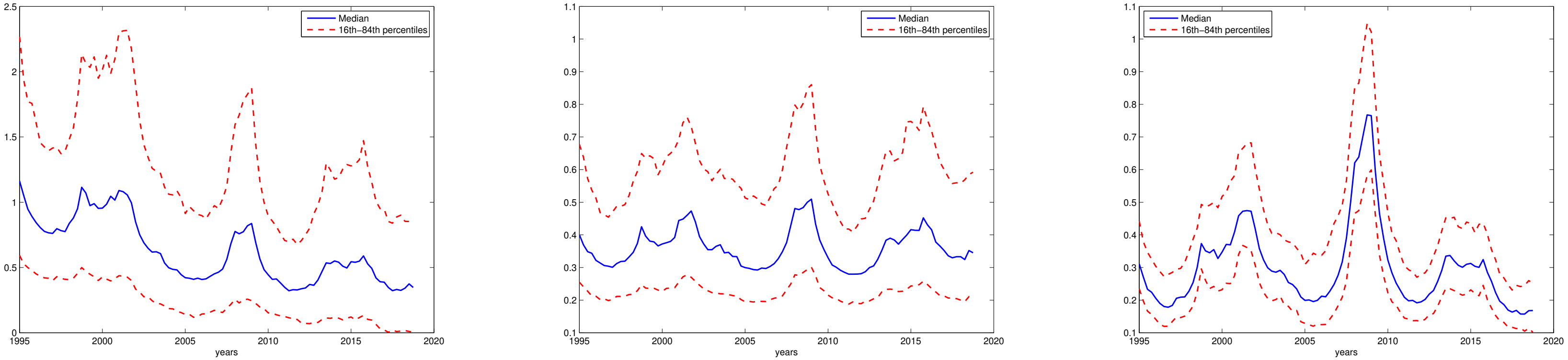


(a) US (b) Euro Area

Short and long-run coefficients are given by the following figures (19 to 22). Although the tables containing the mean and the median coefficients are not reported here, one can graphically deduce that the path of the coefficients from the model estimated with Wu and Xia's shadow rate are quite the same than the model estimated with Krippner's shadow rate, except concerning the peak after the 2008 crisis. Whereas the estimation with Krippner's shadow short rate gives contemporaneous coefficients at a level similar to the one observed in the early 1980s, the estimation with Wu and Xia's shadow rate gives post-crisis short-run coefficients without any obvious significant change during this period. However, the results seem to be robust to the shadow rate specification when considering the volatility of monetary policy shocks, interest rate smoothing and long-term coefficients on inflation and output.

[12]The US shadow rate data are available on Jing Cynthia Wu's webpage: `https://sites.google.com/view/jingcynthiawu/shadow-rates`. I am very grateful to her for providing Euro Area shadow rate data.

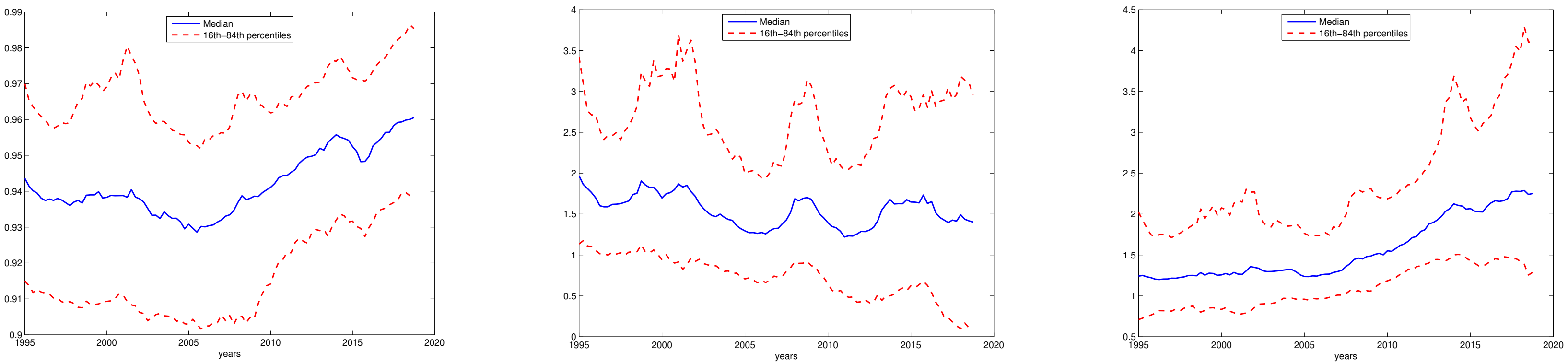
Figure 19: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility in the US since 1995Q1 (Wu and Xia's shadow rate)



(a) Contemporaneous coefficient on inflation (b) Contemporaneous coefficient on the output gap (c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

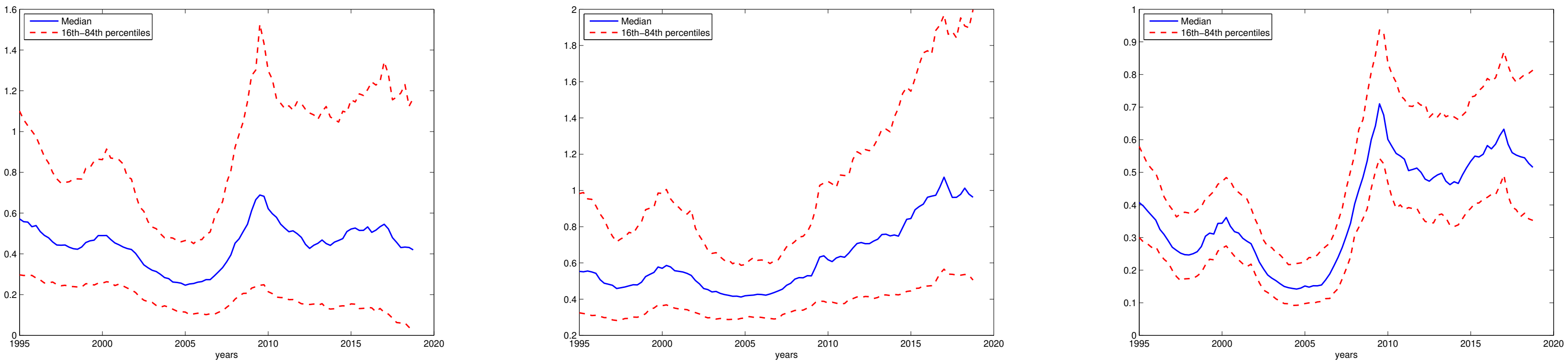
Figure 20: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule in the US since 1995Q1 (Wu and Xia's shadow rate)



(a) Interest rate smoothing (b) Long-run coefficient on inflation (c) Long-run coefficient on the output gap

Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

Figure 21: Contemporaneous coefficients from the estimated monetary policy rule and monetary policy shock volatility in the Euro Area since 1995Q1 (Wu and Xia's shadow rate)



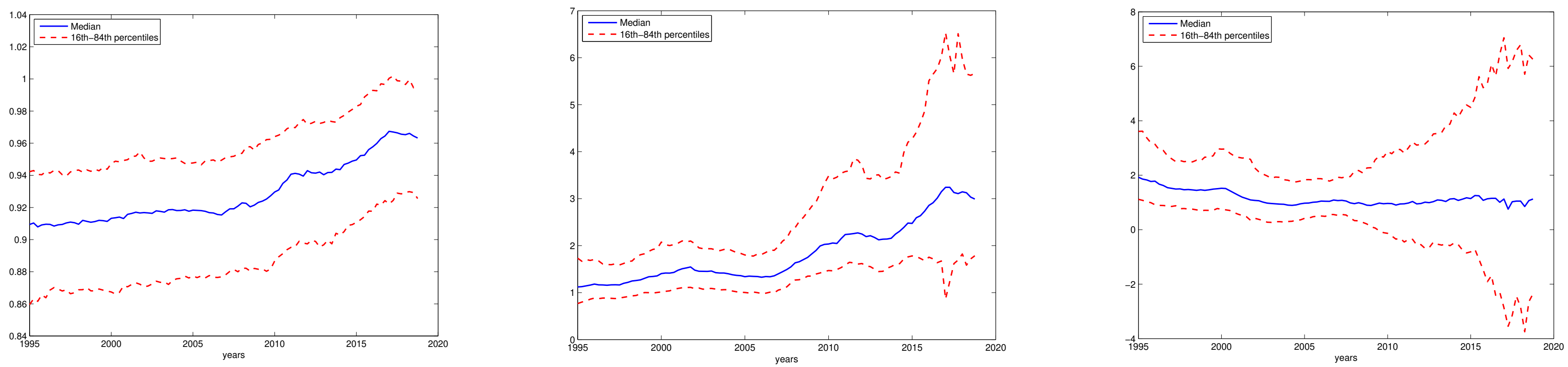
(a) Contemporaneous coefficient on inflation

(b) Contemporaneous coefficient on the output gap

(c) Monetary policy shock volatility

Note: Contemporaneous coefficients on inflation and output gap are respectively given by $c_{r\pi,t}$ and $c_{rg,t}$, and the volatility of monetary policy shocks is captured by $\delta_{r,t}$ in Equation (3)

Figure 22: Interest rate smoothing and long-run coefficients from the estimated monetary policy rule in the Euro Area since 1995Q1 (Wu and Xia's shadow rate)



(a) Interest rate smoothing

(b) Long-run coefficient on inflation

(c) Long-run coefficient on the output gap

Note: Interest rate smoothing is given by the sum $\gamma_{1,rr,t} + \gamma_{2,rr,t}$, and long-run coefficients on inflation and output gap are respectively given by $(c_{r\pi,t} + \gamma_{1,r\pi,t} + \gamma_{2,r\pi,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ and $(c_{rg,t} + \gamma_{1,rg,t} + \gamma_{2,rg,t})/(1 - \gamma_{1,rr,t} - \gamma_{2,rr,t})$ in Equation (3)

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