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# Forecast Uncertainty and the Taylor Rule*

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**Abstract**

In this paper, we derive a modification of a forward-looking Taylor rule by integrating two variables that measure the uncertainty of inflation and GDP growth forecasts into an otherwise standard New Keynesian model. We show that certainty-equivalence in New Keynesian models is a consequence of log-linearization and that a second-order Taylor approximation leads to a reaction function that includes the uncertainty of macroeconomic expectations. To test the model empirically, we use the standard deviation of individual forecasts around the median Consensus Forecast as a proxy for forecast uncertainty. Our sample covers the euro area, the United Kingdom, and the United States for the period 1990Q1–2016Q4. We find that the Bank of England and the European Central Bank have a significantly negative reaction to inflation forecast uncertainty. Our findings also reveal that the Federal Reserve (Bank of England) lowers (raises) its interest rate in response to higher GDP growth forecast uncertainty. We conclude by offering some implications for optimal monetary policy rules and central bank watchers.

**JEL Codes**: E52, E58.

**Keywords**: Certainty-Equivalence, Consensus Forecasts, Forecast Uncertainty, Global Financial Crisis, Optimal Monetary Policy, Taylor Rule.

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# 1 Introduction

The former Chairman of the Federal Reserve (Fed), Alan Greenspan, when writing about his inside view on how monetary policy is instituted, states that the Fed is well aware of the effects of uncertainty on macroeconomic variables (Greenspan 2004). Such uncertainties may stem from two sources. On the one hand, future values of macroeconomic variables are part of the central bank's policy objectives and their expectations influence current values. On the other hand, there are unobservable variables and problems with measuring the relevant variables in real-time.

The relevance of macroeconomic uncertainty for the rule formation of central banks has been extensively discussed in the theoretical literature. Swanson (2004) states that "a standard result in the literature of monetary policy is that of certainty-equivalence: Given the expected value of the state variables of the economy, policy should be independent of the higher moments of those variables." This view is based on a series of seminal papers. Orphanides (2003) shows that certainty-equivalence holds for linear-quadratic models with unobserved or real-time data and emphasizes that the independence of the parameters holds only if the optimal rule is based on the expected values of the macroeconomic variables rather than their measured values. Svensson and Woodford (2003) find that "the optimal response to the optimal estimate of potential output displays certainty-equivalence, whereas the optimal response to the imperfect observation of output depends on the noise in this observation."

These and all subsequent papers on certainty-equivalence deal with more or less complex, but still linear models of the economy. Central bankers consider this linearity to be a shortcoming of these models. Greenspan (2004), for example, states that when making their decisions, the Fed takes into account the insufficiencies of the commonly used linear macroeconomic models. Nevertheless, to this point in time and to the best of our knowledge, the certainty-equivalence principle holds for all derivations of monetary policy rules in linear New Keynesian models (NKM) (see also, the textbooks by Gali 2008 and Walsh 2010).

So far, few alternatives have been analyzed. For instance, Swanson (2004) shows that an exception to the result of certainty-equivalence is possible only if the policy rule is expressed in reduced form and relevant unobserved variables are estimated in a signal extraction sense. Consequently, our paper's first contribution is to close this gap between academic theory and the de facto behavior of central bankers. Our results indicate that a small deviation from log-linearization, the second-order approximation of the DIS, leads to a failure of certainty-equivalence. The basic intuition is quite simple. Log-linearizing the variables within the expectation operator eliminates higher order moments. In contrast, using a second-order Taylor approximation preserves the second moments and the variance remains relevant for the optimal policy rule.[1]

Accordingly, we present a modification of a forward-looking Taylor rule, which integrates two variables measuring the uncertainty of inflation and GDP growth forecasts into an otherwise standard NKM. One implication is that Taylor-type optimal policy rules should not ignore the uncertainty of macroeconomic variables when taking the cautious behavior of central bankers seriously. Because we do not rely on the signal extraction interpretation of the unobserved variables, but rather on a finer approximation of the optimization calculus, our policy rule is different from that developed by Swanson (2004). As a consequence, uncertainty enters the reaction function in Swanson's model (2004) via the weight of the level variables, whereas our approach allows for a separate reaction to forecast uncertainty.[2]

There has also been little research into the question of how central banks empirically deal with the uncertainty of macroeconomic forecasts in their reaction function. Extant papers on the Taylor rule (1993) and its modifications (see among many others, Clarida et al 1998 and Orphanides 2001) have focused on the point estimates of macroeconomic forecasts and ignored the uncertainty of these forecasts. To the best of our knowledge, there are only three exceptions. Branch (2014) augments a Tay-

[1]The results of Schmitt-Grohe and Uribe (2004), who discuss the properties of second-order Taylor approximations of a certain class of DSGE models, are not directly applicable to NKMs.

[2]We also use the dataset and empirical methodology described in Section 3 to estimate Swanson's model (2004). However, the resulting coefficients on the uncertainty weights are, if significant at all, not robust for the three different sets of estimations.

lor rule for the US with indicators of uncertainty obtained from the *Survey of Professional Forecasters*. He finds that the Fed negatively responded to both uncertainty in the inflation nowcast and uncertainty to the output gap nowcast during the period 1993Q1−2008Q3. In addition, Milas and Martin (2009) assume noise dependent coefficients for a rule based on expected values and find that the Fed responded less vigorously to inflation and the output gap when these variables are observed with less certainty during the period 1983Q1−2003Q4. Gnabo and Moccero (2015) find in a regime switching model that risk in the inflation outlook and volatility in financial markets are a powerful driver of monetary policy regime changes in the US.

Another branch of the empirical Taylor rule literature, which is closely related to this paper, includes work by Nobay and Peel (2003). If central bankers have an asymmetric loss function, this might translate into a reaction function with larger parameters for negative (positive) deviations of inflation or output from target compared to positive (negative) deviations, or into state-dependent parameters for contractions and expansions.[3] Such an asymmetric loss function might also be relevant in the context of macroeconomic forecasts. As mentioned before, monetary policy is supposed to be forward-looking. Consequently, policymakers have to deal with more or less certain forecasts when they determine the appropriate level of the policy rate. They have to decide whether to weigh the upward and downward risks of a forecast as balanced, or to give one of these risks more weight in formulating their decision. For instance, a high degree of inflation forecast uncertainty, and a relatively stronger aversion of overshooting the inflation target (IT), should translate into a positive reaction to the uncertainty of inflation expectations. Similarly, when the central bank is more recession-averse and observes a high degree of GDP forecast uncertainty it should lower its policy rate. From this point of view, there are also possible scenarios that might compel a central bank to react to the second moment of inflation or growth expectations.[4]

[3]Empirical contributions include, among others, Ruge-Murcia (2003) and Surico (2007a and 2007b).

[4]In addition, an asymmetric loss function can be relevant in the forecast-generating process, as well. See, for instance, Patton and Timmermann (2007) and Capistran (2008). If central bankers fear underpredicting inflation they will adjust their forecast of inflation up by a factor that increases in forecast uncertainty.

Given the scant empirical literature on how central bankers deal with the uncertainty of macroeconomic forecasts, the second contribution of our paper is to empirically test a forward-looking Taylor rule with inflation forecast uncertainty and GDP growth forecast uncertainty. For that purpose, we rely on the dataset of individual forecasters provided by *Consensus Economics* and use the standard deviation of individual forecasts around the median forecast as a proxy for forecast uncertainty.[5] Our sample covers, arguably, the three largest and most important central banks worldwide: the European Central Bank (ECB), the Bank of England (BOE), and the Fed for the period 1990Q1−2016Q4. Using this sample and time period allows us to compare not only the reaction to uncertainty of several central banks, but also to look at their forecast error risk aversion during normal times and during the episode of the global financial crisis and thereafter. Our results indicate that, in fact, real policy behavior accounts for uncertainty in accordance with the model's predictions. We find that the BOE and the ECB have a significantly negative reaction to inflation forecast uncertainty. Our findings also reveal that the Fed (BOE) lowers (raises) its interest rate in reaction to higher growth forecast uncertainty.

The remainder of our paper is divided into four sections. Section 2 presents the modified New Keynesian model. Section 3 introduces the data set and the empirical methodology. Section 4 discusses the empirical results, and Section 5 offers concluding remarks.

## 2 Theoretical Model

In this section, we present a modification of an otherwise standard NKM resulting in a monetary policy reaction function that includes the second moments of inflation expectations and GDP growth expectations.[6] The model setup follows Gali (2008).[7]

[5] These forecasts are a reasonable proxy for central bank forecasts, because professional forecasters have very similar backgrounds to staff economists at central banks.

[6] Other approaches, for instance, Swanson (2004), introduce uncertainty variables into a monetary policy rule based on a signaling approach and yield uncertainty dependent coefficients for inflation and output. Our approach allows us to separate the coefficients for inflation and output uncertainty.

[7] For simplicity of notation, we abstract from supply and demand shocks in Section 2. We present a solution with exogenous demand and supply shocks and unobservable error terms in Appendix A.

Similar to the conventional linear-quadratic approach, we use a *quadratic approximation* of the firm's objective function resulting in a *linearized* New Keynesian Phillips Curve (NKPC). In the standard approach, to get the same degree for the dynamic IS (DIS) curve and the NKPC, the DIS curve is derived using log-linearization, that is, a first-order approximation. This (alongside the central bank's quadratic loss function) would lead to a linear targeting rule. However, we differ from the standard setup by applying a *second-order approximation* to the households' Euler equation when deriving the DIS curve. This leads to a *quadratic* DIS and allows us to include second-order moments in the New Keynesian model.[8] As a consequence, certainty-equivalence no longer holds.

## 2.1 The New Keynesian Phillips Curve

### Consumer, Prices, and Aggregation

We start with a standard monopolistic Dixit-Stiglitz type competition model. Firms have pricing power on a continuum of differentiated goods indexed by $i \in [0,1]$. We assume that the elasticity of substitution between goods $\varepsilon > 1$ is constant and common amongst all economic subjects. $C(i)$ denotes the consumption level and $P(i)$ is the price of good $i$.[9] Consequently, the total expenditure on consumption is $\int_0^1 P(i)C(i)di$ and the composite consumption index $C$ is

$$C = \left( \int_0^1 C(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}}. \tag{1}$$

[8]Clearly, it would be preferable to apply a second-order approximation to the solution of the firm's objective function as well, resulting in a quadratic NKPC. However, the infinite sums of second-order polynomials in the modified FOC do not allow for a solution in terms of current and one-period ahead (expected) variables. The resulting NKPC would, on the one hand, include the variance of inflation and squares of the output gap and, on the other hand, infinite sums of future prices and other intermediate variables.

[9]To keep the notation as simple as possible we omit the time index as long as we treat only a single period.

The representative consumer minimizes the expenditure for $C$ units of aggregate consumption yielding the following Lagrangian

$$L = \int_0^1 P(i)C(i)di - \lambda\left(\left(\int_0^1 C(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}} - C\right). \tag{2}$$

Using the first-order conditions

$$P(i) = \lambda C(i)^{-\frac{1}{\varepsilon}} \left(\int_0^1 C(j)^{\frac{\varepsilon-1}{\varepsilon}} dj\right)^{\frac{1}{\varepsilon-1}} \tag{3}$$

results in

$$\frac{C(i)}{C} = \left(\frac{P(i)}{P}\right)^{-\varepsilon}, \tag{4}$$

which—after taking the $\frac{\varepsilon}{\varepsilon-1}th$ root and integration with respect to $i$—yields the price index

$$P = \left(\int_0^1 P(i)^{1-\varepsilon} di\right)^{\frac{1}{1-\varepsilon}}. \tag{5}$$

**The Firms' Problem**

$K$ denotes the firms' cost functions in real terms of quantities $Y(i)$ and $Z(i) \equiv K'(Y(i))$ the marginal costs. We assume that the log deviations of marginal costs from their long-run trend values $z(i)$ are linear, that is,

$$z(i) \equiv \ln Z(i) = \gamma y(i).$$

The firm's real profits are given by

$$\Pi(i) = \frac{P(i)Y(i)}{P} - K(Y(i)). \tag{6}$$

Since any single firm is too small to directly influence other firms or the whole economy, each firm takes the demand function and aggregate prices as given. It sets its own price $P(i)$ to maximize profits. Standard optimization yields a fixed mark-up over marginal costs:[10]

$$\frac{P(i)^*}{P} = \left(\frac{\varepsilon}{\varepsilon - 1}\right) K'\left(\left(\frac{P(i)}{P}\right)^{-\varepsilon} Y\right) = \left(\frac{\varepsilon}{\varepsilon - 1}\right) K'(Y(i)). \tag{7}$$

We denote the log deviation of individual prices and the price index from their long-term values by $p \equiv \ln P - \ln \overline{P}$ and $p(i) \equiv \ln P(i) - \ln \overline{P}$. Taking logs and substituting the demand function in logs $y(i) - y = -\varepsilon(p(i) - p)$ yields

$$p(i)^* - p = \left(\frac{\gamma}{1 + \varepsilon\gamma}\right)\widehat{y} = \alpha\widehat{y} \tag{8}$$

with $\alpha \equiv \left(\frac{\gamma}{1+\varepsilon\gamma}\right) \in [0, 1[$.

**Price Rigidity: Calvo Pricing**

Each firm has a constant probability $1 - \phi$ of being able to update its price in each period, and the turns are independently distributed among firms and periods. This implies a probability of $\phi^j$ for having the same price in $j$ periods as today. We denote the reset price as $x_t = p_t(i)$. This may deviate from the optimal price $p_t^*$ under flexible price setting, because firms will act on the probability of not to being able to adjust prices in future periods. Indeed, the optimal reset price is determined by the discounted sum of future profits. We use a quadratic approximation of the per-period deviation from maximum-possible profit with $\beta$ as discount factor

$$-\frac{c}{2}\sum_{j=0}^{\infty} \beta^j \phi^j E_t\left[\left(x_t - p_{t+j}^*\right)^2\right]. \tag{9}$$

The first-order condition yields

$$\begin{aligned} x_t &= (1 - \beta\phi)\sum_{j=0}^{\infty} (\beta\phi)^j E_t\left[p_{t+j}^*\right] \\ &= \beta\phi E_t\left[x_{t+1}\right] + (1 - \beta\phi)\, p_t^*. \end{aligned} \tag{10}$$

[10]Note that the steady state log marginal costs is equal to negative markup in logs: $z_{ss} = -\ln(\frac{\varepsilon}{\varepsilon-1})$.

We know from its definition and the definition of the price updating probability $\phi$ that the aggregate price level evolves according to

$$p_t = \phi p_{t-1} + (1-\phi) x_t. \tag{11}$$

Using (10) to substitute for $x_t$ yields

$$p_t - \phi p_{t-1} = (1-\phi)(\beta\phi E_t[x_{t+1}] + (1-\beta\phi) p_t^*). \tag{12}$$

(12) can further be simplified by defining inflation as $\pi_t \equiv p_t - p_{t-1}$ to

$$\pi_t = \beta E_t[\pi_{t+1}] + \left(\frac{(1-\phi)(1-\beta\phi)}{\phi}\right)(p_t^* - p_t). \tag{13}$$

Recalling the optimal price equation (8) and defining $\kappa \equiv \frac{\alpha(1-\phi)(1-\beta\phi)}{\phi}$ yields the NKPC

$$\pi_t = \beta E_t[\pi_{t+1}] + \kappa \widehat{y_t}. \tag{14}$$

## 2.2 The Quadratic DIS Curve

Households maximize their discounted expected utility $E_t \sum_{s=t}^{\infty} \beta^{s-t} U(C_s)$ under a dynamic budget constraint with the interest rate $i_t$. This leads to the Euler equation[11]

$$\frac{U'(C_t)}{P_t} = \beta(1+i_t) E_t\left(\frac{U'(C_{t+1})}{P_{t+1}}\right).$$

Consumption enters the utility as $C_t^{1-\sigma}$ with an elasticity of intertemporal substitution of $1/\sigma$ which yields

$$\frac{1}{\beta(1+i_t)} = E_t\left(\frac{P_t}{P_{t+1}}\left(\frac{Y_{t+1}}{Y_t}\right)^{-\sigma}\right). \tag{15}$$

We choose $\beta = \frac{1}{1+r}$ with $r$ being the real interest rate, so that the left-hand side of equation (15) yields $1 + r - i_t$, which is consistent with the long-run equilibrium. We

[11] Although the utility function could incorporate other factors, such as money or working hours, in a standard way, this would not influence our analysis since we rely only on the Euler equation.

define the growth rate $\Delta y_{t+1} = \ln Y_{t+1} - \ln Y_t$ and the output gap $\widehat{y_t} = y_t - y_{ss}$.[12]

$$r - i_t = E_t\left(\exp\left(-\pi_{t+1} - \sigma\Delta\widehat{y_{t+1}}\right) - 1\right). \tag{16}$$

We now deviate from the standard derivation of the DIS curve and use a quadratic approximation $\exp(x) \approx 1 + x + \frac{1}{2}x^2$.[13]

$$r - i_t \approx E_t\left(-\pi_{t+1} - \sigma\Delta\widehat{y_{t+1}} + \frac{1}{2}\left(\pi_{t+1} + \sigma\left(\Delta\widehat{y_{t+1}}\right)\right)^2\right). \tag{17}$$

Solving for the output gap yields the quadratic DIS (QDIS) curve

$$\widehat{y_t} = E_t\left(\widehat{y_{t+1}}\right) - \frac{1}{\sigma}\left(i_t - r - E_t\pi_{t+1}\right) - \frac{1}{2\sigma}E_t\pi_{t+1}^2 - \frac{\sigma}{2}E_t\left(\Delta\widehat{y_{t+1}}\right)^2 - E_t\left(\pi_{t+1}\Delta\widehat{y_{t+1}}\right). \tag{18}$$

The variance parameters enter the QDIS curve, but not the NKPC. In the derivation of the QDIS curve, we approximate the Euler equation, which includes non-$t$-measurable variables, that is, the future price level and future output. Consequently, higher order moments of these variables remain after the second-order approximation. In the derivation of the NKPC, we approximate the objective function around the $t$-measurable optimizing variable $x_t$ in the expectation operator and get a standard linear-quadratic optimization problem. Consequently, the first-order conditions are linear in $x_t$ and in the log price level. Therefore, the main difference in the microfounded derivation of both curves is that the approximated variable is $t$-measurable for the NKPC but not for the QDIS curve.

[12]It is straightforward to show that the growth rate of the output and the growth rate of the output gap is the same: $\Delta y_{t+1} = y_{t+1} - y_{ss} - (y_t - y_{ss}) = \Delta\widehat{y_{t+1}}$.

[13]This step is the crucial difference to the standard derivation of the DIS curve. If we apply a log-linearization, the term $\frac{1}{2}x^2$ would be left out. In this case, the term within the expectation operator would be linear and we are left with separated terms of expected inflation and the expected output gap, that is, the standard derivation of the DIS curve. Note, however, that including moments higher than second-order would make the model intractable.

## 2.3 Monetary Policy under Discretion

The central bank chooses its policy rate $i_t$ to minimize squared fluctuations of inflation around a constant target $\pi^*$, being set to zero for convenience, and squared fluctuations of the output gap weighted by $\delta > 0$:

$$\mathcal{L} = \frac{1}{2}\pi_t^2 + \frac{\delta}{2}\widehat{y_t}^2 \tag{19}$$

We assume that the central bank is unable to commit to the fully optimal, that is, inertial, policy plan. Instead, monetary policy operates under discretion and takes expectations of future inflation and future output as given.

Recall the NKPC (14) and the quadratic DIS curve (18)

$$\begin{aligned}
\pi_t &= \beta E_t \pi_{t+1} + \kappa \widehat{y_t} \\
\widehat{y_t} &= E_t\left(\widehat{y_{t+1}}\right) - \frac{1}{\sigma}\left(i_t - r - E_t\pi_{t+1}\right) - \frac{1}{2\sigma}E_t\pi_{t+1}^2 - \frac{\sigma}{2}E_t\left(\Delta\widehat{y_{t+1}}\right)^2 - E_t\left(\pi_{t+1}\Delta\widehat{y_{t+1}}\right),
\end{aligned}$$

where the parameters $\beta$, $\kappa$, and $\sigma$ are strictly positive. Minimizing equation (19) with respect to inflation and the output gap, subject to the NKPC and the QDIS curve, results in two first-order conditions $\lambda = -\pi_t$ and $\lambda = \frac{\delta}{\kappa}\widehat{y_t}$ that can be combined to the standard targeting rule

$$\pi_t = -\frac{\delta}{\kappa}\widehat{y_t}. \tag{20}$$

According to this rule, the central bank "leans against the wind" and depresses the real economy to counteract positive deviations from the inflation target. The strength of the economic contraction needed to fight an inflation deviation increases in the slope of the NKPC and decreases in the central bank's weight on output stabilization. Inserting the standard targeting rule (20) into the NKPC yields:

$$\widehat{y_t} = -\frac{\beta\kappa}{\delta + \kappa^2}E_t\pi_{t+1} \tag{21}$$

To obtain the interest rate rule followed by the central bank we insert (21) into the quadratic DIS curve and solve for the central bank's policy rate:[14]

$$\begin{aligned} i_t = r &+ \left(1+\frac{\sigma\kappa\beta}{\delta+\kappa^2}\right)E_t\pi_{t+1} + \sigma E_t\left(\widehat{y_{t+1}}\right) \\ &+ \left(\frac{\sigma\kappa}{\delta}-\frac{1}{2}\right)Var_t\left(\pi_{t+1}\right) - \frac{\sigma^2}{2}Var_t\left(\widehat{y_{t+1}}\right) \\ &+ \left(\frac{\sigma\kappa}{\delta}-\frac{1}{2}-\frac{\sigma\beta\kappa}{\delta+\kappa^2}\right)\left(E_t\pi_{t+1}\right)^2 - \frac{\sigma^2}{2}\left(E_t\widehat{y_{t+1}}-\widehat{y_t}\right)^2 \end{aligned} \tag{22}$$

Next, we utilize the "lean against the wind" condition to clarify the relation between the coefficients and get as a target interest rate

$$i_t = r + \lambda_1 E_t\left(\pi_{t+1}\right) + \lambda_2 E_t\left(\widehat{y_{t+1}}\right) + \lambda_3 Var_t\left(\pi_{t+1}\right) + \lambda_4 Var_t\left(\widehat{y_{t+1}}\right) + \xi \tag{23}$$

with

$$\begin{aligned} -\frac{\delta}{\kappa}\lambda_1 + \lambda_2 &= \sigma - \frac{\delta}{\kappa}\left(1+\frac{\sigma\beta\kappa}{\delta+\kappa^2}\right) \\ \left(\frac{\delta}{\kappa}\right)^2\lambda_3 + \lambda_4 &= -\frac{\sigma^2}{2} - \left(\frac{\delta}{\kappa}\right)^2\left(\frac{\sigma\kappa}{\delta}-\frac{1}{2}\right) \\ \xi &= \left(\frac{\sigma\kappa}{\delta}-\frac{1}{2}-\frac{\sigma\beta\kappa}{\delta+\kappa^2}\right)\left(E_t\pi_{t+1}\right)^2 - \frac{\sigma^2}{2}\left(E_t\widehat{y_{t+1}}-\widehat{y_t}\right)^2. \end{aligned}$$

The optimal policy rate depends on the inflation and output gap variance and, thus, certainty-equivalence no longer holds. The term $\xi$ can be neglected, as the squared expected inflation rate and the squared expected output gap growth rate take very small values for advanced economies.

In a final step, we derive the expected signs of the coefficients for $Var_t(\pi_{t+1})$ and $Var_t(\widehat{y_{t+1}})$. Following Woodford (2003), we assume a value of 1 for the inverse of the intertemporal elasticity of substitution $\sigma$. McCallum and Nelson (2004) suggest a range of between 0.01 and 0.05 for the slope of the NKPC $\kappa$. In line with Walsh (2010), we set the weight on output fluctuations $\delta$ to 0.25. This yields a coefficient range between

[14]In particular, we use $Var(x) = E\left(x^2\right) - (Ex)^2$.

−0.3 and −0.46 for the variance of expected inflation ($\sigma\kappa/\delta - 0.5$) and a coefficient of −0.5 for the variance of the expected output gap $-\sigma^2/2$.

# 3 Data and Empirical Methodology

## 3.1 Data

Our empirical analysis focuses on, arguably, the three largest and most important central banks worldwide, that is, the ECB, the BOE, and Fed for the period 1990Q1–2016Q4. In the case of the euro area, the sample starts in 2002Q4, because individual forecasts by *Consensus Economics* for the entire euro area (EA) first became available in December 2002.[15] Similarly, the sample for the United Kingdom (UK) begins in 1992Q4 as the BOE first introduced an inflation target in October 1992. For the United States (US), we use data for the full sample period.

Our data set includes the end of quarter policy rates obtained from the central bank websites. Since our sample includes a prolonged episode of interest rates very close to or at the zero-lower bound of interest rates, we also utilize the shadow interest rate by Wu and Xia (2016). These provide a quantification of all unconventional monetary policy measures in a single interest rate and also allow for negative interest rates when the actual policy rate is at the zero-lower bound. We create a composite interest rate indicator by using the actual interest rate before the Lehman collapse and the shadow interest rates from 2008Q3 onwards.[16]

In addition, *Consensus Economics* typically offers 30–50 individual forecasts for expected inflation and real GDP growth for each country for the current calendar year and the next calendar year. In a first step, these individual forecasts are transformed

[15] Note, that it is common practice to use real-time national GDP weights to aggregate national inflation forecasts and growth forecasts as a proxy for the euro area forecasts before December 2002. Such an approach—which is well-suited for the level of forecasts— performs poorly for the second moment of forecasts as indicated by a comparison of the actual uncertainty of euro area forecasts and this proxy measure for the period after December 2002.

[16] Note that Wu and Xia (2016) provide shadow rates for the US only until November 2015, the month before the Fed first raised its policy rate. Consequently, the composite interest rate indicator for the US utilizes the shadow interest rate for the period 2008Q3–2015Q3 and the conventional policy rate otherwise.

into 12-month ahead forecasts using the following formula.

$$E_{t,i}x_{t+12} = \frac{12-m}{12}E_{t,i}x_{cy} + \frac{m}{12}E_{t,i}x_{ny} \tag{24}$$

$E_{t,i}x_{t+12}$ is the 12-month ahead forecast, while $E_{t,i}x_{cy}$ and $E_{t,i}x_{ny}$ are the corresponding forecasts for the current calendar year and the next calendar year. The individual forecaster is denoted by $i$ and $m$ refers to the month in which the forecast was made, that is, $m = 3$ for March, $m = 6$ for June, $m = 9$ for September and, $m = 12$ for December. In a second step, we calculate the median of these individual forecasts for each country and month. In the following, we will refer to these medians as "expected inflation" and "expected GDP growth." Finally, we obtain the standard deviation around the median for each country and forecast to proxy the "uncertainty of inflation expectations" and "uncertainty of growth expectations" by the dispersion of the forecasts. This implies that both uncertainty measures are conditional on the time when the forecast is made. In contrast to the theoretical model in Section 2, we use the standard deviation around the median instead of the variance, as the standard deviation has the same dimension as the median and, therefore, these figures are easier to interpret.[17]

Figure B1 in the Appendix shows the (shadow) policy rates, inflation and growth expectations, and the uncertainty of expectations over time. Table B1 presents the corresponding descriptive statistics. A couple of things are worth highlighting. First, the uncertainty of inflation expectations is (slightly) lower than the uncertainty of growth expectations in all three economies. Second, the uncertainty of inflation expectations is less volatile than the uncertainty of growth expectations in the EA and the US (only for the pre-crisis period), whereas we observe the opposite in the UK.

Table B2 provides further interesting insights by showing bivariate correlations between the five (six) variables. First, there is a positive correlation between both forecast uncertainty measures in all three economies. The strongest positive correlation is found for the EA (0.80 during the pre-crisis period, 0.41 for the full sample), the

[17]Note that the results (not shown but available on request) hold qualitatively when using the variance around the median instead of the standard deviation.

weakest for the UK (0.10 for the pre-crisis period, 0.19 for the full sample). Second, in times of higher expected growth both, inflation and GDP forecast uncertainty is generally lower, indicating a "common belief in optimism." Third, there is a positive correlation between both forecast uncertainty variables and the expected level of inflation in the UK and the US (only during the pre-crisis period), whereas we observe the opposite for the EA.

## 3.2 Empirical Methodology

To assess the impact of inflation and growth forecast uncertainty on the central bank policy rate we, first, estimate a forward-looking Taylor rule without forecast uncertainty as a benchmark. To reconcile our theoretical model in Section 2 with the recent empirical literature (Coibion and Gorodnichenko 2012), we allow for both, interest rate smoothing of second-order and a first-order autoregressive error term specification:[18]

$$\begin{aligned} i_t &= \rho_{i,1} i_{t-1} + \rho_{i,2} i_{t-2} + \alpha + \beta_1 (E_t \pi_{t+12} - \pi^*) + \beta_2 (E_t y_{t+12} - y^*) + u_t \qquad \text{(M1)} \\ u_t &= \rho_u u_{t-1} + e_t \end{aligned}$$

$i_t$ is the policy rate, $E_t \pi_{t+12} - \pi^*$ the 12-month ahead expected inflation rate minus the IT, that is, the "expected inflation gap," and $E_t y_{t+12} - y^*$ the 12-month ahead expected GDP growth rate minus potential output, that is, the "expected output gap."[19] $\pi^*$ takes the values of 2% for the EA, the UK (from 2004Q1 onwards), and the US. Before 2003Q4, we use a target value of 2.5% for the UK.[20] Following the recent literature on Taylor rules (see, for instance, Gorter et al 2008; Neuenkirch and Siklos

[18] Put differently, we use the dynamic version of the intertemporal solution (22) derived in Section 2.3 (see, e.g., Wälde 2011 for an overview). See, also, Rudebusch (2006) and Consolo and Favero (2009) for a discussion of whether to include a partial adjustment mechanism and/or an autoregressive error term into the reaction function.

[19] We choose not to add an exchange rate variable. Research on estimated, as well as optimal, Taylor rules (see, among others, Clarida 2001; Collins and Siklos 2004), suggests that adding this variable does not substantively change inferences based on the standard Taylor rule specification.

[20] In 2004Q1, the IT in the UK was changed from 2.5% in the retail price index to 2% in the harmonized index of consumer prices.

2013; Neuenkirch and Tillmann 2014) we use a simple deviation from a constant output growth trend (2%) as proxy for the output gap.[21] Finally, reflecting the findings of Orphanides (2001), we analyze monetary policy decisions in real-time, which implies that the end of quarter policy rate is regressed on the respective latest available forecast, that is the March, June, September, or December forecast. Since all right-hand side variables are observables, we estimate (M1) using conditional least squares (see Coibion and Gorodnichenko 2011).

Next, we augment (M1) with variables measuring the uncertainty of inflation forecasts and the uncertainty of growth forecasts:

$$\begin{aligned} i_t &= \rho_{i,1} i_{t-1} + \rho_{i,2} i_{t-2} + \alpha + \beta_1 (E_t \pi_{t+12} - \pi^*) + \beta_2 (E_t y_{t+12} - y^*) \\ &\quad + \gamma_1 SD(E_t \pi_{t+12}) + \gamma_2 SD(E_t y_{t+12}) + u_t \\ u_t &= \rho_u u_{t-1} + e_t \end{aligned} \tag{M2}$$

$SD(E_t \pi_{t+12})$ is the uncertainty of inflation expectations and $SD(E_t y_{t+12})$ is the uncertainty of growth forecasts. The variables $i_t$, $E_t \pi_{t+12} - \pi^*$, and $E_t y_{t+12} - y^*$ are defined as above and (M2) is estimated using conditional least squares.

We provide three different set of estimates. First, we restrict the sample to the pre-crisis period (until 2007Q4) to ensure that our results concerning the uncertainty of forecasts are not driven by some extraordinary circumstances during the financial crisis, which might have caused a higher uncertainty in general.[22] Second, we use the full sample period and the conventional policy rates. Third, to overcome a potential bias due to the zero-lower bound of interest rates we also estimate (M2) for the full

[21] This reflects common practice by many central banks in their communications, as these focus on expected GDP growth rather than on the expected GDP gap (Gerlach 2007), probably due to the difficulty of measuring the latter in real-time (see also Orphanides and van Norden 2002). A widely followed practice in the relevant literature suggests employing the Hodrick and Prescott (1997) filter with the standard smoothing parameter $\lambda = 1600$. However, this assumes perfect knowledge of all future expected output observations since it estimates trend output based on a two-sided filter. Alternative formulations of this filter address some of the drawbacks with the standard version but these alternatives remain more ad hoc than the definitions we rely upon in the empirical work below.

[22] For these estimations, we rely on an ARMA(1,1) structure as the AR(2) coefficients are highly insignificant for all three economies.

sample period with the composite interest rate indicator based on the actual policy rates and the shadow interest rates. We will refer to this model as (M2 S).[23]

# 4 Empirical Results

## 4.1 Pre-Crisis Period

Table 1 sets out the results for the pre-crisis period. Columns (M1) and (M2) refer to specifications without and with forecast uncertainty, respectively. To conserve space, the following interpretation refers only to the augmented specifications (M2). We observe a (very) high degree of interest rate smoothing that ranges between 0.89 for the ECB and 0.97 for the BOE and the Fed. We also have evidence for persistent monetary policy shocks in case of the UK and the US as the autoregressive error term is significant for these countries. Roughly 25% (UK) and 49% (US) of the last period's shock carries over to the current period.

The ECB neither significantly reacts to the forecast levels nor to the forecast uncertainty measures. This is presumably due to the very low number of observations for the pre-crisis period (20) as the standard errors decrease considerably once we utilize the full sample period (see Section 4.2 below). In case of the BOE, we find a significant and positive reaction to the expected GDP gap and a significant and negative reaction to inflation forecast uncertainty.[24] The Fed reacts to increases in the expected inflation gap and the expected output gap with a raise in its policy rate. Finally, in times of higher growth forecast uncertainty we observe a significant decrease in the Fed's policy rate.

[23] Tables C1–C3 in the Appendix provide results for contemporaneous Taylor rules. Data sources for realized data: ECB, Office for National Statistics, and Federal Reserve Bank of St. Louis. Similar to the forecast uncertainty measures, we also created uncertainty measures for the realized values of inflation and GDP growth. For that purpose, we calculated the standard deviations of both variables over the past four and eight quarters, respectively. However, these volatility measures are never significant in the contemporaneous Taylor rules, which is why we only report the baseline contemporaneous specifications in the Appendix. All omitted results are available on request.

[24] Note that the $p$-value for the expected inflation gap is 0.101 for (M2) in the case of the UK and, therefore, marginally insignificant at the 10% level.

Table 1: Taylor Rules: Pre-Crisis Period

| | EA (M1) | EA (M2) | UK (M1) | UK (M2) | US (M1) | US (M2) |
|---|---|---|---|---|---|---|
| $\rho_{i,1} : i_{t-1}$ | 0.875*** | 0.886*** | 0.930*** | 0.967*** | 0.982*** | 0.967*** |
| | (0.062) | (0.065) | (0.046) | (0.058) | (0.037) | (0.034) |
| $\rho_u : u_{t-1}$ | 0.148 | 0.144 | 0.338** | 0.249* | 0.444*** | 0.485*** |
| | (0.274) | (0.318) | (0.132) | (0.132) | (0.112) | (0.116) |
| $\alpha$ | 0.484** | 0.757** | 0.112 | −0.022 | −0.459** | 0.253 |
| | (0.178) | (0.290) | (0.239) | (0.409) | (0.186) | (0.258) |
| $\beta_1 : E_t\pi_{t+12} - \pi^*$ | 0.335 | 0.403 | 0.125 | 0.209 | 0.193** | 0.207** |
| | (0.243) | (0.298) | (0.121) | (0.125) | (0.095) | (0.086) |
| $\beta_2 : E_t y_{t+12} - y^*$ | 0.452*** | 0.261 | 0.500*** | 0.497*** | 0.448*** | 0.319*** |
| | (0.135) | (0.217) | (0.110) | (0.101) | (0.071) | (0.070) |
| $\gamma_1 : SD(E_t\pi_{t+12})$ | | −1.221 | | −0.692** | | −0.103 |
| | | (2.178) | | (0.309) | | (0.591) |
| $\gamma_2 : SD(E_t y_{t+12})$ | | −0.876 | | 0.308 | | −1.750*** |
| | | (1.443) | | (0.473) | | (0.408) |
| $R^2$ | 0.98 | 0.98 | 0.94 | 0.95 | 0.97 | 0.98 |
| $\sigma$ | 0.14 | 0.14 | 0.25 | 0.24 | 0.31 | 0.28 |
| AIC | −0.89 | −0.80 | 0.12 | 0.10 | 0.59 | 0.36 |
| SC | −0.64 | −0.46 | 0.29 | 0.34 | 0.75 | 0.59 |
| Breusch-Godfrey Test | 1.8 | 5.0 | 6.8 | 1.7 | 5.1 | 3.2 |
| White Test | 1.5 | 3.0 | 11.8** | 14.7** | 5.9 | 9.4 |
| Standard Errors | | | W | W | | |

*Notes*: Estimation of (M1) and (M2) using conditional least squares. Standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Number of observations: 20 (EA), 60 (UK), and 71 (US). $\sigma$: standard error of regression; AIC: Akaike information criterion; SC: Schwarz criterion; *W*: White (1980) standard errors.

Our results thus provide evidence that the BOE—as an inflation targeting central bank—reacts negatively to inflation forecast uncertainty during the pre-crisis period, whereas the Fed—with its dual mandate of achieving stable prices and maximum sustainable employment—decreases its policy rate in times of higher growth forecast uncertainty.

## 4.2 Full Sample

Table 2 sets out the results for the full sample with both forecast uncertainty measures.[25] Columns (M2) and (M2 S) refer to specifications with the conventional policy rate and with the composite interest rate indicator that utilizes the shadow interest rate, respectively. Again, we observe a (very) high degree of interest rate smoothing that ranges between 0.84 for the ECB (M2) and 0.98 for the Fed (M2 S). We also have evidence of persistent monetary policy shocks in the case of all three central banks, as 52–64% of the last period's error carry over to the current period.

The ECB positively reacts to changes in the expected inflation gap and the expected GDP gap (when employing the conventional policy rate). The same holds for the BOE, whereas the Fed changes its policy rate only in response to expected growth fluctuations. More interestingly, we observe a significantly negative reaction to inflation (growth) forecast uncertainty in the EA (US). Finally, the BOE decreases interest rates in times of higher inflation forecast uncertainty but increases these whenever growth forecast uncertainty is particularly large.

The results for the full sample period confirm the two findings from the pre-crisis period: (i) the BOE reacts negatively to inflation forecast uncertainty and, (ii) the Fed decreases its policy rate in times of higher growth forecast uncertainty. In addition, the ECB—as a central bank with an inflation objective—also decreases interest rates in times of higher inflation forecast uncertainty when estimating reactions functions for the full sample. Finally, the positive coefficient on growth forecast uncertainty for the UK (partly) offsets the negative coefficient for inflation forecast uncertainty.

[25] Results for models without forecast uncertainty are available on request.

Table 2: Taylor Rules: Full Sample

| | EA (M2) | EA (M2 S) | UK (M2) | UK (M2 S) | US (M2) | US (M2 S) |
|---|---|---|---|---|---|---|
| $\rho_{i,1} : i_{t-1}$ | 0.387 | 0.318 | 0.565*** | 0.211** | 0.760*** | 0.629*** |
| | (0.259) | (0.278) | (0.160) | (0.102) | (0.185) | (0.229) |
| $\rho_{i,2} : i_{t-2}$ | 0.449** | 0.550** | 0.351** | 0.681*** | 0.189 | 0.348 |
| | (0.208) | (0.259) | (0.142) | (0.102) | (0.185) | (0.240) |
| $\rho_{i,1} + \rho_{i,2}$ | 0.836*** | 0.868*** | 0.916*** | 0.892*** | 0.949*** | 0.977*** |
| | (0.073) | (0.054) | (0.028) | (0.036) | (0.023) | (0.029) |
| $\rho_u : u_{t-1}$ | 0.546** | 0.521** | 0.606*** | 0.636*** | 0.549** | 0.622*** |
| | (0.211) | (0.239) | (0.152) | (0.132) | (0.211) | (0.192) |
| $\alpha$ | 0.864*** | 1.118*** | 0.247 | 0.204 | 0.652*** | 0.462 |
| | (0.240) | (0.353) | (0.191) | (0.279) | (0.234) | (0.321) |
| $\beta_1 : E_t\pi_{t+12} - \pi^*$ | 0.278** | 0.575*** | 0.307** | 0.539*** | 0.013 | −0.061 |
| | (0.120) | (0.163) | (0.119) | (0.149) | (0.091) | (0.124) |
| $\beta_2 : E_t y_{t+12} - y^*$ | 0.248** | 0.178 | 0.410*** | 0.648*** | 0.186*** | 0.246*** |
| | (0.098) | (0.211) | (0.119) | (0.121) | (0.066) | (0.075) |
| $\gamma_1 : SD(E_t\pi_{t+12})$ | −1.791** | −3.659** | −1.027** | −1.516*** | −0.937 | −0.496 |
| | (0.682) | (1.503) | (0.464) | (0.524) | (0.657) | (0.831) |
| $\gamma_2 : SD(E_t y_{t+12})$ | −0.251 | −1.028 | 0.594* | 0.954** | −1.233** | −1.367*** |
| | (0.407) | (1.233) | (0.305) | (0.427) | (0.529) | (0.481) |
| $R^2$ | 0.98 | 0.97 | 0.99 | 0.98 | 0.98 | 0.98 |
| $\sigma$ | 0.19 | 0.45 | 0.28 | 0.44 | 0.34 | 0.41 |
| AIC | −0.32 | 1.39 | 0.37 | 1.29 | 0.77 | 1.12 |
| SC | −0.02 | 1.68 | 0.58 | 1.51 | 0.97 | 1.32 |
| Breusch-Godfrey Test | 0.8 | 2.9 | 3.1 | 5.6 | 12.7** | 19.7*** |
| White Test | 28.4*** | 16.1** | 54.5*** | 19.5** | 15.5 | 23.5*** |
| Standard Errors | W | W | W | W | N/W | N/W |

*Notes*: Estimation of (M2) and (M2 S) using conditional least squares. Standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Number of observations: 55 (EA), 95 (UK), and 106 (US). $\sigma$: standard error of regression; AIC: Akaike information criterion; SC: Schwarz criterion; *W*: White (1980) standard errors; *N/W*: Newey and West (1980) standard errors.

### 4.3 Discussion

To this point, we have not interpreted the size of the significant estimates. Some of these effects appear to be of remarkable magnitude, in particular, when considering that Tables 1 and 2 report the short-run reaction of the interest rate.[26] One reason for these large coefficients is that some of the variables in the augmented Taylor rules (M2) and (M2 S) offset each other in their partial effect on the policy rate. Therefore, instead of an isolated interpretation of the coefficients' size, we highlight the variation of the partial effects of the forecast uncertainty variables, and the corresponding level variables, over time. The left panel in Figure 1 shows the partial short-run effect of inflation expectation uncertainty and growth expectation uncertainty on the policy rate for the three central banks in each quarter based on estimations for the full sample using the shadow rates.[27]

If we examine the ECB, the partial effect of inflation expectations uncertainty (dark grey bars) ranges between −0.25 percentage points (pp) and −1.07 pp with the latter value occurring in the 2008Q4, when central banks worldwide aggressively cut their policy rates in the aftermath of the Lehman collapse. The partial effect of growth uncertainty (light grey bars), albeit insignificant in Table 2, is also noticeable as it takes values between −0.08 pp and −0.66 pp. Here, the maximum impact (in absolute terms) on the policy rate is found during 2011Q4, when the sovereign debt crisis in the EA intensified considerably.

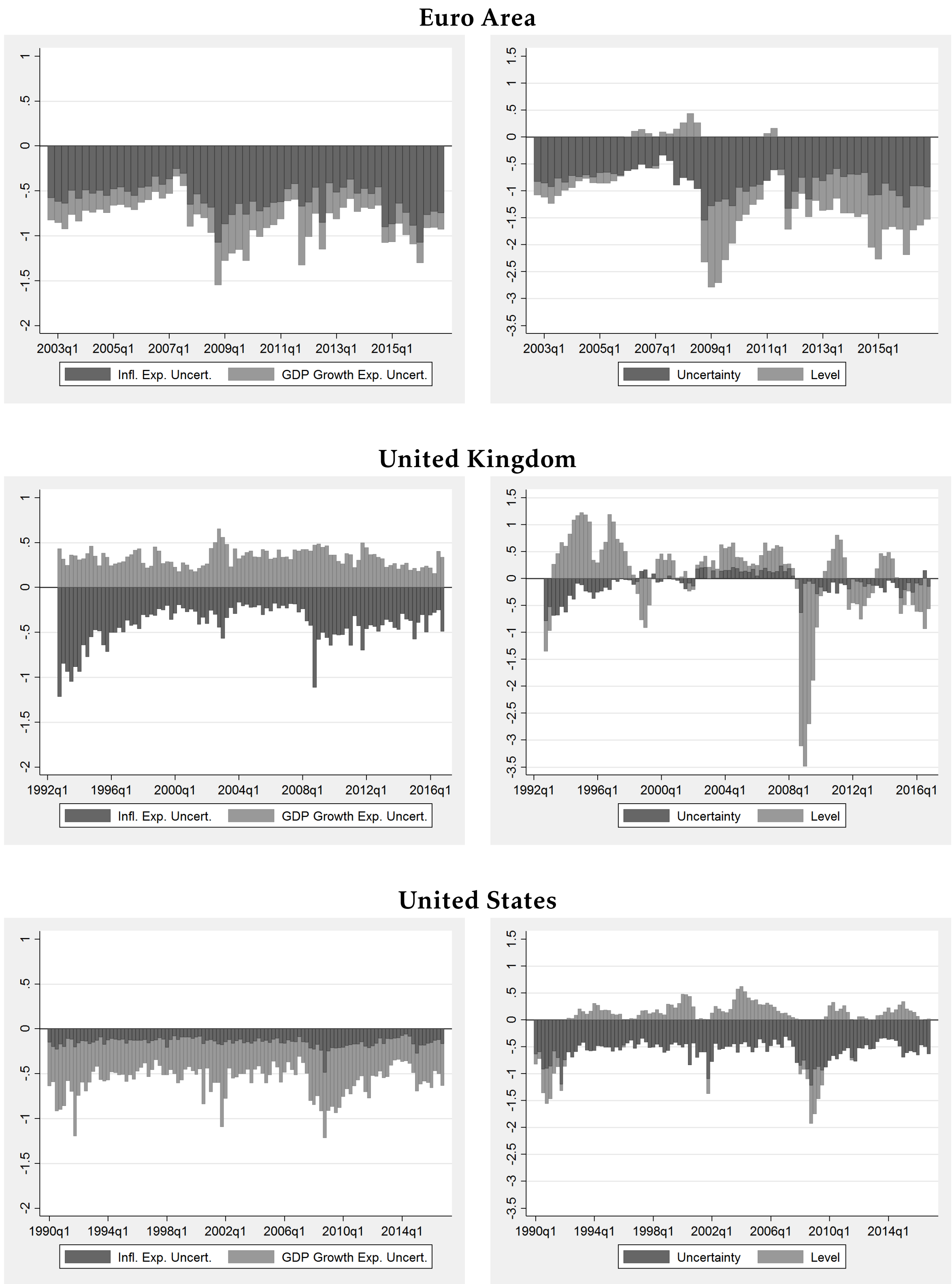
The partial effects for the BOE illustrate the (partially) offsetting effects of both forecast uncertainty measures. The negative effect on inflation expectation uncertainty on the policy rate ranges between −0.17 pp and −1.22 pp, whereas the positive influence of growth uncertainty takes values between 0.16 pp and 0.66 pp. The maximum impact of inflation expectation uncertainty on the policy rate is found right after the inception of the IT in 1992Q4 and, similar to the EA, in 2008Q4. When considering

[26] To obtain the steady-state coefficients, the interested reader should divide $\alpha$, $\beta_1$, $\beta_2$, $\gamma_1$, and $\gamma_2$ by $(1-\rho_{i,1})$ in Table 1, and by $(1-\rho_{i,1}-\rho_{i,2})$ in Table 2, respectively.

[27] Note that these results qualitatively hold when relying on the estimates for the pre-crisis subsample or those using the conventional policy rate for the full sample. See Figures D1 and D2 in the Appendix.

growth forecast uncertainty, the maximum is found during relatively tranquil times in 2002Q4.

Figure 1: Partial Effect of Expectation Uncertainty on the Policy Rate: Full Sample with Shadow Rates



Turning to the Fed, the partial effects of growth forecast uncertainty takes values between −0.22 pp and −0.99 pp with the maximum negative impact occurring in 1991Q4, right after the 1990–1991 recession in the US. The effect of inflation expectation uncertainty, despite being insignificant in Table 2, is also noticeable, with a range of −0.06 pp to −0.49 pp. Similar to the EA and the UK, the peak effect is found in 2008Q4.

The right panel in Figure 1 compares the combined short-run effect of inflation and growth forecast uncertainty (dark grey bars) on the policy rate with the combined partial short-run effects of the expected inflation gap and the expected output gap (light grey bars).

The figures indicate that the second moment of forecasts has a substantial influence on the policy rate for the EA and the US, even when compared to the level of macroeconomic forecasts. In case of the ECB, the maximum effect of forecast uncertainty is −1.55 pp (in 2008Q4), whereas the maximum combined effect of both level forecasts is −1.52 pp (in 2009Q1). For the Fed, the maximum combined effect of forecast uncertainty is −1.22 pp (in 2008Q4) and the maximum effect of the level variables amounts to −0.84 pp (in 2009Q1). In case of the UK, however, the reaction to the first moments is, on average, stronger, especially during the height of the financial crisis. The maximum effect of both level variables is −3.39 pp (in 2009Q1), whereas the maximum combined effect of both (partially) offsetting uncertainty measures amounts to −0.78 pp (in 1992Q4).

One caveat is warranted. The uncertainty measures based on standard deviations are naturally positive, which implies that the constant terms might get abnormally large for negative estimates of forecast uncertainty, as these also absorb the positive means of the uncertainty measures. However, we chose not to center the uncertainty measures like we did with the forecast levels as, in our view, there is no "undisputable target value" like, for instance, 2% in case of inflation. Therefore, when interpreting Figure 1 one should also consider the impact of the means of the uncertainty variables on the constant terms, which amounts to 0.84 pp (EA), 0.09 pp (UK), and 0.58 pp (US), respectively.

At the end of Section 2.3, we derived expected coefficients for the variance of expected inflation (between $-0.3$ and $-0.46$) and the variance of the expected output gap ($-0.5$). In the previous subsections, we presented empirical short-run estimates for the standard deviation of expected inflation and the standard deviation of expected GDP growth based on ARMA models. Therefore, we can compare the sign of these estimates to the theoretically-derived parameters. All empirical estimates, with those for the standard deviation of expected GDP in the UK being the only exception, are negative. In case of the UK, the sum of the partial effects of inflation forecast uncertainty and growth forecast uncertainty is, on average, negative, which at least partly confirms the expectations from Section 2.3. Finally, our findings of mostly negative coefficients on the uncertainty measures is well in line with the previous literature for the Fed (Branch 2014; Milas and Martin 2009).

# 5 Conclusions

In this paper, we derive a modification of a forward-looking Taylor rule by integrating two variables that measure the uncertainty of inflation and GDP growth forecasts into an otherwise standard New Keynesian model. We show that certainty-equivalence in New Keynesian models is a consequence of log-linearization and that a second-order Taylor approximation leads to a reaction function which includes the uncertainty of macroeconomic expectations.

To test the model empirically, we rely on the dataset of individual forecasters provided by *Consensus Economics* and use the standard deviation of individual forecasts around the median forecast as a proxy for forecast uncertainty. Our sample covers the European Central Bank, the Bank of England, and the Federal Reserve, for the period 1990Q1–2016Q4. Our results indicate that, in fact, real policy behavior accounts for uncertainty in accordance with the model's predictions. We find that the BOE and the ECB have a significantly negative reaction to inflation forecast uncertainty. In addition, the Fed (BOE) is found to lower (raise) its interest rate in reaction to higher growth forecast uncertainty.

Our results show that certainty-equivalence cannot be taken as a given. Research should take this into consideration when addressing optimal monetary policy rules. If the cautious behavior of central bankers is to be taken seriously, Taylor-type optimal policy rules should account for the uncertainty of macroeconomic variables. Indeed, in accordance with our model's predictions, anecdotal evidence (Greenspan 2004) and our results indicate that real policy behavior recognizes the uncertainty of macroeconomic forecasts.

Central bank watchers often use the Taylor rule as a short-hand expression to evaluate the stance of monetary policy. Consequently, our paper also has some implications for monetary policy observers. Neglecting the uncertainty around macroeconomic expectations might lead to incorrectly assess the situation central bankers face at the time of their decision.

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# Appendix

## A Model Solution with Exogenous Demand and Supply Shocks and Unobservable Error Terms

Here, we analyze the effects of unobservable shocks to the inflation rate and the output gap. Let $\pi_t' = E_t\pi_t$ and $\widehat{y_t}' = E_t\widehat{y_t}$ denote the $t$-observable part of $\pi_t$ and $\widehat{y_t}$, that is,

$$\pi_t = \pi_t' + \varepsilon_t \text{ and } \widehat{y_t} = \widehat{y_t}' + \mu_t,$$

where $\varepsilon_t$ and $\mu_t$ are i.i.d. with zero mean and variances $\sigma_\varepsilon^2$ and $\sigma_\mu^2$. Together with an exogenous demand shock $g_t$ and an exogenous supply shock $u_t$ we get

$$\pi_t' + \varepsilon_t = \beta E_t\pi_{t+1} + \kappa\left(\widehat{y_t}' + \mu_t\right) + u_t \tag{A1}$$

$$\widehat{y_t}' + \mu_t = E_t\left(\widehat{y_{t+1}}\right) - \frac{1}{\sigma}\left(i_t - r - E_t\pi_{t+1}\right) - \frac{1}{2\sigma}E_t\pi_{t+1}^2 - \frac{\sigma}{2}E_t\left(\Delta\widehat{y_{t+1}}\right)^2 - E_t\left(\pi_{t+1}\Delta\widehat{y_{t+1}}\right) + g_t \tag{A2}$$

for the NKPC and the quadratic DIS curve. This is equivalent to

$$\pi_t' = \beta E_t\pi_{t+1} + \kappa\widehat{y_t}' + E_t\widetilde{u_t} \tag{A3}$$

$$\widehat{y_t}' = E_t\left(\widehat{y_{t+1}}\right) - \frac{1}{\sigma}\left(i_t - r - E_t\pi_{t+1}\right) - \frac{1}{2\sigma}E_t\pi_{t+1}^2 - \frac{\sigma}{2}E_t\left(\Delta\widehat{y_{t+1}}\right)^2 - E_t\left(\pi_{t+1}\Delta\widehat{y_{t+1}}\right) + E_t\widetilde{g_t} \tag{A4}$$

with $\widetilde{u_t} = u_t - \varepsilon_t + \kappa\mu_t$ and $\widetilde{g_t} = g_t - \mu_t$. The central bank's loss function (19) changes to

$$\mathcal{L} = E_t\left(\frac{1}{2}\pi_t^2 + \frac{\delta}{2}\widehat{y_t}^2\right) = \frac{1}{2}\pi_t'^2 + \frac{\delta}{2}\widehat{y_t}'^2 + \frac{1}{2}\left(\sigma_\varepsilon^2 + \delta\sigma_\mu^2\right) \tag{A5}$$

where the latter part holds due to $E_t\varepsilon_t = E_t\mu_t = 0$. Optimizing (A5) with respect to $\pi_t'$ and $\widehat{y_t}'$ and subject to equations (A3) and (A4) yields the standard targeting rule for the observable variables:

$$\pi_t' = -\frac{\delta}{\kappa}\widehat{y_t}' \tag{A6}$$

This "lean against the wind" rule is analogous to the one presented in the main text. Inserting (A6) into the NKPC (A3) yields:

$$\widehat{y_t} = -\frac{\beta\kappa}{\delta+\kappa^2} E_t \pi_{t+1} - \frac{\kappa}{\delta+\kappa^2} E_t \widetilde{u_t}, \tag{A7}$$

which now includes the observable part of the shocks. To obtain the interest rate rule we insert (A7) into the quadratic DIS curve (A4) and solve for the central bank's policy rate:

$$\begin{aligned} i_t = r &+ \left(1 + \frac{\sigma\kappa}{\delta+\kappa^2}\left(\beta - E_t \widetilde{u_t}\right)\right) E_t \pi_{t+1} \\ &+ \sigma E_t\left(\widehat{y_{t+1}}\right) + \left(\frac{\sigma\kappa}{\delta} - \frac{1}{2}\right) Var_t\left(\pi_{t+1}\right) - \frac{\sigma^2}{2} Var\left(\widehat{y_{t+1}}\right) \\ &+ \left(\frac{\sigma\kappa}{\delta} - \frac{1}{2} - \frac{\sigma\beta\kappa}{\delta+\kappa^2}\right)\left(E_t \pi_{t+1}\right)^2 - \frac{\sigma^2}{2}\left(E_t \widehat{y_{t+1}} - \widehat{y_t}'\right)^2 + \sigma\left(\frac{\kappa}{\delta+\kappa^2} E_t \widetilde{u_t} + E_t \widetilde{g_t}\right) \end{aligned} \tag{A8}$$

Similar to Section 2.3, we utilize the "lean against the wind condition" to write (A8) in a more compact way:

$$i_t = r + \lambda_1 E_t\left(\pi_{t+1}\right) + \lambda_2 E_t\left(\widehat{y_{t+1}}\right) + \lambda_3 Var_t\left(\pi_{t+1}\right) + \lambda_4 Var\left(\widehat{y_{t+1}}\right) + \sigma\left(\frac{\kappa}{\delta+\kappa^2} E_t \widetilde{u_t} + E_t \widetilde{g_t}\right) + \xi \tag{A9}$$

There are two differences to the interest rate rule (23) in Section 2.3. First, (A9) features the observable part of a linear combination of the supply and demand shocks. Second, the central bank's reaction on expected inflation depends partly on the observable part of the shocks. However, neither difference leads to a substantial change in the basic form, structure, or properties of the result in the main text of the paper.

# B Descriptive Statistics

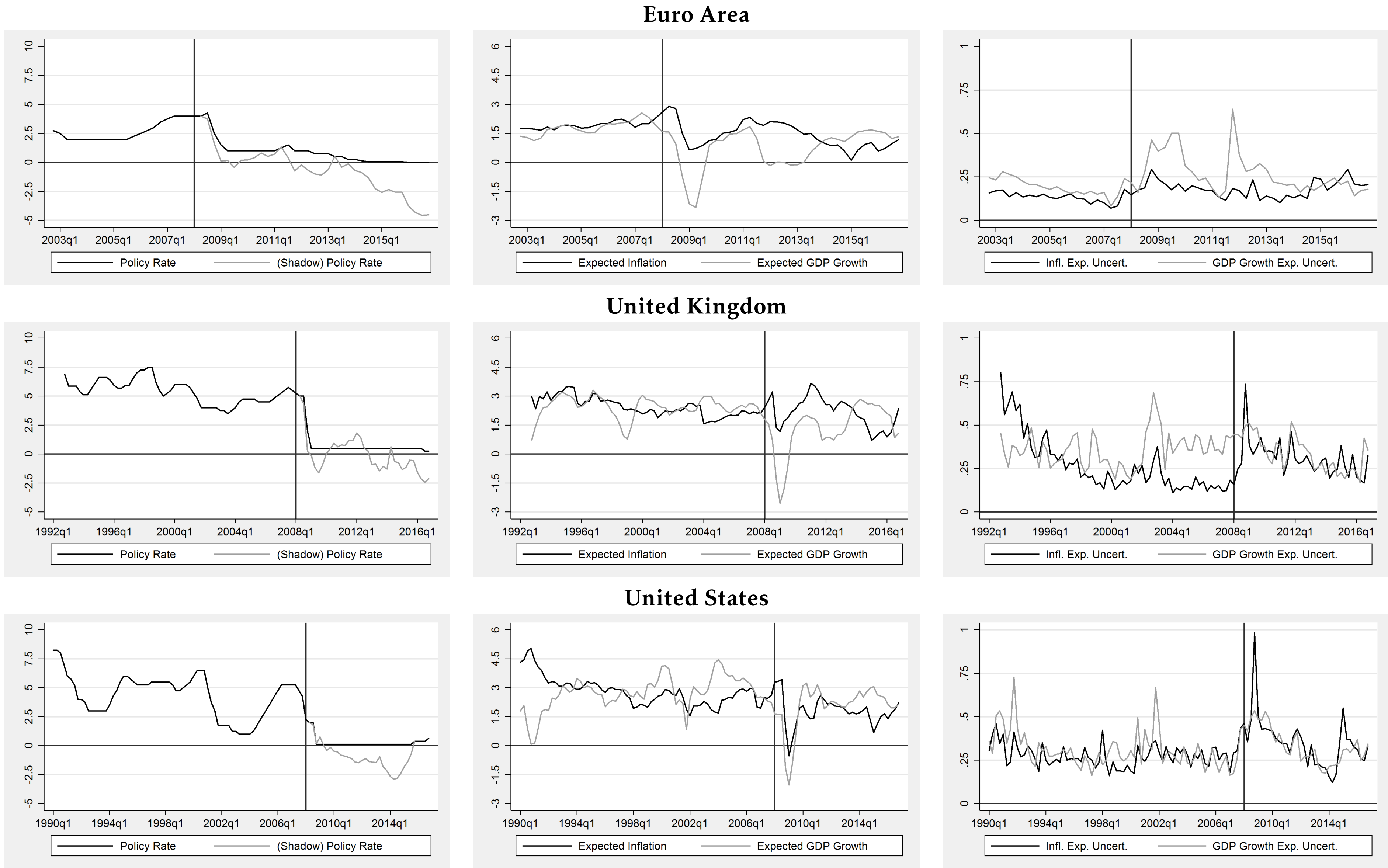
Table B1: Summary Statistics

| | Pre-Crisis (2002Q4–2007Q4) | | | | Full Sample (2002Q4–2016Q4) | | | |
|---|---|---|---|---|---|---|---|---|
| **Euro Area** | Mean | S.D. | Min | Max | Mean | S.D. | Min | Max |
| $i_t$ | 2.62 | 0.77 | 2.00 | 4.00 | 1.56 | 1.28 | 0.00 | 4.25 |
| $i_t^s$ | — | — | — | — | 0.63 | 2.30 | −4.57 | 4.00 |
| $E_t\pi_{t+12}$ | 1.92 | 0.18 | 1.67 | 2.28 | 1.60 | 0.60 | 0.12 | 2.90 |
| $E_t y_{t+12}$ | 1.81 | 0.37 | 1.13 | 2.55 | 1.14 | 0.99 | −2.34 | 2.55 |
| $SD(E_t\pi_{t+12})$ | 0.13 | 0.03 | 0.07 | 0.18 | 0.16 | 0.05 | 0.07 | 0.29 |
| $SD(E_t y_{t+12})$ | 0.19 | 0.05 | 0.08 | 0.28 | 0.24 | 0.10 | 0.08 | 0.64 |
| Observations | 21 | | | | 57 | | | |
| | Pre-Crisis (1992Q4–2007Q4) | | | | Full Sample (1992Q4–2016Q4) | | | |
| **United Kingdom** | Mean | S.D. | Min | Max | Mean | S.D. | Min | Max |
| $i_t$ | 5.40 | 1.02 | 3.50 | 7.50 | 3.74 | 2.46 | 0.25 | 7.50 |
| $i_t^s$ | — | — | — | — | 3.43 | 2.92 | −2.43 | 7.50 |
| $E_t\pi_{t+12}$ | 2.45 | 0.48 | 1.58 | 3.50 | 2.34 | 0.62 | 0.70 | 3.65 |
| $E_t y_{t+12}$ | 2.43 | 0.55 | 0.74 | 3.31 | 2.03 | 1.02 | −2.55 | 3.31 |
| $SD(E_t\pi_{t+12})$ | 0.27 | 0.16 | 0.11 | 0.80 | 0.28 | 0.14 | 0.11 | 0.80 |
| $SD(E_t y_{t+12})$ | 0.36 | 0.10 | 0.19 | 0.69 | 0.35 | 0.10 | 0.17 | 0.69 |
| Observations | 61 | | | | 97 | | | |
| | Pre-Crisis (1990Q1–2007Q4) | | | | Full Sample (1990Q1–2016Q4) | | | |
| **United States** | Mean | S.D. | Min | Max | Mean | S.D. | Min | Max |
| $i_t$ | 4.36 | 1.81 | 1.00 | 8.25 | 3.02 | 2.43 | 0.13 | 8.25 |
| $i_t^s$ | — | — | — | — | 2.67 | 2.91 | −2.89 | 8.25 |
| $E_t\pi_{t+12}$ | 2.81 | 0.72 | 1.55 | 5.04 | 2.46 | 0.88 | −0.52 | 5.04 |
| $E_t y_{t+12}$ | 2.72 | 0.86 | 0.08 | 4.45 | 2.49 | 1.02 | −2.03 | 4.45 |
| $SD(E_t\pi_{t+12})$ | 0.28 | 0.06 | 0.16 | 0.46 | 0.30 | 0.11 | 0.12 | 0.98 |
| $SD(E_t y_{t+12})$ | 0.31 | 0.11 | 0.16 | 0.73 | 0.32 | 0.10 | 0.16 | 0.73 |
| Observations | 72 | | | | 108 | | | |

Table B2: Correlation Matrixes

| | Pre-Crisis (2002Q4–2007Q4) | | | | | Full Sample (2002Q4–2016Q4) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Euro Area** | $i_t$ | $i_t^s$ | $E_t\pi_{t+12}$ | $E_t y_{t+12}$ | $SD(E_t\pi_{t+12})$ | $i_t$ | $i_t^s$ | $E_t\pi_{t+12}$ | $E_t y_{t+12}$ | $SD(E_t\pi_{t+12})$ |
| $i_t$ | 1 | | | | | 1 | | | | |
| $i_t^s$ | — | — | | | | 0.92 | 1 | | | |
| $E_t\pi_{t+12}$ | 0.57 | — | 1 | | | 0.74 | 0.75 | 1 | | |
| $E_t y_{t+12}$ | 0.69 | — | 0.61 | 1 | | 0.33 | 0.30 | 0.30 | 1 | |
| $SD(E_t\pi_{t+12})$ | −0.51 | — | −0.26 | −0.74 | 1 | −0.40 | −0.53 | −0.50 | −0.38 | 1 |
| $SD(E_t y_{t+12})$ | −0.50 | — | −0.51 | −0.81 | 0.80 | −0.18 | −0.15 | −0.16 | −0.73 | 0.41 |
| | Pre-Crisis (1992Q4–2007Q4) | | | | | Full Sample (1992Q4–2016Q4) | | | | |
| **United Kingdom** | $i_t$ | $i_t^s$ | $E_t\pi_{t+12}$ | $E_t y_{t+12}$ | $SD(E_t\pi_{t+12})$ | $i_t$ | $i_t^s$ | $E_t\pi_{t+12}$ | $E_t y_{t+12}$ | $SD(E_t\pi_{t+12})$ |
| $i_t$ | 1 | | | | | 1 | | | | |
| $i_t^s$ | — | — | | | | 0.97 | 1 | | | |
| $E_t\pi_{t+12}$ | 0.50 | — | 1 | | | 0.36 | 0.43 | 1 | | |
| $E_t y_{t+12}$ | −0.03 | — | 0.14 | 1 | | 0.44 | 0.45 | 0.16 | 1 | |
| $SD(E_t\pi_{t+12})$ | 0.30 | — | 0.65 | −0.13 | 1 | −0.04 | −0.05 | 0.33 | −0.28 | 1 |
| $SD(E_t y_{t+12})$ | −0.28 | — | 0.05 | −0.10 | 0.10 | 0.07 | 0.11 | 0.18 | −0.34 | 0.19 |
| | Pre-Crisis (1990Q1–2007Q4) | | | | | Full Sample (1990Q1–2016Q4) | | | | |
| **United States** | $i_t$ | $i_t^s$ | $E_t\pi_{t+12}$ | $E_t y_{t+12}$ | $SD(E_t\pi_{t+12})$ | $i_t$ | $i_t^s$ | $E_t\pi_{t+12}$ | $E_t y_{t+12}$ | $SD(E_t\pi_{t+12})$ |
| $i_t$ | 1 | | | | | 1 | | | | |
| $i_t^s$ | — | — | | | | 0.98 | 1 | | | |
| $E_t\pi_{t+12}$ | 0.58 | — | 1 | | | 0.71 | 0.68 | 1 | | |
| $E_t y_{t+12}$ | −0.35 | — | −0.55 | 1 | | 0.10 | 0.07 | 0.07 | 1 | |
| $SD(E_t\pi_{t+12})$ | 0.02 | — | 0.30 | −0.41 | 1 | −0.24 | −0.19 | −0.17 | −0.54 | 1 |
| $SD(E_t y_{t+12})$ | 0.05 | — | 0.33 | −0.53 | 0.47 | −0.05 | 0.01 | 0.09 | −0.56 | 0.56 |

Figure B1: Policy Rate, Inflation and Growth Expectations, and Uncertainty of Expectations




*Notes*: Vertical lines indicate the end of the pre-crisis period in 2007Q4.

# C Contemporaneous Taylor Rules

Table C1: Taylor Rules with Contemporaneous Data: Pre-Crisis Period

| | EA (M2') | UK (M2') | US (M2') |
|---|---|---|---|
| $\rho_{i,1} : i_{t-1}$ | 0.928*** | 0.814*** | 0.903*** |
| | (0.022) | (0.059) | (0.035) |
| $\rho_u : u_{t-1}$ | −1.105*** | 0.472*** | 0.545*** |
| | (0.369) | (0.127) | (0.105) |
| $\alpha$ | 0.221*** | 0.871** | 0.052 |
| | (0.049) | (0.331) | (0.163) |
| $\beta_1 : \pi_t - \pi^*$ | −0.076 | 0.193*** | 0.125** |
| | (0.068) | (0.072) | (0.057) |
| $\beta_2 : y_t - y^*$ | 0.215*** | 0.106 | 0.214*** |
| | (0.011) | (0.067) | (0.041) |
| $R^2$ | 0.99 | 0.92 | 0.97 |
| $\sigma$ | 0.10 | 0.30 | 0.33 |
| AIC | −1.56 | 0.50 | 0.68 |
| SC | −1.31 | 0.67 | 0.84 |
| Breusch-Godfrey Test | 12.8** | 3.2 | 4.4 |
| White Test | 5.9 | 5.3 | 4.0 |
| Standard Errors | N/W | | |

*Notes*: Estimation of (M1) using conditional least squares and contemporaneous data for inflation and GDP growth. Standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Number of observations: 20 (EA), 60 (UK), and 71 (US). $\sigma$: standard error of regression; AIC: Akaike information criterion; SC: Schwarz criterion; *N/W*: Newey and West (1980) standard errors.

Table C2: Taylor Rules with Contemporaneous Data: Full Sample

| | EA (M2') | UK (M2') | US (M2') |
|---|---|---|---|
| $\rho_{i,1} : i_{t-1}$ | 0.104 | 0.687** | 0.583*** |
| | (0.190) | (0.313) | (0.196) |
| $\rho_{i,2} : i_{t-2}$ | 0.770*** | 0.244 | 0.309* |
| | (0.164) | (0.277) | (0.185) |
| $\rho_{i,1} + \rho_{i,2}$ | 0.874*** | 0.931*** | 0.892*** |
| | (0.097) | (0.043) | (0.029) |
| $\rho_u : u_{t-1}$ | 0.815*** | 0.577** | 0.743*** |
| | (0.137) | (0.232) | (0.144) |
| $\alpha$ | 0.305* | 0.128 | 0.134 |
| | (0.177) | (0.088) | (0.081) |
| $\beta_1 : \pi_t - \pi^*$ | 0.115 | 0.111* | 0.082** |
| | (0.075) | (0.063) | (0.037) |
| $\beta_2 : y_t - y^*$ | 0.175*** | 0.179 | 0.179*** |
| | (0.055) | (0.125) | (0.047) |
| $R^2$ | 0.97 | 0.98 | 0.98 |
| $\sigma$ | 0.25 | 0.35 | 0.37 |
| AIC | 0.13 | 0.82 | 0.92 |
| SC | 0.35 | 0.98 | 1.07 |
| Breusch-Godfrey Test | 2.4 | 6.0 | 9.7** |
| White Test | 27.8*** | 64.0*** | 4.7 |
| Standard Errors | W | W | N/W |

*Notes*: Estimation of (M1) using conditional least squares and contemporaneous data for inflation and GDP growth. Standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Number of observations: 55 (EA), 95 (UK), and 106 (US). $\sigma$: standard error of regression; AIC: Akaike information criterion; SC: Schwarz criterion; $W$: White (1980) standard errors; $N/W$: Newey and West (1980) standard errors.

Table C3: Taylor Rules with Contemporaneous Data: Full Sample with Shadow Rates

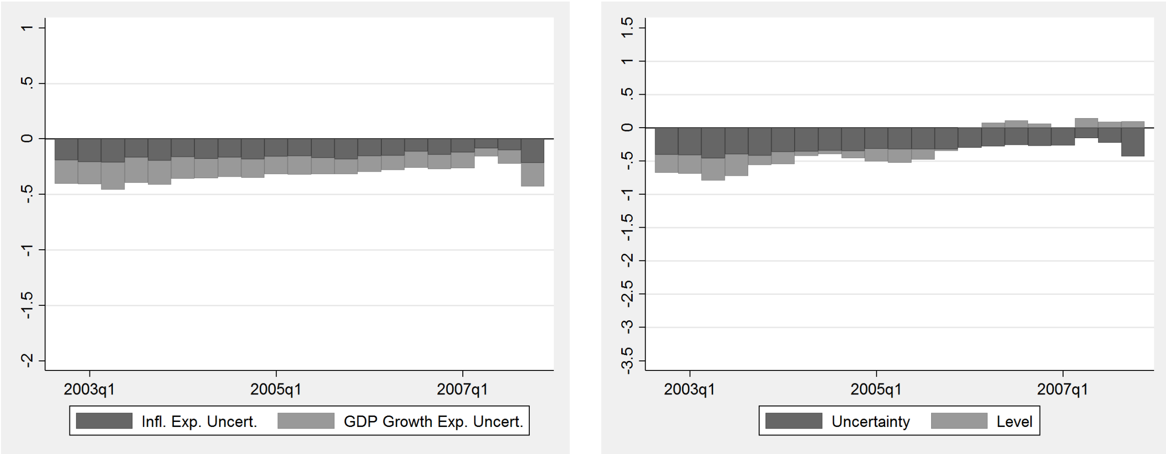
| | EA (M2') | UK (M2') | US (M2') |
|---|---|---|---|
| $\rho_{i,1} : i^s_{t-1}$ | 0.238 | 0.260 | 1.576*** |
| | (0.247) | (0.187) | (0.120) |
| $\rho_{i,2} : i^s_{t-2}$ | 0.670** | 0.640*** | −0.608*** |
| | (0.253) | (0.150) | (0.112) |
| $\rho_{i,1} + \rho_{i,2}$ | 0.908*** | 0.900*** | 0.968*** |
| | (0.068) | (0.052) | (0.015) |
| $\rho_u : u_{t-1}$ | 0.792*** | 0.653*** | −0.375* |
| | (0.219) | (0.188) | (0.213) |
| $\alpha$ | 0.091 | 0.087 | 0.036 |
| | (0.150) | (0.192) | (0.036) |
| $\beta_1 : \pi_t - \pi^*$ | 0.277** | 0.279*** | −0.014 |
| | (0.130) | (0.087) | (0.027) |
| $\beta_2 : y_t - y^*$ | 0.170** | 0.322*** | 0.067*** |
| | (0.067) | (0.099) | (0.025) |
| $R^2$ | 0.96 | 0.97 | 0.98 |
| $\sigma$ | 0.50 | 0.53 | 0.42 |
| AIC | 1.56 | 1.64 | 1.18 |
| SC | 1.78 | 1.80 | 1.33 |
| Breusch-Godfrey Test | 1.4 | 10.1** | 11.9** |
| White Test | 5.1 | 28.2*** | 8.8 |
| Standard Errors | | N/W | N/W |

*Notes*: Estimation of (M1) using conditional least squares and contemporaneous data for inflation and GDP growth. Standard errors are in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Number of observations: 55 (EA), 95 (UK), and 106 (US). $\sigma$: standard error of regression; AIC: Akaike information criterion; SC: Schwarz criterion; $N/W$: Newey and West (1980) standard errors.

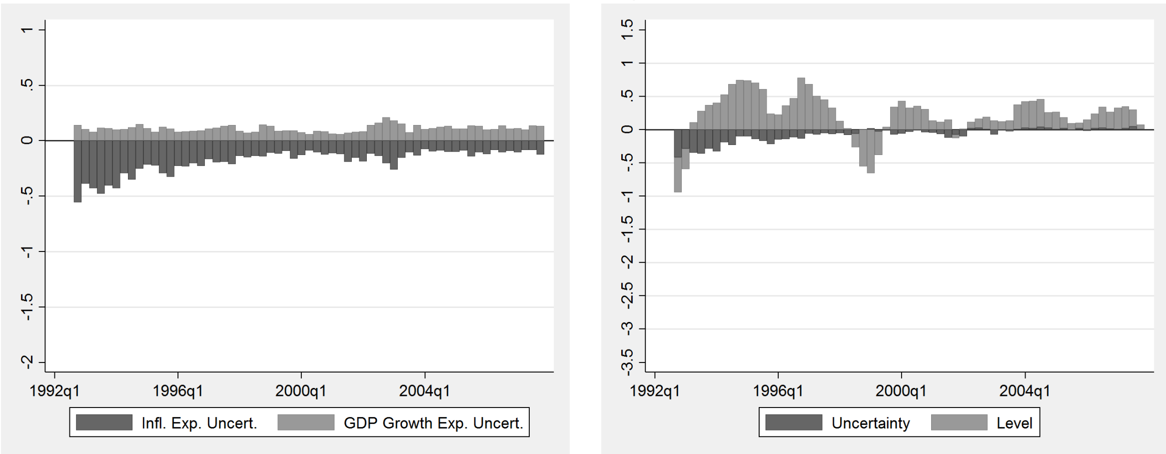
# D Additional Partial Effects of Expectation Uncertainty

Figure D1: Partial Effect of Expectation Uncertainty on the Policy Rate: Pre-Crisis Period

**Euro Area**




**United Kingdom**




**United States**

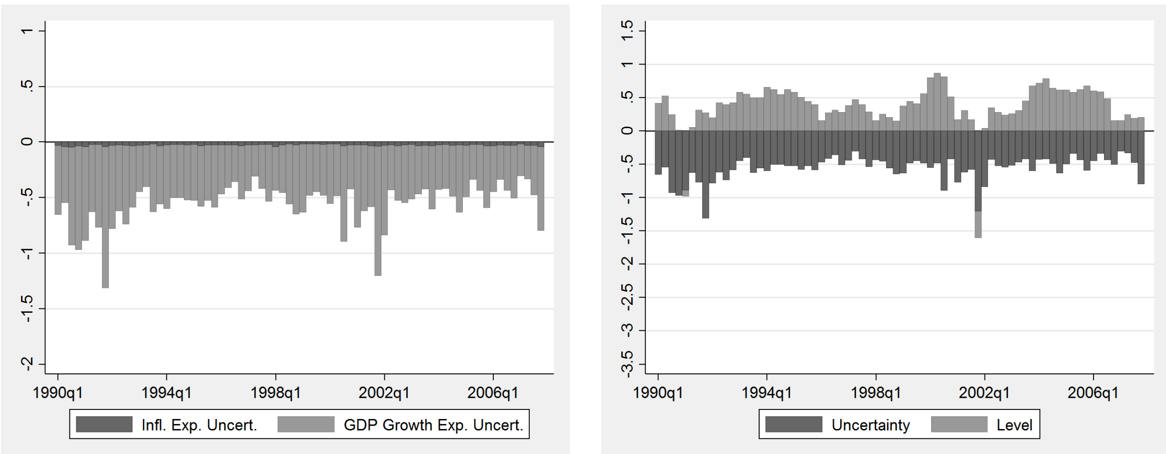
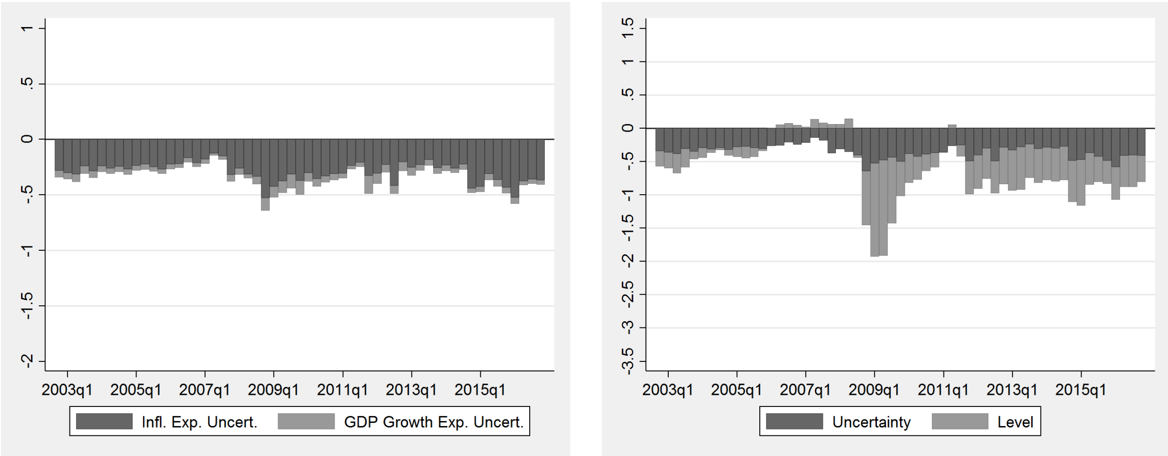
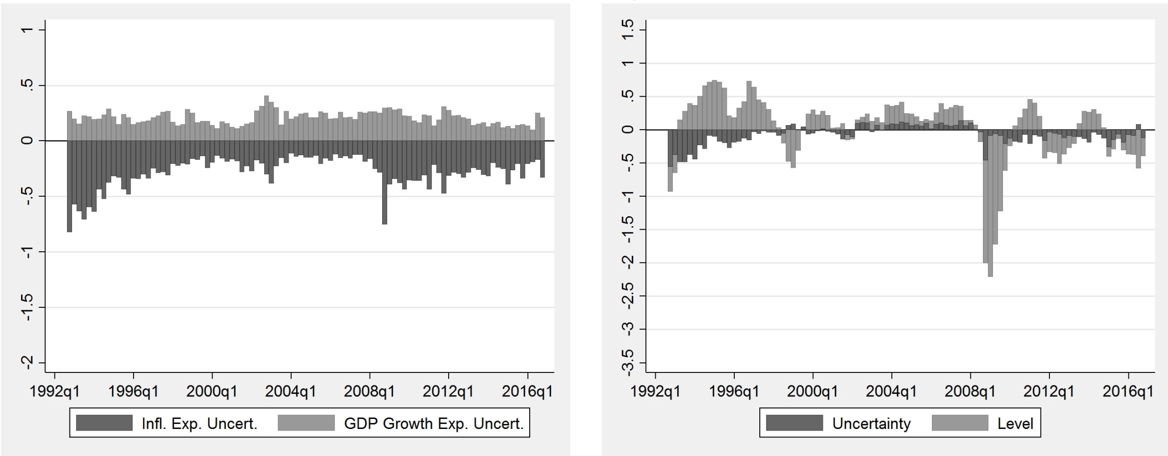


Figure D2: Partial Effect of Expectation Uncertainty on the Policy Rate: Full Sample

## Euro Area




## United Kingdom




## United States