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The Response of Monetary Policy to Uncertainty: Theory and Empirical Evidence for the US

by

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Abstract This paper developes a theoretical model to analyse the impact of uncertainty about the true state of the economy on monetary policy. The theoretical model is tested on US data since the early 1980s. Our estimates suggest that the effect of uncertainty on interest rates was most marked in 1983, when uncertainty increased interest rates by up to 140 basis points, in 1990-91, when uncertainty reduced interest rates by up to 80 basis points and in 1996-2001 when uncertainty reduced interest rates by up to 70 basis points over five years.

Keywords Monetary policy, Uncertainty.

J.E.L. Class C51; C52; E52; E58

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“Uncertainty is not just an important feature of the monetary policy landscape; it is the defining characteristic of that landscape” (Greenspan, 2003).

1) Introduction

Uncertainty is a central issue in monetary policy, as the quote from Alan Greenspan above illustrates. Empirical models, however, rarely take account of this, effectively assuming that policymakers ignore uncertainty. The evident focus of policymakers on uncertainty suggests that this assumption is invalid and therefore that empirical models of monetary policy must account for uncertainty. This paper considers the effects of uncertainty about the true state of the economy on monetary policy, estimating a monetary policy rule that allows for this.

Our empirical model combines elements of Svensson’s (1997) model of inflation forecast targeting with models drawn from the theoretical literature on optimal monetary policy when there is uncertainty about the true state of the economy, most prominently Svensson and Woodford (2003, 2004) and Swanson (2004). In existing models of monetary policy under certainty, monetary policy affects inflation and the output gap directly, so it is optimal for policymakers to use these variables in forming monetary policy. This is the basis for the Taylor rule (Taylor, 1993) model of monetary policy and its’ subsequent refinements (eg Woodford, 2003).

Following the literature on monetary policy under uncertainty, our model assumes instead that monetary policy affects the state of the economy, which in turn affects inflation and the output gap. The optimal monetary policy rule is then a certainty equivalent function of the state of the economy. However, the state of the economy is unobserved, so policymakers must infer this from observations of inflation and the output gap. These latter variables therefore act as indicator variables for monetary policy. The optimal predictor of the true state of the economy is a linear function of inflation and the output gap whose parameters are functions of the variances of these variables, which we assume to be time-varying.

The resultant empirical model resembles the familiar Taylor rule but where the coefficients on inflation and the output gap are functions of the variances of these variables. An increase in, for example, the variance of inflation reduces the parameter on inflation and increases the parameter on the output gap in the equation for the expected state of the economy. This leads to a smaller weight on inflation and a larger weight on the output gap in the monetary policy rule. Similarly, an increase in the variance of the output gap reduces the weight on the output gap and increases the weight on inflation in the equation for the expected state of the economy, resulting in a lower weight on the output gap and a corresponding larger weight on inflation. As a result, the model makes two main testable predictions. First, policymakers should respond less vigorously to variables that are more uncertain, so the weight on inflation in the policy rule should be lower when inflation is more uncertain and similarly for the output gap (cf Peersman and Smets, 1999, Rudebusch, 2001, Soderstrom, 2002, Smets, 2002, Srour, 2003, Walsh, 2004 and Swanson, 2004). Second, uncertainty about one variable may strengthen the response to the other variable, so the weight on the output gap may be larger when inflation is less certain, and vice versa (cf Peersman and Smets, 1999, and Swanson, 2004).[1]

We estimate a system of equations, comprising a monetary policy rule whose parameters are functions of the variances of inflation and the output gap and equations for inflation and the output gap whose error terms have GARCH processes, from which these variances are derived. We use data since 1983 since this is when the Fed switched to using the interest rate as the tool of monetary policy and since continuity in monetary policy objectives has allowed stable policy rules to be estimated over this period (eg Judd and Rudebusch, 1998). We find that the behaviour of monetary policymakers is consistent with the predictions of the theoretical literature. Monetary policy responds less to inflation and the output gap when these variables are more uncertain. We also find that the response to inflation is stronger when the output gap is more uncertain, and vice versa. We quantify the impact of uncertainty by constructing a measure of the counterfactual interest rate, which would have been observed if there had been no uncertainty. We find that the impact of uncertainty was most marked in 1983, when uncertainty increased interest rates by up to 140 basis points, in 1990-91, when uncertainty reduced interest rates by up to 80 basis points and in 1996-2001 when uncertainty reduced interest rates by up to 70 basis points over five years.

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[1] Senda (2005) provides evidence on how the parameters of the Taylor rule affect inflation and output variability. A higher response to inflation lowers the variance of inflation but increases the variance of the output gap, whereas a higher response to the output gap has the effect of reducing both the variances of inflation and the output gap.

The remainder of the paper is structured as follows. Section 2 explains our methodology. Section 3 presents our estimates. Section 4 summarizes our findings and offers some conclusions.

2) Methodology

The central bank has the loss function

$$E_{t-1}\sum_{i=0}^{\infty}\delta^{i}\{\frac{1}{2}[(\pi_{t+i}-\pi^{T})^{2}+\lambda y^{2}{}_{t+i}]\} \tag{1}$$

where we assume

$$y_{t+1}=\beta_{x}X_{t+1}+\beta_{y}y_{t}+\eta_{t+1} \tag{2}$$

$$\pi_{t+1}=\pi_{t}+\alpha_{x}X_{t}+\alpha_{y}y_{t}+\upsilon_{t+1} \tag{3}$$

$$X_{t+1}=\phi X_{t}-\alpha_{r}(i_{t}-E_{t}\pi_{t+1})+\varepsilon_{t+1} \tag{4}$$

y is the output gap, X is the state of the economy[2], π is the inflation rate, π^{T} is the inflation target, i is the nominal interest rate and δ is the discount factor.

Equation (2) is an aggregate demand equation in which the output gap at time *t* is affected by the state of the economy. η is a demand shock, assumed to be distributed as $N(0,\sigma_{\eta t}^{2})$. The variance of η evolves as a GARCH(1,1)

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[2] Although we treat X as a scalar for simplicity, in general it may have many elements; see Swanson (2004).

process, since we assume $\sigma^2_{\eta t} = \lambda_0 + \lambda_1 \eta^2_{t-1} + \lambda_2 \sigma^2_{\eta t-1}$ and λ_0, λ_1 and λ_2 are parameters. We use the implied variance of η to measure uncertainty about the output gap (for a similar approach, see Grier and Perry, 2000). Equation (3) is a Phillips curve in which inflation at time *t* is affected by lagged inflation and the state of the economy and the output gap at time (t-1). υ_t is a shock to inflation assumed to be distributed as $N(0, \sigma^2_{\pi t})$. The variance of υ_t also evolves as a GARCH(1,1) process, since we assume $\sigma^2_{\pi t} = k_0 + k_1 \upsilon^2_{t-1} + k_2 \sigma^2_{\pi t-1}$ and k_0, k_1 and k_2 are parameters, allowing us to use the implied variance of υ_t to measure uncertainty about inflation. Equation (4) describes how the state of the economy at time *t* is affected by the state of the economy in the previous period and by the real interest rate at time (t-1), where ε is a shock to the state of the economy that is assumed to be distributed as $N(0, \sigma^2_{\varepsilon})$.

We begin by analyzing the problem in the case where X is observed by the policymaker. Policymakers are assumed to act at the beginning of period t and know all parameters of the model and the history of all variables up to the end of period (t-1).[3]

We solve the policymaker's optimization problem using the approach of Svensson (1997). Since a change in the nominal interest rate affects *X* in the next period, which in turn affect inflation with a further one-period lag, it is convenient to express the first-order condition in terms of *X* and then infer the

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[3] The model differs from the model of Brainard (1967) in that there is no uncertainty about the values of parameters.

optimal monetary policy rule from (4). Following Svensson (1997), we express the policymaker's problem as

(5) $$V(\pi_t) = \min_{X_t}\{(\frac{1}{2}[(\pi_t - \pi^T)^2 + \lambda y^2{}_t]) + \delta E_{t-1}V(\pi_{t+1})\}$$

where

(6) $$V(\pi_t) = \kappa_0 + \frac{\kappa}{2}(\pi_t - \pi^T)^2$$

The parameters κ_0 and κ are functions of the other parameters of the model. The first order condition is

(7) $$\begin{aligned} &E_{t-1}\{\lambda y_t \frac{dy_t}{dX_t} + \delta \frac{dV(\pi_{t+1})}{d\pi_{t+1}} \frac{d\pi_{t+1}}{dX_t}\} = \lambda\beta_x E_{t-1}y_t + \alpha_x \delta\kappa E_{t-1}(\pi_{t+1} - \pi^T) \\ &= \lambda\beta_x{}^2 X_t + \lambda\beta_x\beta_y y_{t-1} + \alpha_x\delta\kappa E_{t-1}(\pi_{t+1} - \pi^T) = 0 \end{aligned}$$

or

(8) $$E_{t-1}X_{t+1} = -\theta E_{t-1}(\pi_{t+2} - \pi^T) - \frac{\beta_y}{\beta_x} E_{t-1}y_t$$

where $\theta = \frac{\alpha_x \delta k}{\lambda\beta_x{}^2}$. θ is a function of the other parameters of the model. Svensson (1997) discusses options for determining κ, but we do not analyze this as we do not seek to identify the structural parameters of the model.

Using (4), (3) and (2), we can express (8) as

$$\begin{aligned} & E_{t-1}[\phi X_t - \alpha_r(i_t - E_{t-1}\pi_{t+1})] = -\theta E_{t-1}(\pi_{t+2} - \pi^T) - \frac{\beta_y}{\beta_x} E_{t-1} y_t \\ & = -\theta E_{t-1}\{\pi_{t+1} + \alpha_x X_{t+1} + \alpha_y y_{t+1} - \pi^T\} - \frac{\beta_y}{\beta_x} E_{t-1} y_t \\ & = -\theta E_{t-1}\{(\pi_{t+1} - \pi^T) + \alpha_y y_{t+1} + \alpha_x[\phi X_t - \alpha_r(i_t - E_{t-1}\pi_{t+1})]\} \\ & -\frac{1}{\beta_x} E_{t-1} y_{t+1} + E_{t-1}[\phi X_t - \alpha_r(i_t - E_{t-1}\pi_{t+1})] \end{aligned} \tag{9}$$

Gathering terms and solving for the interest rate, the optimal policy rule is

$$\hat{i}_t = -\frac{\pi^T}{\alpha_r \alpha_x} + \frac{\phi}{\alpha_r} E_{t-1} X_t + (1 + \frac{1}{\alpha_r \alpha_x}) E_{t-1}\pi_{t+1} + \frac{1 + \theta \alpha_y \beta_x}{\theta \alpha_r \alpha_x \beta_x} E_{t-1} y_{t+1} \tag{10}$$

where $\hat{i}$ is the desired nominal interest rate. This is the optimal monetary policy rule in the case where X is observed. This rule satisfies certainty equivalence. The coefficient on expected inflation in (10) exceeds unity, so the Taylor Principle is satisfied. We also note that we could express both X and π in terms of variables dated at period (t-1) and earlier. However, it is more convenient for our purposes to use (10).

We now analyze the case where X is unobservable. Here, policymakers must use the expectation of X given information available. Following Swanson (2004), we note that since X, y and $\pi - \pi^T$ are jointly normally distributed, we can express the expectation of the unobservable variable X as a function of the other two variables:

(11) $$E_{t-1}X_t = \gamma_{1t}E_{t-1}(\pi_{t+1} - \pi^T) + \gamma_{2t}E_{t-1}y_{t+1}$$

Equation (11) is the optimal linear predictor of X given the information available to the policymaker at time (t-1). As with the policy rule in (10), the expectation of X can also be expressed in terms of variables dated at time (t-1) and earlier (again, see Swanson, 2004, for an example of this), but it is again more convenient for our purposes to work with (11). The coefficients of (11) vary over time; specifically, they are functions of the volatilities of the shocks to inflation and the output gap. Thus, an increase in the volatility of η, the disturbance to the output gap equation will reduce γ_{2t} and increase γ_{1t}. Similarly, an increase in υ, the volatility of the inflation equation will reduce γ_{1t} but increase γ_{2t} (see the discussion in Swanson, 2004, for details).

Substituting (11) into (10) we obtain the optimal monetary policy rule in terms of observables:

(12) $$\hat{i}_t = \omega_{0t} + \omega_{1t}E_{t-1}\pi_{t+1} + \omega_{2t}E_{t-1}y_{t+1},$$

where

$\omega_{0t} = -\dfrac{\pi^T(1+\gamma_{1t}\phi\alpha_x)}{\alpha_r\alpha_x}$, $\omega_{1t} = 1 + \dfrac{1+\gamma_{1t}\phi\alpha_x}{\alpha_r\alpha_x}$, and $\omega_{2t} = \dfrac{\gamma_{2t}\phi}{\alpha_r} + \dfrac{1+\theta\alpha_y\beta_x}{\theta\alpha_r\alpha_x\beta_x}$.

In contrast to (10), the policy rule in (12) does not satisfy certainty equivalence since the coefficients depend on the volatilities of the inflation and the output gap equations (although we note that the Taylor Principle is still satisfied). Non-certainty equivalence arises because the expected value of X must be inferred from observations of inflation and the output gap, so these latter variables act as indicator variables for monetary policy (Svensson and Woodford, 2003, 2004).

It is convenient to re-write the policy rule in (12) as

$$\hat{i}_t = \rho_{0t} + \rho_{\pi t} E_{t-1}\pi_{t+1} + \rho_{yt} E_{t-1} y_{t+1} \tag{13}$$

where

$\rho_{0t} = \rho_0 + \rho_0^{\pi}\sigma_{\pi t}^2 + \rho_0^{y}\sigma_{yt}^2$, $\rho_{\pi t} = \rho_{\pi} + \rho_{\pi}^{\pi}\sigma_{\pi t}^2 + \rho_{\pi}^{y}\sigma_{yt}^2$ and $\rho_{yt} = \rho_y + \rho_y^{\pi}\sigma_{\pi t}^2 + \rho_y^{y}\sigma_{yt}^2$. The inverse relationship between the volatility of the disturbance to the inflation equation and γ_{1t} implies that $\rho_{\pi}^{\pi} < 0$ in (13), while the inverse relationship between the volatility of the disturbance to the output gap equation and γ_{2t} implies that $\rho_y^y < 0$. The positive relationship between the volatilities of the inflation and output gap equation disturbances and γ_{2t} and γ_{1t} respectively implies $\rho_{\pi}^{y} > 0$ and $\rho_y^{\pi} > 0$. All the parameters of (13) are identifiable.

The adjustment of the actual interest rate towards the target is described by

(14) $$i_t = \rho_i(L)i_{t-1} + (1-\rho_i)\hat{i}_t\,,$$

where $\hat{i}_t$ is given by (13), $\rho_i(L) = \rho_{i1} + \rho_{i2}L + ... + \rho_{in}L^{n-1}$ and we can use $\rho_i \equiv \rho_i(1)$ as a measure of interest rate persistence. Using (13), we write (14) as[4]

(15) $$i_t = (1-\rho_i)\rho_{0t} + \rho_i(L)i_{t-1} + (1-\rho_i)\left\{\rho_{\pi t}E_{t-1}\pi_{t+1} + \rho_{yt}E_{t-1}y_{t+1}\right\}$$

In (2), aggregate demand depends on the unobserved state of the economy. We therefore substitute (4) into (2):

(16) $$y_t = \theta_{y1}y_{t-1} - \theta_{y2}y_{t-2} - \theta_r(i_{t-1} - E_{t-1}\pi_t) + \xi_t$$

where $\theta_{y1} = \phi + \beta_y$, $\theta_{y2} = \phi\beta_y$, $\theta_r = \alpha_r\beta_x$, $\xi_t = \eta_t - \phi\eta_{t-1} + \beta_x\varepsilon_t$. ξ is a demand shock, assumed to be distributed as $N(0,\sigma_{yt}^2)$. Since the variance of ξ is proportional to that of η, we assume that this also evolves as a GARCH(1,1)

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[4] Equation (15) encompasses an alternative model of the effects of uncertainty on monetary policy, given by $i_t = (1-\rho_i)\rho_0 + \rho_i(L)i_{t-1} + (1-\rho_i)\left\{\rho_{\pi t}E_t\pi_{t+1} + \rho_{yt}E_t y_{t+1} + \rho_{\sigma_\pi}\sigma_{\pi t}^2 + \rho_{\sigma_y}\sigma_{yt}^2\right\}$. This model simplifies to the model in Dolado et al (2004) if $\rho_\pi^\pi = \rho_\pi^y = \rho_y^\pi = \rho_y^y = 0$. The model in Dolado et al (2004) can be derived from a second-order approximation to a non-quadratic objective function in which policymakers care about inflation and the output gap in the context of a model that also comprises a linear aggregate demand and a non-linear aggregate supply equation. The Dolado et al (2004) model differs from the model in (15), in that uncertainty does not affect the response of policymakers to inflation or output.

process, so $\sigma_{yt}^2 = \phi_0 + \phi_1 \xi_{t-1}^2 + \phi_2 \sigma_{yt-1}^2$ where ϕ_0 , ϕ_1 and ϕ_2 are parameters. We can then use the implied variance of ξ to measure uncertainty about the output gap.

Using (2), we can express the Phillips curve (3) as

(17) $$\pi_t = \pi_{t-1} + \delta_{y1} y_{t-1} - \delta_{y2} y_{t-2} + \zeta_t$$

where $\delta_{y1} = \alpha_y + \frac{\alpha_x}{\beta_x}$, $\delta_{y2} = \frac{\alpha_x \beta_y}{\beta_x}$ and $\zeta_t = \upsilon_t - \frac{\alpha_x}{\beta_x} \eta_{t-1}$. Since the variance of ζ is proportional to that of υ, we assume that this also evolves as a GARCH(1,1) process, so $\sigma_{\pi t}^2 = \mu_0 + \mu_1 \zeta_{t-1}^2 + \mu_2 \sigma_{\pi t-1}^2$ and μ_0 , μ_1 and μ_2 are parameters, allowing us to use the implied variance of ζ to measure uncertainty about inflation. Our empirical model comprises (15), (16) and (17).

We can illustrate the effects of uncertainty on monetary policy by using estimates of our model of monetary policy under uncertainty to infer what interest rates would have been if there had been no uncertainty. This is given by the counterfactual interest rate

(18) $$i_t^c = (1-\hat{\rho}_i)\hat{\rho}_0 + \hat{\rho}_i(L) i_{t-1} + (1-\hat{\rho}_i)\left\{\hat{\rho}_\pi E_{t-1}\pi_{t+1} + \hat{\rho}_y E_{t-1} y_{t+1}\right\}$$

where $\hat{\rho}_0$, $\hat{\rho}_i$, $\hat{\rho}_\pi$ and $\hat{\rho}_y$ are estimates of the corresponding parameters in (15). Equation (18) is simply the fitted value of (15) but where $\sigma_{\pi t}^2 = \sigma_{yt}^2 = 0$ for all *t*. We can quantify the effect of uncertainty on monetary policy using $\hat{i}_t - i_t^C$, the gap between the fitted value of the interest rate from estimates of (15) and the counterfactual interest rate, where a positive value of this gap indicates that interest rates were higher because of uncertainty.

3) Empirical Results

We use quarterly data for 1983Q1-2003Q4. The sample corresponds to the chairmanships of Paul Volcker and Alan Greenspan, but excludes the period when the Federal Reserve targeted non-borrowed reserves, rather than interest rates[5]. We use the Effective Federal Funds rate as the nominal interest rate, inflation is the annual proportional change in the consumer price index and the output gap is the difference between the logarithm of GDP and the logarithm of the Congressional Budget Office measure of potential GDP. Preliminary unit root analysis (the results are not reported but are available on request) showed that the output gap is stationary whereas the order of integration of the interest rate and inflation is more ambiguous; we assume that all variables are stationary (see also Dolado et al, 2004 and Clarida et al, 2000, for a discussion of similar issues).

We begin with estimates of a simple Taylor rule model of monetary policy, in which the weights on inflation and the output gap are not functions of the volatilities of inflation and the output gap. This is obtained by setting $\rho_0^\pi = \rho_0^y = \rho_\pi^\pi = \rho_\pi^y = \rho_y^\pi = \rho_y^y = 0$ in (15). This simple model will serve as a reference point for other estimates. Our estimates are presented in column (i) of

Table 1a. We find that the data prefer a specification in which interest rates respond to the expected values of inflation and the output gap one quarter ahead and in which two lags of the interest rate are used to capture the persistence effect. We treat inflation and the output gap as endogenous, replacing expected future variables with actual values and then estimate by GMM using lagged variables as instruments. We estimate that the weight on inflation is 1.58, that on output is 0.84 and the persistence parameter is 0.96. These estimates, which are comparable to other results in the literature (eg Judd and Rudebusch, 1998, Clarida et al, 2000, Dolado et al, 2004, Castelnuovo, 2003), satisfy the Taylor principle that excessive inflation should trigger increases in the real interest rate. They also indicate a moderately relatively strong response to the output gap (although this effect is insignificant) and show considerable interest rate smoothing. However, as Table 1b shows, the estimates fail the parameter stability test.

Column (ii) of Table 1a presents estimates of the system comprising equations (15), (16) and (17), while Table 1b presents measures of goodness of fit and misspecification tests[6]. Since the conditional variance for inflation and output are generated regressors (see e.g. Pagan, 1984 and Pagan and Ullah, 1988), the estimated variances from equations (16) and (17) may be biased and inconsistent measures of the true level of uncertainty if these equations are

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[5] Rudebusch (1998) points out that it is hard to estimate a stable US policy rule for the whole postwar period.

[6] We experimented with a variety of alternative leads and lags for the variables in (15), (16) and (17) but obtained best results for the specification used in the main text. Full details of these and other unreported estimates are available from the authors.

misspecified. To check this, we follow Pagan and Ullah (1988) in testing the squared residuals of the estimated GARCH models for neglected serial correlation of up to order 4.

The estimates of equations (16) and (17) seem sensible; the negative estimate on θ_{y2} is consistent with (16), whereas the negative estimate on δ_{y2} is consistent with (17). The tests presented in Table 1b do not indicate misspecification, suggesting that we may have adequate measures of the conditional heteroscedasticity of inflation and the output gap. The variances of inflation and the output gap implied by the estimates in column (ii) are presented in figure 1.

Our measures of uncertainty, presented in figure 1 seem plausible. Inflation uncertainty is greatest in the early part of the sample, following the change in Fed Chair in 1987, in the early 1990s and after the third quarter of 2001. Output gap uncertainty declines throughout the 1980s with resurgences in the early 1990s and after late 1999. The low levels of uncertainty shown in figure 1 in the 1990s reflects the unusual stability of output and inflation in that period that has been noted by, among others, Mankiw (2001).

Considering estimates of the policy rule (15) in column (ii) of Table 1a, we find that ρ_π, ρ_π^π, ρ_π^y, ρ_y, ρ_y^π and ρ_y^y are significant but that ρ_0^π and ρ_0^y are not. There is no evidence of parameter instability (in contrast to the estimates in column (i)). Eliminating insignificant variables from the system, we obtain a simplified model whose estimates are presented in column (iii). The inclusion of uncertainty effects improves the fit of the interest rate equation model and the estimates of this equation now pass the parameter stability test. The effects of uncertainty are statistically well-determined. We find that $\rho_\pi^\pi < 0$ and $\rho_y^y < 0$, indicating that monetary policy is less responsive to inflation and the output gap when these are more uncertain. We also find that $\rho_\pi^y > 0$ and $\rho_y^\pi > 0$, showing that monetary policy is more responsive to one variable when the other is more uncertain. These estimates are consistent with the predictions of the theoretical literature, suggesting that the behavior of policymakers in the face of uncertainty conforms to these requirements for optimal monetary policy. [7]

We illustrate the impact of uncertainty on interest rates in figure 2, where we plot $\hat{i}_t - i_t^C$, the gap between the fitted and counterfactual interest rates, with estimated confidence intervals of +/- two standard errors[8]. There are three periods in which uncertainty had a significant effect on interest rates: early-mid 1983, when uncertainty increased interest rates by up to 140 basis points, 1990-91 when uncertainty reduced interest rates by up to 80 basis points and 1996-2001 when uncertainty reduced interest rates by up to 70 basis points over five years.

These are plausible findings. The large effect in 1983 reflects uncertainty about the effects of the switch to the interest rate as the policy instrument and may also reflect continuing uncertainty about change in policy instituted by Paul Volcker a few years earlier; the effect of the early 1990s may reflect the

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[7] The constant in this model reflects the neutral rate of interest; the fact that the estimates in columns (ii) and (iii) of Table 1 do not fail the parameter stability test suggests that the data do not reject the assumption that the neutral rate of interest is constant.

recession of 1990-1, while the sustained effect of the late 1990s reflects the debate about whether the increase in output over the 1990s reflected a rapid increase in the underlying equilibrium level of output (e.g. Gordon, 1997). We can calculate the relative contributions of inflation and output gap uncertainty to the gap between the fitted and counterfactual interest rates using[9]

(19) $$\hat{i}_t - i_t^c = (1-\hat{\rho}_i)\{[\hat{\rho}_\pi^\pi E_t\pi_{t+1} + \hat{\rho}_y^\pi E_t y_{t+1}]\sigma^2{}_{\pi t} + [\hat{\rho}_\pi^y E_t\pi_{t+1} + \hat{\rho}_y^y E_t y_{t+1}]\sigma^2{}_{yt}\}$$

Figure 3 depicts the contributions of inflation and output gap uncertainty to the gap between the fitted and counterfactual interest rates, constructed using the decomposition in (19). The gap is more closely correlated with the output gap effect, suggesting that the impact of uncertainty on interest rates is largely driven by output gap uncertainty, which generally outweighs the effect of inflation uncertainty. This is consistent with the comments of policymakers, whose focus is usually on output uncertainty (e.g. Meyer, 1999, Greenspan, 2003, and Yellen, 2003).

Our model assumes that the only effect of uncertainty on monetary policy rules is on the response of the interest rate to inflation and the output gap. We also considered a model in which uncertainty affects the degree of interest rate

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[8] Recursive GMM is used to derive recursive estimates and standard errors of the parameters reported in (15) which are then used to construct $\hat{i}_t - i_t^C$ +/- two standard errors.

[9] We use our preferred specification in column (iii) of Table 1; this does not include the term $(1-\hat{\rho}_i)[\hat{\rho}_0^\pi\sigma^2{}_{\pi t} + \hat{\rho}_0^y\sigma^2{}_{yt}]$.

smoothing[10]. This was not successful. We also considered an alternative model in which interest rates are affected by asset price disequilibria, measured by the lag of the log(dividend-price ratio) based on the S&P composite stock price index. As an alternative measure of asset prices, we also considered whether interest rates are affected by the growth of the S&P index (following Bernanke and Gertler, 1999, 2001). Consistent with Bernanke and Gertler (1999), we failed to find any effect.

We performed a number of robustness checks. We estimated our system using two alternative volatility measures, (i) derived from recursive estimates of our GARCH systems and (ii) measured as a four quarter backward-looking moving average of the measures derived from the estimates of Table 1. We also used the Kalman Filter to estimate the equation for the unobserved state of the economy equation in (4) jointly with the aggregate demand equation in (2), the Phillips curve in (3) and the optimal monetary policy rule in (15).[11] We also used alternative measures of the output gap, obtained by (i) using the Hodrick-Prescott

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[10] The model estimated was $i_t = \rho_0 + \rho_{it}(L)i_{t-1} + (1-\rho_{it})\{\rho_{\pi t}E_t\pi_{t+1} + \rho_{yt}E_t y_{t+1}\}$, where $\rho_{it}(L) = \rho_{i1t} + \rho_{i2t}L + ... + \rho_{\text{int}}L^{n-1}$ and $\rho_{ijt} = \rho_{ij} + \rho_{ij}^{\pi}\sigma_{\pi t}^2 + \rho_{ij}^{y}\sigma_{yt}^2$, *j*=1,…,n. If policymakers adjust interest rates less frequently when uncertainty is greater (eg, Goodhart, 1999) then $\rho_{ij}^{\pi} > 0$ and $\rho_{ij}^{y} > 0$.

[11] Using the Kalman Filter, we estimated: $\phi =$0.879 (standard error = 0.064), $\alpha_r =$–0.071 (standard error = 0.032), $\beta_x =$0.676 (standard error = 0.039), $\beta_y =$0.408 (standard error = 0.110), $\alpha_x =$0.073 (standard error = 0.002) and $\alpha_y =$0.010 (standard error = 0.002). These estimates suggest: $\theta_{y1} = \phi + \beta_y =$ 1.287, $\theta_{y2} = \phi\beta_y =$ -0.358, $\theta_r = \alpha_r\beta_x =$ -0.048, $\delta_{y1} = \alpha_y + \frac{\alpha_x}{\beta_x} =$0.118, and $\delta_{y2} = \frac{\alpha_x\beta_y}{\beta_x} =$ -0.044. These are comparable to the direct estimates of θ_{y1}, θ_{y2}, θ_r, δ_{y1} and δ_{y2} reported in column (iii) of Table 1.

(1997) filtered level of output as a measure of potential output and (ii) using real-time output data from the database maintained by the Federal Reserve Bank of Philadelphia. We detrended the real-time output using two different filters, namely the Hodrick-Prescott filter and the band pass filter of Christiano and Fitzgerald (2003). We also estimated our system using a measure of the average real interest rate, constructed as the difference between a four quarter moving average of the nominal interest rate and a four quarter moving average of the inflation rate (see Rudebusch, 2001). Table 2 summarises the average weights on inflation and the output gap implied by these estimates and the correlations between the implied values of $\rho_{\pi t}$ and ρ_{yt} and those implied by the estimates reported in column (iii) of Table 1. In most cases, the average weights on inflation and the output gap are similar to those in Table 1, with correspondingly high correlations.

4) Conclusions

This paper has argued that the effects of uncertainty about the true state of the economy can be analyzed using a simple 3-equation system that captures the main features of the theoretical literature on optimal monetary policy in this case. The system features a monetary policy rule that extends the familiar Taylor rule representation of monetary policy by allowing the weights on inflation and the output gap to depend on the variances of inflation and the output gap, these latter being derived from GARCH models. Estimating our model using data since the early 1980s, we have found that the actions of policymakers are consistent with the principles of optimal policy in that they respond less vigorously to inflation and the output gap when these are less certain. They also respond more strongly to one variable when the other is more uncertain.

We have used our model to calculate the counterfactual interest rate that our estimates suggest would have been observed if there had been no uncertainty. Using this, we found that uncertainty has a marked impact on monetary policy in three periods. We find that uncertainty increased interest rates following the switch to the interest rate as the tool of policy in the early 1980s, but that uncertainty reduced interest rates during the recession of the early 1990s and during the long expansion of the mid- late 1990s, when debate concerned the sustainability of high output growth.

Our findings suggest that the effects of uncertainty can be detected using simple empirical models of monetary policy rules. Our work can be extended in several ways. We might embed on analysis of monetary policy in a more sophisticated structural model in order to estimate the parameters of a structural model of optimal monetary policy. We might estimate our model over different time periods in order to identify occasions when the behavior of policymakers was not consistent with the predictions of models of optimal monetary policy. We might estimate our model using data for different countries in order to investigate the impact of different monetary policy regimes on the response to uncertainty. We intend to address these issues in future work.

Table 1
Model estimates using GMM. Sample: 1983Q1-2003Q4

Interest rate equation: $i_t = (1-\rho_i)\rho_{0t} + \rho_i(L)i_{t-1} + (1-\rho_i)\left\{\rho_{\pi t}E_{t-1}\pi_{t+1} + \rho_{yt}E_{t-1}y_{t+1}\right\}$, where

$\rho_{0t} = \rho_0 + \rho_0^{\pi}\sigma_{\pi t}^2 + \rho_0^{y}\sigma_{yt}^2$, $\rho_{\pi t} = \rho_\pi + \rho_\pi^{\pi}\sigma_{\pi t}^2 + \rho_\pi^{y}\sigma_{yt}^2$ and $\rho_{yt} = \rho_y + \rho_y^{\pi}\sigma_{\pi t}^2 + \rho_y^{y}\sigma_{yt}^2$.

Output gap equation: $y_t = \theta_{y1}y_{t-1} - \theta_{y2}y_{t-2} - \theta_r(i_{t-1} - E_{t-1}\pi_t) + \xi_t$, $\sigma_{yt}^2 = \phi_0 + \phi_1\xi_{t-1}^2 + \phi_2\sigma_{yt-1}^2$.

Inflation equation: $\pi_t = \pi_{t-1} + \delta_{y1}y_{t-1} - \delta_{y2}y_{t-2} + \zeta_t$, $\sigma_{\pi t}^2 = \mu_0 + \mu_1\zeta_{t-1}^2 + \mu_2\sigma_{\pi t-1}^2$.

a) parameter estimates

	(i)	(ii)	(iii)
Interest rate equation			
ρ_0^{π}		-5.125 (13.290)	
ρ_0^{y}		10.641 (14.084)	
ρ_i	0.956 (0.032)	0.880 (0.014)	0.848 (0.015)
ρ_π	1.584 (0.749)	1.652 (0.425)	1.614 (0.225)
ρ_π^{π}		-1.585 (0.512)	-4.402 (0.562)
ρ_π^{y}		1.915 (0.498)	5.614 (0.461)
ρ_y	0.836 (0.530)	1.226 (0.401)	1.229 (0.132)
ρ_y^{π}		2.071 (0.407)	2.644 (0.341)
ρ_y^{y}		-2.734 (0.602)	-3.634 (0.436)
Output gap equation			
θ_{y1}		1.237 (0.117)	1.256 (0.025)
θ_{y2}		-0.343 (0.113)	-0.344 (0.023)
θ_r		-0.026 (0.007)	-0.024 (0.003)
ϕ_0		0.015 (0.014)	0.013 (0.013)
ϕ_1		0.115 (0.041)	0.112 (0.040)
ϕ_2		0.875 (0.050)	0.864 (0.046)
Inflation equation			
δ_{y1}		0.139 (0.040)	0.136 (0.034)
δ_{y2}		-0.119 (0.034)	-0.120 (0.033)
μ_0		0.042 (0.019)	0.040 (0.016)
μ_1		0.600 (0.180)	0.594 (0.169)
μ_2		0.336 (0.141)	0.357 (0.138)

Notes: Column (i) reports the parameter estimates of equation (15) in main text where we have imposed $\rho_0^\pi = \rho_0^y = \rho_\pi^\pi = \rho_\pi^y = \rho_y^\pi = \rho_y^y = 0$. Columns (ii)-(iii) report the parameter estimates of the system involving equations (15), (16) and (17) in main text. Numbers in parentheses are the standard errors of the estimates.

b) Goodness of fit and diagnostics

	(i)	(ii)	(iii)
Interest rate equation			
Average inflation effect	1.584	1.951	2.555
Average output gap effect	0.836	0.741	0.571
Adjust. R^2	0.961	0.963	0.964
s.e. of regression	0.471	0.451	0.451
J stat	11.00 [0.81]	17.92 [0.12]	17.99 [0.12]
Parameter stability	2.11 [0.03]	0.14 [0.97]	0.15 [0.97]
Output gap equation			
Adjust. R^2		0.943	0.943
s.e. of regression		0.494	0.497
Parameter stability		0.13 [0.93]	0.14 [0.93]
Neglected ARCH		0.47 [0.75]	0.48 [0.75]
Inflation equation			
Adjust. R^2		0.786	0.792
s.e. of regression		0.489	0.487
Parameter stability		1.61 [0.20]	1.62 [0.20]
Neglected ARCH		0.87 [0.48]	0.88 [0.48]

Notes: For column (i), J stat is a chi-square test of the model's overidentifying restrictions (Hansen, 1982). For columns (ii) and (iii), J stat is a chi-square test of the system's overidentifying restrictions. The instruments are a constant, one lag of σ_{yt}^2 and $\sigma_{\pi t}^2$ and six lags of the interest rate, inflation and the output gap. Parameter stability is an F test of parameter stability (see Lin and Teräsvirta, 1994, and Eitrheim and Teräsvirta, 1996). Neglected ARCH is the Pagan and Ullah (1988) Lagrange Multiplier F test on the squared residuals for remaining serial correlation of order 4. Numbers in square brackets are the probability values of the test statistics.

Table 2

Estimates based on alternatives measures

	Recursive estimates	4-quarter MA estimates	Kalman Filter estimates	Hodrick-Prescott Filter estimates	Real-time output estimates (HP)	Real-time output estimates (BP)	Average real interest rate estimates
Average inflation effect	2.334	1.930	1.693	1.350	1.778	1.380	2.594
Correlation [1]	0.672	0.520	0.560	0.872	0.558	0.501	0.994
Average output gap effect	1.070	0.420	1.073	1.709	1.444	1.748	0.772
Correlation [2]	0.685	0.564	0.515	0.907	0.646	0.534	0.985

Notes:

[1] Correlation between the implied values of $\rho_{\pi t} = \rho_{\pi} + \rho_{\pi}^{\pi}\sigma_{\pi t}^{2} + \rho_{\pi}^{y}\sigma_{yt}^{2}$ and that implied by the estimate of Table 1 column (iii).

[2] Correlation between the implied values of $\rho_{yt} = \rho_{y} + \rho_{y}^{\pi}\sigma_{\pi t}^{2} + \rho_{y}^{y}\sigma_{yt}^{2}$ and that implied by the estimate of Table 1 column (iii).

[3] The average real interest rate is the difference between $\bar{i}_{t-1}$ and $E_{t-1}\bar{\pi}_{t}$, where $\bar{i}_{t-1}$ and $E_{t-1}\bar{\pi}_{t}$ are the four quarter moving averages of the nominal interest and inflation rates respectively.

[4] Real-time output estimates (HP) use the Hodrick-Prescott Filter.

[5] Real-time output estimates (BP) use the Band Pass Filter.

Figure 1

The implied variance of inflation and the output gap

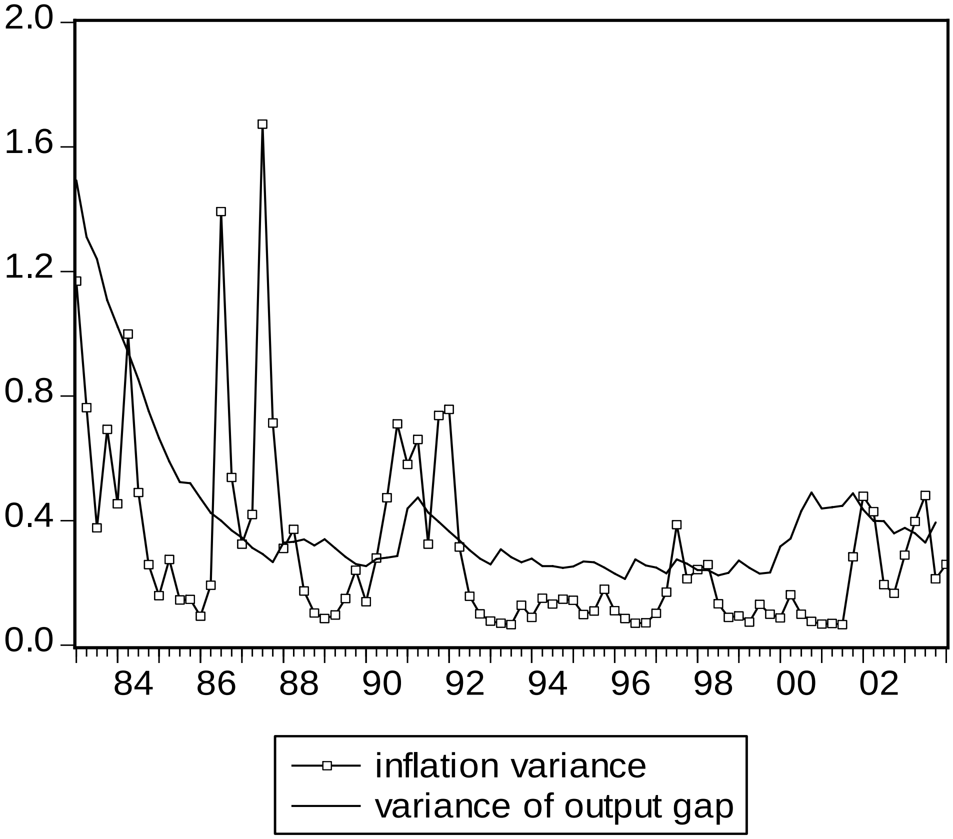


Figure 2

The gap between fitted and counterfactual interest rates

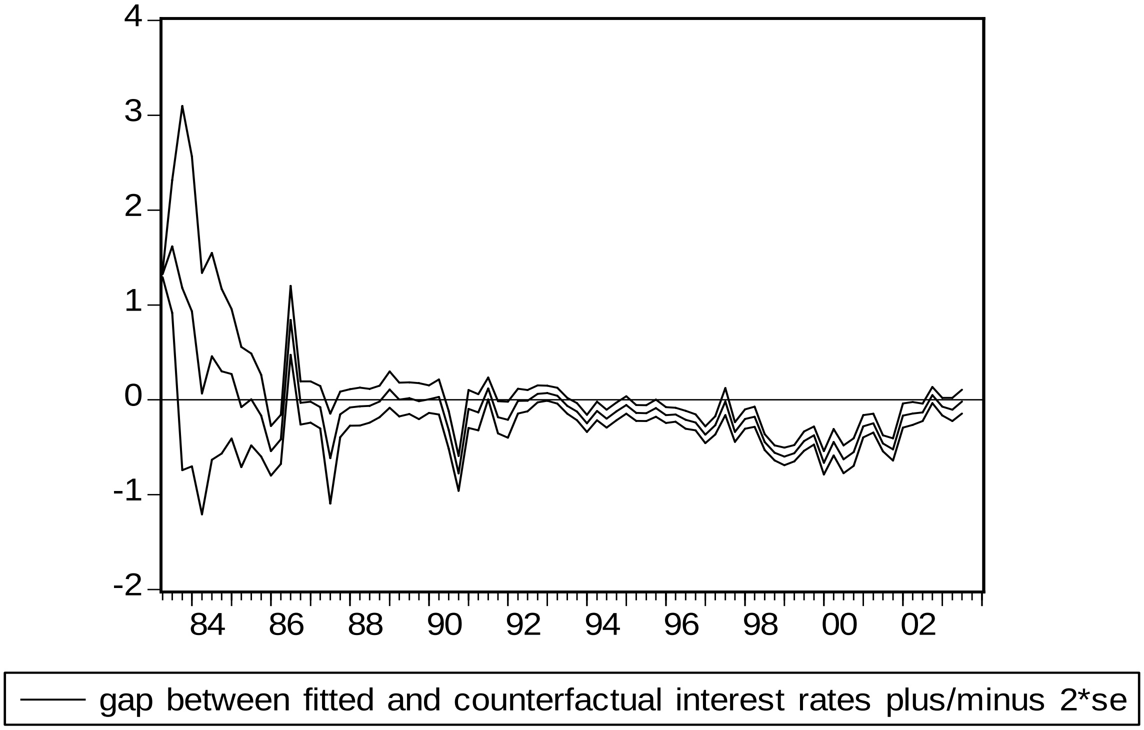
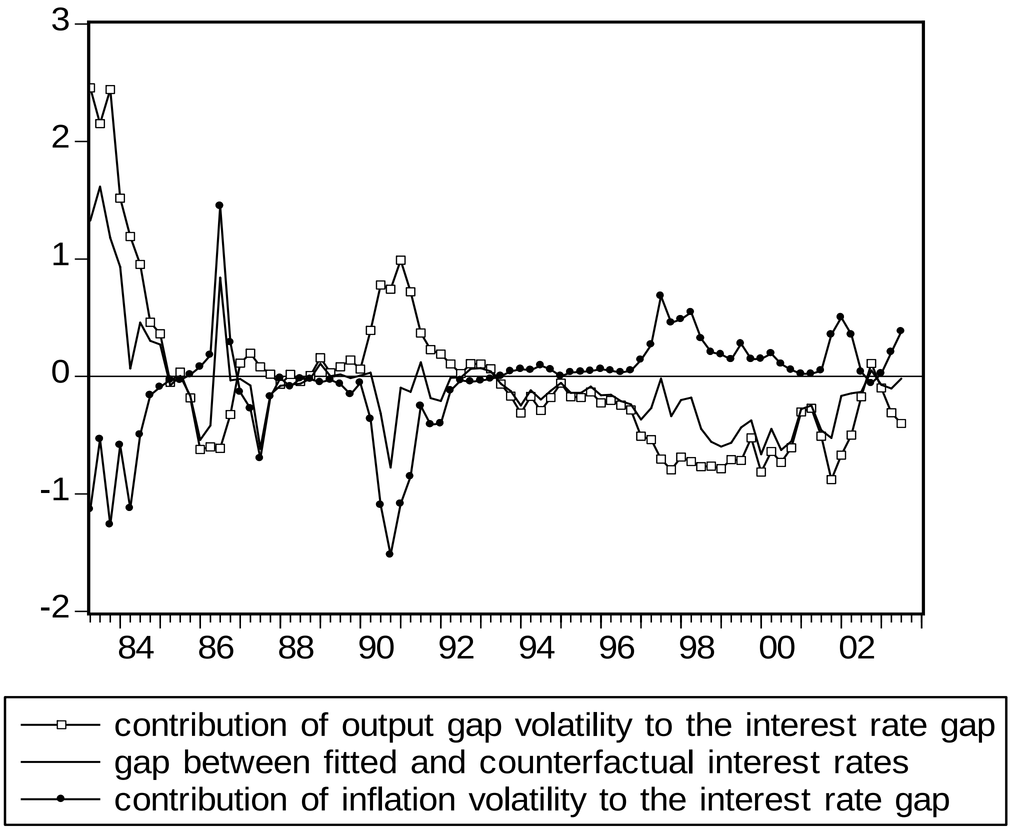


Figure 3

The contributions of inflation and output gap uncertainty to the gap between fitted and counterfactual interest rates



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