Monetary policy shocks: Testing identification conditions under time-varying conditional volatility [☆]

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Abstract

We propose an empirical procedure, which exploits the conditional heteroscedasticity of fundamental disturbances, to test the targeting and orthogonality restrictions imposed in the recent VAR literature to identify monetary policy shocks. Based on U.S. monthly data for the post-1982 period, we reject the non-borrowed-reserve and interest-rate targeting procedures. In contrast, we present evidence supporting targeting procedures implying more than one policy variable. We also always reject the orthogonality conditions between policy shocks and macroeconomic variables. We show that using invalid restrictions often produces misleading policy measures and dynamic responses. These results have important implications for the measurement of policy shocks and their temporal effects as well as for the estimation of the monetary authority's reaction function.
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1. Introduction

There has been in recent years a considerable interest in the identification of monetary policy shocks and measurement of their effects on the economy.[1] An important strand of literature uses vector autoregressions (VAR) to generate various data-based measures of policy shocks. These shocks are typically identified by imposing targeting and orthogonality restrictions. The targeting restrictions define the monetary policy indicator, while the orthogonality conditions imply that the policy shocks have no current effects on macroeconomic variables such as output and price indices. Unfortunately, it is impossible to formally verify the validity of these identifying restrictions by performing joint statistical tests. Rather, the selection of the restrictions relies on prior beliefs about the Federal Reserve operating procedures and about the signs, shapes, and persistence of certain dynamic responses to policy shocks. Thus, this approach entails a certain amount of subjectivity.

This paper proposes a procedure which permits for the first time formal testing of the identifying conditions assumed in the VAR-based literature. For this purpose, we use a flexible structural VAR (SVAR) that displays three important features. First, unlike previous studies, it relaxes the assumption that the fundamental disturbances are conditionally homoscedastic. Importantly, accounting for time-varying conditional volatilities leads to the overidentification of the SVAR (e.g. Sentana, 1992; King et al., 1994; Sentana and Fiorentini, 2001; Normandin, 2004). Hence, the restrictions typically imposed in earlier work to identify monetary policy shocks become individually and jointly testable.

Second, our SVAR incorporates a standard model of the market for bank reserves (e.g. Brunner, 1994; Gordon and Leeper, 1994; Bernanke and Mihov, 1998). This model nests the most popular monetary policy indicators. This allows us to test the indicators related to interest-rate targeting (e.g. Bernanke and Blinder, 1992; Sims, 1992), non-borrowed-reserve targeting (e.g. Eichenbaum, 1992; Christiano and Eichenbaum, 1992), borrowed-reserve targeting (e.g. Cosimano and Sheehan, 1994), adjusted non-borrowed-reserve targeting (e.g. Strongin, 1995), and mixed interest-rate and reserve targeting (e.g. Bernanke and Mihov, 1998).

Third, our SVAR admits current interactions between the monetary policy variables and macroeconomic aggregates such as output and prices. This allows us to test the orthogonality conditions. To do so, we verify whether the policy variables directly affect current output and prices. Moreover, we check whether the policy variables indirectly affect contemporaneous output and prices through their current impacts on other non-policy variables.

We estimate our SVAR using U.S. monthly data for the post-1982 period. The estimates reveal that all, but one, structural innovations display time-varying conditional variances. In particular, the policy shocks exhibit pronounced volatilities for the 1984:05–1985:02 and 1988:04–1991:03 periods. Interestingly, the first episode coincides almost exactly with the Continental Illinois incident, where the Fed has

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[1]See Pagan and Robertson (1995), Bernanke and Mihov (1998), Christiano et al. (1999) and the references therein.

sterilized the effects of its extensive lending to this commercial bank. The second episode is consistent with the 1988 contractionary monetary policy reported by Romer and Romer (1994), and accords with common observations about changes in monetary policy through the 1990–1991 recession (e.g. Strongin, 1995). These major volatility shifts allow the identification of the policy shocks, without having to resort to the traditional restrictions.

We test the identifying restrictions behind the various targeting procedures. The restrictions associated with interest-rate or non-borrowed-reserve targeting are strongly rejected, whereas those implying the other targeting procedures are not. These results sharply discriminate between interest-rate and borrowed-reserve targetings, which many observers believe to be very close in practice and empirically hard to distinguish. Our findings also help to isolate the causes for rejecting some policy indicators. For example, interest-rate targeting is rejected because the assumption that the Fed fully offsets shocks to the borrowing demand is inconsistent with evidence, while non-borrowed-reserve targeting is refuted since the requirement that the Fed does not respond to shocks to total reserves is not supported by the data.

We also find that the orthogonality conditions are strongly rejected. Specifically, the direct effects of policy shocks are significant for interest-rate and mixed interest-rate and reserve targetings, where for both procedures the interest rate represents a policy variable. The indirect effects are statistically important for the other procedures, where the interest rate is a non-policy variable. Consequently, our results suggest that the policy shocks have most of their current effects on output and prices through the adjustment of interest rates.

Next, we document the implications of these test results for policy. To do this, we first compare key policy measures obtained from various sets of restrictions with the valid counterparts derived from our flexible SVAR. The measures decompose the monetary authority's reaction function into policy shocks and feedback effects, and distinguish between the Fed's exogenous changes in policy and systematic responses to fluctuations in output and prices. Interestingly, the true targeting restrictions produce policy shocks and feedback effects that track remarkably well the valid policy measures. In contrast, the false interest-rate targeting restrictions yield policy shocks and feedback effects that often display the wrong signs, while the invalid non-borrowed-reserve targeting restrictions lead to reasonable policy shocks but misleading feedback effects. In addition, the false orthogonality conditions always distort the measures of policy shocks and feedback effects. Overall, these findings reveal that the specification of the Fed's reaction function must involve valid policy indicators. These indicators are combinations of the different reserve variables, rather than a single variable such as the interest rate or non-borrowed reserves. Also, the estimation of the Fed's feedback rule must rely on methods that relax the orthogonality conditions. Such methods include the instrumental-variable approach, but not the ordinary-least-square technique.

We complete the analysis of the implications for policy by confronting the temporal effects of policy shocks derived from different sets of restrictions with the

valid dynamic responses computed from our flexible SVAR. The true targeting restrictions produce dynamic responses that are very close to their valid counterparts. However, the invalid restrictions associated with the interest-rate indicator substantially overpredict the response of output, underpredict the response of prices, and overestimate the liquidity effect. The invalid restrictions behind the non-borrowed-reserve targeting greatly underestimate the response of output and overstate the response of prices. Finally, the false orthogonality restrictions always overstate the magnitude and persistence of the responses of output.

The paper is organized as follows. Section 2 presents our flexible SVAR specification. Section 3 discusses identification issues. Section 4 reports the estimates of the SVAR parameters. Section 5 tests the standard targeting and orthogonality restrictions. Sections 6 and 7 analyze the consequences of the various sets of restrictions for policy measures and there dynamic effects, respectively. Section 8 concludes.

2. Specification

We identify monetary policy shocks and estimate their effects on macroeconomic variables using the following SVAR system, which expresses the contemporaneous interactions between the variables in innovation form:

$$Av_t = \varepsilon_t, \tag{1}$$

where v_t is a vector of statistical innovations extracted from the observed macroeconomic variables and ε_t is a vector of unobserved fundamental innovations which are normalized (without loss of generality) by fixing their unconditional variances to unity. The matrix A measures the interactions between current statistical innovations and $B = A^{-1}$ measures the impact responses of the variables to the fundamental disturbances. The dynamic responses of the variables are obtained by substituting the impact responses into the VAR.

Throughout our analysis, we establish a distinction between variables which are outside the market for bank reserves or non-reserve variables, and variables that belong to the market for bank reserves or reserve variables. The non-reserve variables are total output, y_t, the price level, p_t, and the commodity price, cp_t, while the reserve variables are the non-borrowed reserves, nbr_t, the total reserves, tr_t, and the federal funds rate, ff_t. Hence, the SVAR used for estimation is

$$
\begin{pmatrix}
a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\
a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\
a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\
a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\
a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\
a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66}
\end{pmatrix}
\begin{pmatrix}
v_{y,t} \\
v_{p,t} \\
v_{cp,t} \\
v_{nbr,t} \\
v_{tr,t} \\
v_{ff,t}
\end{pmatrix}
=
\begin{pmatrix}
\varepsilon_{1,t} \\
\varepsilon_{2,t} \\
\varepsilon_{3,t} \\
\varepsilon_{4,t} \\
\varepsilon_{5,t} \\
\varepsilon_{6,t}
\end{pmatrix},
\tag{2}
$$

where the a_{ij}'s are unconstrained parameters. This system allows for interactions between the terms within and across the blocks of reserve and non-reserve variables. Thus, all variables may contemporaneously be affected by the structural shocks.

We further develop the reserve block in (2) by incorporating a model of the market for bank reserves:

$$v_{nbr,t} = \phi_d \sigma_d \varepsilon_{d,t} - \phi_b \sigma_b \varepsilon_{b,t} + \sigma_s \varepsilon_{s,t}, \tag{3.1}$$

$$v_{tr,t} = -\alpha v_{ff,t} + \sigma_d \varepsilon_{d,t}, \tag{3.2}$$

$$(v_{tr,t} - v_{nbr,t}) = \beta v_{ff,t} - \sigma_b \varepsilon_{b,t}. \tag{3.3}$$

The term $\varepsilon_{s,t}$ is a shock representing an exogenous policy action taken by the Fed or monetary policy shock, while $\varepsilon_{d,t}$ and $\varepsilon_{b,t}$ denote respectively the fundamental disturbances of the demand for total reserves and borrowed reserves by commercial banks. The parameters σ_s, σ_d, and σ_b are the standard deviations scaling the structural innovations of interest, while ϕ_d and ϕ_b are unrestricted parameters, and α and β are positive parameters. Eq. (3.1) describes the procedures which may be used by the Fed to select its monetary policy instruments. Eq. (3.2) represents the banks' demand for total reserves in innovation form. Eq. (3.3) is the banks' demand for borrowed reserves in innovation form, under the assumption of a zero discount-rate innovation. Inserting the equilibrium solution of the reserve-market model (3) in system (2) gives:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & (1+\phi_b)/\sigma_s & -(\phi_d+\phi_b)/\sigma_s & (\beta\phi_b - \alpha\phi_d)/\sigma_s \\ a_{51} & a_{52} & a_{53} & 0 & 1/\sigma_d & \alpha/\sigma_d \\ a_{61} & a_{62} & a_{63} & 1/\sigma_b & -1/\sigma_b & \beta/\sigma_b \end{pmatrix}$$

$$\times \begin{pmatrix} v_{y,t} \\ v_{p,t} \\ v_{cp,t} \\ v_{nbr,t} \\ v_{tr,t} \\ v_{ff,t} \end{pmatrix} = \begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \\ \varepsilon_{s,t} \\ \varepsilon_{d,t} \\ \varepsilon_{b,t} \end{pmatrix}. \tag{4}$$

Our analysis relies on both systems (2) and (4). The conditional scedastic structure of the systems is

$$A\Sigma_t A' = \Gamma_t, \tag{5}$$

where A is specified as in (2) or (4), while $\Sigma_t = E_{t-1}(v_t v_t')$ measures the conditional non-diagonal covariance matrix of the non-orthogonal statistical innovations. The conditional diagonal covariance matrix of the orthogonal structural innovations is given by $\Gamma_t = E_{t-1}(\varepsilon_t \varepsilon_t')$, while $I = E(\varepsilon_t \varepsilon_t')$ normalizes the unconditional variances of the fundamental disturbances. Conventional VAR-based studies uniformly impose conditional homoscedasticity or $\Gamma_t = I$ and $\Sigma_t = BB'$, implying that the conditional second moments of the statistical innovations are time-invariant. In contrast, our procedure allows the conditional second moments of the statistical disturbances to vary over time. Specifically, in (5), $\Sigma_t \neq BB'$ if the conditional variances of the fundamental shocks are time-varying, that is if $\Gamma_t \neq I$.

Finally, the dynamics of the conditional variances of the structural innovations is specified as

$$\Gamma_t = (I - \Delta_1 - \Delta_2) + \Delta_1 \bullet (\varepsilon_{t-1} \varepsilon_{t-1}') + \Delta_2 \bullet \Gamma_{t-1}. \tag{6}$$

The operator $\bullet$ denotes the element-by-element matrix multiplication, while Δ_1 and Δ_2 are diagonal matrices of parameters. Eq. (6) involves intercepts that are consistent with the normalization $I = E(\varepsilon_t \varepsilon_t')$. Also, (6) implies that all fundamental disturbances are conditionally homoscedastic if Δ_1 and Δ_2 are null. On the other hand, some structural shocks display time-varying conditional variances characterized by univariate generalized autoregressive conditional heteroscedastic [GARCH(1,1)] processes if Δ_1 and Δ_2—which contain the ARCH and GARCH coefficients, respectively—are positive semi-definite and $(I - \Delta_1 - \Delta_2)$ is positive definite. Furthermore, all the conditional variances follow GARCH(1,1) processes if Δ_1, Δ_2, and $(I - \Delta_1 - \Delta_2)$ are positive definite. The evidence presented in Engle (1982), Bollerslev et al. (1992), and Pagan and Robertson (1995), among others, suggests that these processes provide a good description of the alternating periods of volatility and smoothness which characterize the movements of several macro-economic time-series.[2]

3. Identification

3.1. Identification under the conventional VAR-based approach

The conventional VAR-based approach imposes that all fundamental disturbances are conditionally homoscedastic (i.e. Δ_1 and Δ_2 are zero matrices, so $\Gamma_t = I$ is time-invariant). Hence, system (1) is not econometrically identified. To better understand this point, let us consider the alternative specification:

$$A^* v_t = \varepsilon_t^*, \tag{7}$$

where $A^* = QA$, $\varepsilon_t^* = Q\varepsilon_t$, and Q is an orthogonal transformation matrix (i.e. $QQ' = Q'Q = I$). Eq. (7) is observationally equivalent (up to second moments) to (1)

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[2]These processes also have the advantage that they are more parsimonious than alternative large-scale multivariate specifications.

(i.e. $\Sigma_t^* = \Sigma_t = BB'$) with orthogonally rotated fundamental disturbances (i.e. $\Gamma_t^* = Q\Gamma_t Q' = I$ is diagonal) for any admissible transformation matrices. It follows that A is not unique under orthogonal transformations, so monetary policy shocks (or any other fundamental disturbances) are not identified. Accordingly, B is not uniquely defined and the dynamic responses of variables to policy shocks also are unidentified.

A common strategy to identify monetary policy shocks without having to identify the entire system is to impose restrictions on (1). For example, it is sufficient to assume that the non-reserve variables are not contemporaneously affected by the reserve variables ($A_{nr} = [a_{ij}] = 0$ where $i = 1, 2, 3$ and $j = 4, 5, 6$), and that the reserve block ($A_{rr} = [a_{ij}]$ where $i = 4, 5, 6$ and $j = 4, 5, 6$) is identified. These conditions ensure that $A_r = (A'_{nr}|A'_{rr})' = (0'|A'_{rr})'$ is uniquely determined (up to column sign changes), so $Q_{nr} = 0$, and $Q_{rr} = I$ or $Q_{rr} = I^{1/2}$ are the only admissible submatrices. Moreover, fixing the sign of the diagonal elements of A_{rr} guarantees that the policy shocks are globally identified. In this context, $B_r = (B'_{nr}|B'_{rr})' = (0'|A_{rr}^{-1'})'$ is also unique, and thus the responses of non-reserve and reserve variables to policy shocks are identified.

The above restrictions can be interpreted economically. For instance, the fourth equation in (4), representing the monetary authority's feedback rule, can be rewritten as

$$v_{s,t} = \rho_{41} v_{y,t} + \rho_{42} v_{p,t} + \rho_{43} v_{cp,t} + \sigma_s \varepsilon_{s,t}, \tag{8}$$

where $\rho_{4j} = -a_{4j}\sigma_s$ (for $j = 1, 2, 3$) and $v_{s,t} = [(1 + \phi_b)v_{nbr,t} - (\phi_d + \phi_b)v_{tr,t} + (\beta\phi_b - \alpha\phi_d)v_{ff,t}]$ measures the statistical innovation of the monetary policy indicator. This indicator therefore includes some or all of the reserve variables since they convey information about the stance of monetary policy, but none of the non-reserve variables. Moreover, in making its policy the Fed possibly knows current values of output, the price level and commodity prices.

The rule (8) nests several VAR-based policy indicators found in the literature. Each indicator is obtained by imposing restrictions on parameter values of the model of the market for bank reserves, so A_{rr} is identified. These restrictions are the following.

MIX indicator: $\alpha = 0$. Accordingly, the demand for total reserves is inelastic in the short run and $v_{s,t} = [(1 + \phi_b)v_{nbr,t} - (\phi_d + \phi_b)v_{tr,t} + (\beta\phi_b)v_{ff,t}]$.[3] Thus, the policy indicator includes the three reserve variables since the Fed adopts a mixed procedure where it neither pursues pure interest-rate targeting nor strict reserve targeting. The Fed therefore observes and responds to shocks to both total reserves and borrowed reserves within the period. This procedure mainly reflects the Fed's practice of continuously monitoring total reserves (except vault cash) and borrowings.

Adjusted non-borrowed reserve (ANBR) indicator: $\alpha = \phi_b = 0$. Here, shocks to total reserves are purely demand shocks which are fully accomodated by the Fed in the short run. The policy indicator is the adjusted non-borrowed reserves or the

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[3] This corresponds to the just identified indicator proposed by Bernanke and Mihov (1998). The reserve block then involves six unknown parameters which are estimated from six distinct time-invariant covariances.

portion of non-borrowed reserves which is orthogonal to total reserves: $v_{s,t} = [v_{nbr,t} - \phi_d v_{tr,t}]$.

Borrowed reserve (BR) indicator: $\phi_d = 1$ and $\phi_b = \alpha/\beta$. The Fed targets borrowed reserves. As for the ANBR indicator, the policy variables are the non-borrowed reserves and total reserves. But, the policy indicator now reduces to $v_{s,t} = -(1 + \alpha/\beta)(v_{tr,t} - v_{nbr,t})$.

Federal funds rate (FFR) indicator: $\phi_d = 1$ and $\phi_b = -1$. The Fed targets the federal funds rate and decides to fully offset shocks to total reserves and borrowing demand. The federal funds rate is the single policy variable and $v_{s,t} = -(\beta + \alpha)v_{ff,t}$.

Non-borrowed reserve (NBR) indicator: $\phi_d = \phi_b = 0$. The Fed targets the non-borrowed reserves. Thus, the non-borrowed reserves are the single policy variable and $v_{s,t} = v_{nbr,t}$.

Each of these sets of restrictions is combined with the additional identifying condition that the non-reserve variables in (8) are orthogonal to current monetary policy shocks, i.e. A_{nr} is null. These orthogonality conditions reflect the assumption that policy shocks do not impact contemporaneously on non-reserve variables.

By relaxing the orthogonality conditions, we are able to recover direct and indirect effects, which are defined as follows.

Direct effects: These are the contemporaneous responses of output, the price level, and commodity prices to policy variables. For example, if the Fed targets a mix of interest rate and reserves, the direct effects are measured by a_{ij} ($i = 1, 2, 3$ and $j = 4, 5, 6$) in systems (2) and (4). Verifying zero-restrictions on these coefficients would imply that there are no direct effects, in accordance with the orthogonality conditions. On the other hand, if the Fed targets only non-borrowed reserves, the direct effects are measured by the elements a_{i4} ($i = 1, 2, 3$). Again, verifying zero-restrictions on these coefficients would reveal the absence of any direct effects. The direct effects for the other targeting procedures are obtained similarly.

Indirect effects: These are the contemporaneous effects of policy variables on output, the price level, and commodity prices through their current impacts on the non-policy reserve variables. For example, for the MIX indicator, there are no indirect effects because all three reserve variables are policy variables. Instead, for the NBR indicator, the indirect effects are measured by a_{ij} ($i = 1, 2, 3$ and $j = 5, 6$) since the non-borrowed reserves correspond to the policy variable, while the total reserves and federal funds rate are the non-policy reserve variables.

In sum, to generate monetary policy shocks the standard VAR-based procedure imposes the conditional homoscedasticity of SVAR residuals as well as untestable identifying restrictions. Specifically, with single policy variables, the policy shocks are computed from Choleski decompositions of the VAR-residual covariance matrix, which imply that A is lower triangular with positive elements on the diagonal. These decompositions are obtained by ordering the non-reserve variables first, followed by the policy variable, and by the other reserve variables. Since the system is not entirely identified, the particular ordering within the block of non-reserve variables does not affect the measurement of policy shocks.

3.2. Identification under time-varying conditional volatility

The alternative identification strategy exploits the conditional heteroscedasticity of the fundamental disturbances (i.e. Δ_1 and Δ_2 are positive semi-definite or definite matrices, so $\Gamma_t \neq I$ is time-varying). With linearly independent conditional variances of the fundamental disturbances, system (1) is statistically identified. In practice, this condition is satisfied if the conditional variances of at least all, but one, structural shocks are time-varying—given that these variances are empirically parametrized by the GARCH(1,1) processes (6) (e.g. Sentana, 1992; King et al., 1994; Sentana and Fiorentini, 2001; Normandin, 2004). Thus, A is unique (up to column sign changes) under orthogonal transformations, so $Q = I$ and $Q = I^{1/2}$ are the only admissible transformations preserving the orthogonality of the rotated structural innovations in (7) (i.e. $\Gamma_t^* = Q\Gamma_t Q'$ is diagonal). Fixing the sign of the diagonal elements of A ensures global identification. As a result, B is also uniquely defined.

The exactly identified elements in (2) uniquely determine some of the reserve-block parameters in (4), namely,

$$\sigma_d = 1/a_{55},$$
$$\alpha = a_{56}/a_{55}. \tag{9}$$

In turn, these elements imply two distinct values for each of the other key parameters:

$$\sigma_b = 1/a_{64},$$
$$\sigma_s = (a_{66}/a_{64} + a_{56}/a_{55})/d_1,$$
$$\beta = a_{66}/a_{64},$$
$$\phi_d = -(a_{66}a_{45}/a_{64} + a_{46})/d_1,$$
$$\phi_b = (a_{46} - a_{56}a_{45}/a_{55})/d_1, \tag{10}$$

or

$$\sigma_b = -1/a_{65},$$
$$\sigma_s = (-a_{66}/a_{65} + a_{56}/a_{55})/d_2,$$
$$\beta = -a_{66}/a_{65},$$
$$\phi_d = (a_{66}a_{45}/a_{65} - a_{46})/d_2,$$
$$\phi_b = (a_{46} - a_{56}a_{45}/a_{55})/d_2, \tag{11}$$

where $d_1 = (a_{66}a_{44}/a_{64} + a_{56}a_{44}/a_{55} + a_{45}a_{56}/a_{55} - a_{46})$ and $d_2 = (a_{56}a_{44}/a_{55} - a_{66}a_{44}/a_{65} + a_{45}a_{56}/a_{55} - a_{46})$.

With the overidentification of system (4), the restrictions imposed in previous VAR-based studies can be tested econometrically. For instance, the reserve-market specification (3) can be tested through the joint restrictions $a_{54} = 0$ and $a_{64} = -a_{65}$. Under these restrictions, systems (2) and (4) coincide. Hence, policy shocks and their effects on macroeconomic variables are correctly identified and measured from system (4). Testing specific parameters of the market for bank reserves can also provide useful information about the policy variables which compose the monetary

instrument targeted by the Fed. Moreover, it is possible to test whether monetary policy shocks contemporaneously affect non-reserve variables, and if so, via which channels. Finally, the measures and effects of valid policy shocks can be compared to those of invalid ones.

4. Estimation

To implement the identification strategy based on conditional heteroscedasticity, we adopt a two-step estimation procedure. The first step consists in an equation-by-equation ordinary least squares (OLS) estimation of the coefficients of a standard τ-order VAR process, from which the estimates of the statistical innovations v_t and of their conditional covariances Σ_t for $t = (\tau + 1), \ldots, T$ are recovered. More precisely, the estimate for Σ_t is computed by using Eqs. (5) and (6) evaluated for systems (2) and (4), by initializing $\Gamma_\tau = (\varepsilon_\tau \varepsilon_\tau') = I$ from the unconditional moments, and by giving values to the parameters Θ—where Θ is the vector composed of all the unconstrained elements of A, Δ_1, and Δ_2.

The second step is a maximum likelihood (ML) estimation of the parameters included in Θ. To construct the log-likelihood of the sample (ignoring the constant term), we assume that the statistical innovations are conditionally Gaussian:

$$L(v, \Theta) = -\frac{1}{2} \sum_{t=\tau+1}^{T} \log|\Sigma_t| - \frac{1}{2} \sum_{t=\tau+1}^{T} v_t' \Sigma_t^{-1} v_t, \tag{12}$$

where v_t and Σ_t are evaluated at their estimates. The log-likelihood (12) is then maximized over the parameters Θ using the BHHH algorithm.

We use U.S. monthly data for the period 1982:11–1998:12. According to many observers, this period has been characterized by a stable policy environment. The six variables included in the VAR are the industrial production index, y_t, the all-item, all-urban-consumer, price index, p_t, the world export commodity price index, cp_t, the non-borrowed reserves, nbr_t, the total reserves adjusted for changes in reserve requirements, tr_t, and the average of the daily federal funds rate, ff_t. The series y_t, nbr_t, tr_t, and ff_t are released by the Federal Reserve Board of Governors, while p_t and cp_t are taken from the U.S. Bureau of Labor Statistics and the International Financial Statistics. All data are seasonally adjusted and expressed in logs, except for the federal funds rate which is seasonally unadjusted and in percentage.

We set the number of lags in the VAR process to six ($\tau = 6$).[4] We find that, for this lag structure, none of the first 18 autocorrelations for all statistical residuals exceed two asymptotic standard errors. Also, using a heteroscedasticity-robust gauss newton regression (HRGNR) procedure allowing for conditional heteroscedasticity of unknown form (Davidson and Mackinnon, 1993), we are unable to detect first-, third-, sixth-, and 12th-order serial correlation for the VAR residuals at the 5% level.

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[4]This lag structure is also used by Gordon and Leeper (1994), Pagan and Robertson (1995), and Strongin (1995) for a similar data sample.

Interestingly, some of the first 18 autocorrelations are significant at the 5% level for all squared statistical innovations, except for industrial production. Similar results are obtained by applying the Lagrange multiplier (LM) test for first-, third-, and sixth-order ARCH effects. These findings confirm the presence of conditional heteroscedasticity in all, but one, statistical innovations, which is likely to translate into time-varying conditional variances of some, and perhaps, all fundamental shocks—given that $\Sigma_t \neq BB'$ if $\Gamma_t \neq I$.

For the sake of brevity, we present only the ML estimates of the GARCH(1,1) parameters (in this section) and the reserve-market parameters (in the next section). Table 1 shows that the ARCH and GARCH coefficients are almost identical whether they are based on system (2) or (4). Moreover, they systematically imply that $(I - \Delta_1 - \Delta_2)$ is positive definite, and that Δ_1 and Δ_2 are positive semi-definite. This follows from our finding that one structural innovation, ε_{1t}, exhibits a time-invariant conditional variance. In contrast, the fundamental disturbances ε_{3t} and $\varepsilon_{5t}/\varepsilon_{dt}$ display time-varying conditional volatilities that are moderately persistent as measured by the sum of the ARCH and GARCH coefficients, while ε_{2t}, $\varepsilon_{4t}/\varepsilon_{st}$ and $\varepsilon_{6t}/\varepsilon_{bt}$ have highly persistent time-varying conditional variances.

The estimated conditional volatilities also provide an adequate description of the conditional heteroscedasticity of the fundamental innovations. Specifically, none of the first 18 autocorrelations for each squared fundamental shock relative to its conditional variance exceed two asymptotic standard errors. Furthermore, the LM test statistics for GARCH(p,q) are never significant at the 5% level—where $p = 0$ for ε_{1t} and $p = 1$ otherwise, while $q = 3, 6, 12$. Again, these findings hold whether the structural disturbances are estimated from system (2) or (4).

Moreover, the order condition for the identification of systems (2) and (4) is satisfied given that, for each system, five of the six structural innovations display conditional heteroscedasticity. As expected, the rank condition is also verified for both systems, that is, the conditional variances of the fundamental shocks are linearly independent. Specifically, $\lambda = 0$ is the only solution to the system of homogeneous linear equations $\Gamma\lambda = 0$, since empirically $(\Gamma'\Gamma)$ has a large positive determinant and is invertible—where Γ stacks by column the estimates (for $t = (\tau + 1), \ldots, T$) of the conditional volatility for each of the six structural shocks extracted from system (2) or (4). This translates into log-likelihood functions that are not flat. In other words, system (2) or (4) yields similar estimates of the parameters under alternative starting values for Θ. These findings are crucial since they confirm that monetary policy shocks and their effects can be identified without having to resort to restrictions as in previous conditional-homoscedastic VAR-based studies.

5. Test results

Using the ML estimates of systems (2) and (4), we assess the empirical validity of several identifying assumptions typically imposed in the literature. We first focus on the restrictions related to monetary policy indicators. For this purpose, Table 2 presents the estimates of the reserve-market parameters. Our estimates of ϕ_d are

Table 1
Estimates of the GARCH(1,1) parameters

Shocks	Parameters	System (2)	System (4)
ε_{1t}	ARCH	—	—
	GARCH	—	—
ε_{2t}	ARCH	0.213	0.200
		(0.082)	(0.079)
	GARCH	0.739	0.751
		(0.089)	(0.087)
ε_{3t}	ARCH	0.285	0.277
		(0.128)	(0.125)
	GARCH	—	—
$\varepsilon_{4t}/\varepsilon_{st}$	ARCH	0.206	0.208
		(0.052)	(0.051)
	GARCH	0.792	0.791
		(0.052)	(0.051)
$\varepsilon_{5t}/\varepsilon_{dt}$	ARCH	0.435	0.352
		(0.168)	(0.190)
	GARCH	—	—
$\varepsilon_{6t}/\varepsilon_{bt}$	ARCH	0.033	0.033
		(0.026)	(0.023)
	GARCH	0.961	0.960
		(0.032)	(0.028)

Note: Entries are the ML estimates (standard errors) of the ARCH and GARCH coefficients of the GARCH(1,1) processes (6) evaluated for systems (2) and (4). — Indicates that zero-restrictions are imposed to ensure that Δ_1 and Δ_2 are non-negative definite.

close to 0.8 and are always statistically significant. These estimates imply that the Fed has almost fully accommodated shocks to total reserves during the period under study. These findings are consistent with the FFR and BR indicators since both require $\phi_d = 1$, but contradict the NBR indicator which imposes $\phi_d = 0$. The estimated values of ϕ_b are systematically low—between 0.017 and 0.130—and statistically insignificant, and are thus consistent with the restriction $\phi_b = 0$ of the ANBR and NBR indicators but not with $\phi_b = -1$ of the FFR indicator. Our estimates of α are close to zero, while those of β lie between 0.075 and 0.307 and are often statistically insignificant. These estimated values of α are consistent with the MIX and ANBR indicators which both set $\alpha = 0$. Finally, our estimated values of ϕ_b, α and β are consistent with the BR indicator, where $\phi_b = \alpha/\beta$.

Table 3 reports the *p*-values of the χ^2 joint test statistics associated with the various targeting procedures. These tests cannot reject the identifying assumptions behind the MIX, ANBR, and BR indicators. In contrast, the restrictions resulting in the

Table 2
Estimates of the reserve-market parameters

Parameters	System (2)		System (4)
σ_s	(i)	0.033 (0.014)	0.032 (0.013)
	(ii)	0.036 (0.015)	
σ_d		0.008 (0.001)	0.008 (0.001)
σ_b	(i)	0.108 (0.126)	0.104 (0.119)
	(ii)	0.026 (0.013)	
α		0.008 (0.008)	0.004 (0.007)
β	(i)	0.307 (0.365)	0.305 (0.347)
	(ii)	0.075 (0.037)	
ϕ_d	(i)	0.821 (0.121)	0.821 (0.107)
	(ii)	0.804 (0.132)	
ϕ_b	(i)	0.032 (0.038)	0.017 (0.026)
	(ii)	0.130 (0.138)	

Note: Entries are the estimates (standard errors) of the structural parameters of the reserve-market model (3). These statistics are computed from the ML estimates of systems (2) and (4). For system (2), a unique value of the structural parameters σ_d and α is recovered from Eqs. (9), two distinct values of σ_s, σ_b, β, ϕ_d, and ϕ_b are derived from (i) Eqs. (10) and (ii) Eqs. (11), and the covariance matrices of these parameters are $D\Psi D'$—where D are the matrices of numerical derivatives of expressions (i) (9) and (10) and (ii) (9) and (11) with respect to the parameters in (2), and Ψ is the covariance matrix of those parameters. For system (4), the estimates and the covariance matrix of the reserve-market parameters are directly obtained.

FFR and NBR indicators are strongly rejected by the data. These findings are robust whether they are obtained from system (2) or (4).

The test results indicate that only the policy indicators which are constructed from more than one reserve variable receive empirical support. Specifically, the evidence in favour of the MIX indicator suggests that the policy variables correspond to the three reserve variables, while the empirical support for the ANBR and BR indicators reveals that the policy variables are the non-borrowed reserves and total reserves.

Table 3
Tests of identification conditions: monetary policy indicators

Monetary policy indicators	System (2)		System (4)
MIX			
$\alpha = 0$		0.275	0.587
ANBR			
$\alpha = \phi_b = 0$	(i)	0.533	0.795
	(ii)	0.546	
BR			
$\phi_b = \alpha/\beta$ and $\phi_d = 1$	(i)	0.234	0.185
	(ii)	0.245	
FFR			
$\phi_b = -1$ and $\phi_d = 1$	(i)	0.000	0.000
	(ii)	0.000	
NBR			
$\phi_b = \phi_d = 0$	(i)	0.000	0.000
	(ii)	0.000	

Note: Entries are *p*-values of the χ^2 test statistics for various identifying restrictions related to the reserve variables. These statistics are computed from the ML estimates of systems (2) and (4). For system (2), a unique value of the structural parameters σ_d and α is recovered from Eqs. (9), two distinct values of σ_s, σ_b, β, ϕ_d, and ϕ_b are derived from (i) Eqs. (10) and (ii) Eqs. (11), and the covariance matrices of these parameters are $D\Psi D'$—where D are the matrices of numerical derivatives of expressions (i) (9) and (10) and (ii) (9) and (11) with respect to the parameters in (2), and Ψ is the covariance matrix of those parameters. For system (4), the estimates and the covariance matrix of the reserve-market parameters are directly obtained.

Hence, no single variable such as the federal funds rate or the non-borrowed reserves represent by itself the policy variable.

Moreover, the rejection of the NBR indicator appears consistent with the view held by some observers that the Fed has implemented a non-borrowed-reserve targeting procedure only during the brief period from 1979:10 to 1982:09. There is more uncertainty, however, surrounding the procedure used by the Fed after 1982. For instance, some observers believe that the Fed has adopted a federal-funds-rate targeting procedure over that period. However, both the interest-rate and the borrowed-reserve targeting procedures are known to be quite similar in practice (e.g. Strongin, 1995; Bernanke and Mihov, 1998). Our tests clearly reject the FFR indicator in favour of the BR indicator. This can be explained by considering that the difference between the two procedures becomes evident only when there is a shift in the borrowing function. Under the borrowed-reserve targeting, a shift in the borrowing function causes the interest rates to change (i.e. $\phi_b = \alpha/\beta$). Under the federal-funds-rate targeting, the reserve mix is adjusted to exactly offset the shift in the borrowing function and to keep the federal funds rate steady (i.e. $\phi_b = -1$). Our estimates of ϕ_b are low and statistically insignificant, which explains why the joint

Table 4
Tests of identification conditions: direct and indirect effects

Monetary policy indicators	System (2)	System (4)
MIX		
Direct effects: $a_{i4} = a_{i5} = a_{i6} = 0$	0.000	0.000
ANBR		
Direct effects: $a_{i4} = a_{i5} = 0$	0.306	0.248
Indirect effects: $a_{i6} = 0$	0.000	0.000
BR		
Direct effects: $a_{i4} = a_{i5} = 0$	0.306	0.248
Indirect effects: $a_{i6} = 0$	0.000	0.000
FFR		
Direct effects: $a_{i6} = 0$	0.000	0.000
Indirect effects: $a_{i4} = a_{i5} = 0$	0.306	0.248
NBR		
Direct effects: $a_{i4} = 0$	0.831	0.792
Indirect effects: $a_{i5} = a_{i6} = 0$	0.000	0.000

Note: $i = 1, 2, 3$. Entries are *p*-values of the χ^2 test statistics for various identifying restrictions related to the non-reserve variables. These statistics are computed from the ML estimates of systems (2) and (4).

restrictions $\phi_d = 1$ and $\phi_b = -1$ implied by the FFR indicator are strongly rejected. On the other hand, our estimates are not inconsistent with the joint restrictions $\phi_d = 1$ and $\phi_b = \alpha/\beta$ of the BR indicator.

Another important test verifies the validity of the orthogonality conditions. To this end, Table 4 presents the *p*-values of the χ^2 joint test statistics of the restrictions related to the direct and indirect effects of policy shocks. These tests strongly reject the orthogonality conditions according to which policy shocks do not have a contemporaneous impact on non-reserve variables. Specifically, the direct effects of policy shocks are statistically significant when the Fed targets a mix of interest rate and reserves or the federal funds rate exclusively, while indirect effects are statistically significant under the ANBR, BR, or NBR indicators. Considering the definitions of policy variables under the alternative targeting procedures, these results imply that the impact of policy shocks on non-reserve variables is felt mostly through the federal funds rate (i.e. $a_{i6} \neq 0$ where $i = 1, 2, 3$). Again, these findings do not depend on the particular system used.

Finally, the *p*-values of the χ^2 joint test statistics of both the restrictions related to each targeting procedures and the orthogonality conditions are always equal to zero under systems (2) and (4). These test results thus confirm that the various policy measures proposed in the VAR-based literature rely on invalid identifying assumptions.

6. Monetary policy measures

We document the implications of imposing the sets of identifying restrictions tested above on different monetary policy measures. The first measure corresponds to the conditional variance of policy shocks ($\varepsilon_{s,t}$). It provides information about the main volatility shifts which allow for the identificaton of policy shocks. Furthermore, we can have some idea about the sources of these shifts by relating the conditional-variance series to economic and financial events. The second measure extracts the scaled policy shocks ($\sigma_s \varepsilon_{s,t}$) from the Fed's reaction function (8). For ease of interpretation, this noisy (serially uncorrelated) measure is smoothed from a five-month centered, equal-weighted moving average. The smoothed policy shocks capture the Fed's exogenous changes in monetary policy. Negative (positive) values of the smoothed shocks represent contractionary (expansionary) unanticipated monetary policies. The third measure corresponds to the feedback effects ($\rho_{41} v_{y,t} + \rho_{42} v_{p,t} + \rho_{43} v_{cp,t}$) in (8). This component is also smoothed from a five-month centered, equal-weighted moving average. The smoothed feedback effects capture the Fed's systematic responses to changes in non-reserve variables.

We confront different sets of monetary policy measures. One set, which we refer to as the valid measures, is computed from the ML estimates of the parameters of system (4) and of the GARCH(1,1) processes (6). We rely on system (4) as it provides an adequate representation of the reserve market. In particular, as shown previously, system (4) generates estimates of the reserve-market parameters which are similar to those obtained from the unrestricted system (2). Also, the joint restrictions $a_{54} = 0$ and $a_{64} = -a_{65}$ involved in (4) are not rejected, with a p-value of the underlying χ^2 statistic equal to 0.186. The alternative sets of measures are calculated from the ML estimates of restricted systems' parameters and the GARCH(1,1) coefficients. These systems impose various sets of identifying restrictions on targeting procedures, but relax the orthogonality conditions.

Fig. 1 compares the valid measures with those obtained under the BR indicator (first column), the FFR indicator (second column), and the NBR indicator (third column). To facilitate comparisons, the valid and alternative measures are normalized to have the same mean (for the conditional volatilities) and identical variances (for smoothed policy shocks and feedback effects). We do not report the measures related to the MIX and ANBR indicators since they are almost identical to those of the BR indicator.

First, we describe our valid measures. The valid smoothed policy shocks exhibit a very large volatility between 1984:05 and 1985:02 reflecting several major downward surges. Interestingly, this period coincides almost exactly with the episode during which the Fed has sterilized the effects of its extensive lending to the Continental Illinois Bank, via the selling of treasury securities (e.g. Benston et al., 1986). As a result, the total reserves stayed at about the same level, but their composition changed following the increase in borrowed reserves and the decrease in non-borrowed reserves. In terms of innovations, the decrease in non-borrowed reserves during this period constitutes by far the most important variation of all those computed for reserve and non-reserve variables of system (4). Given the feedback
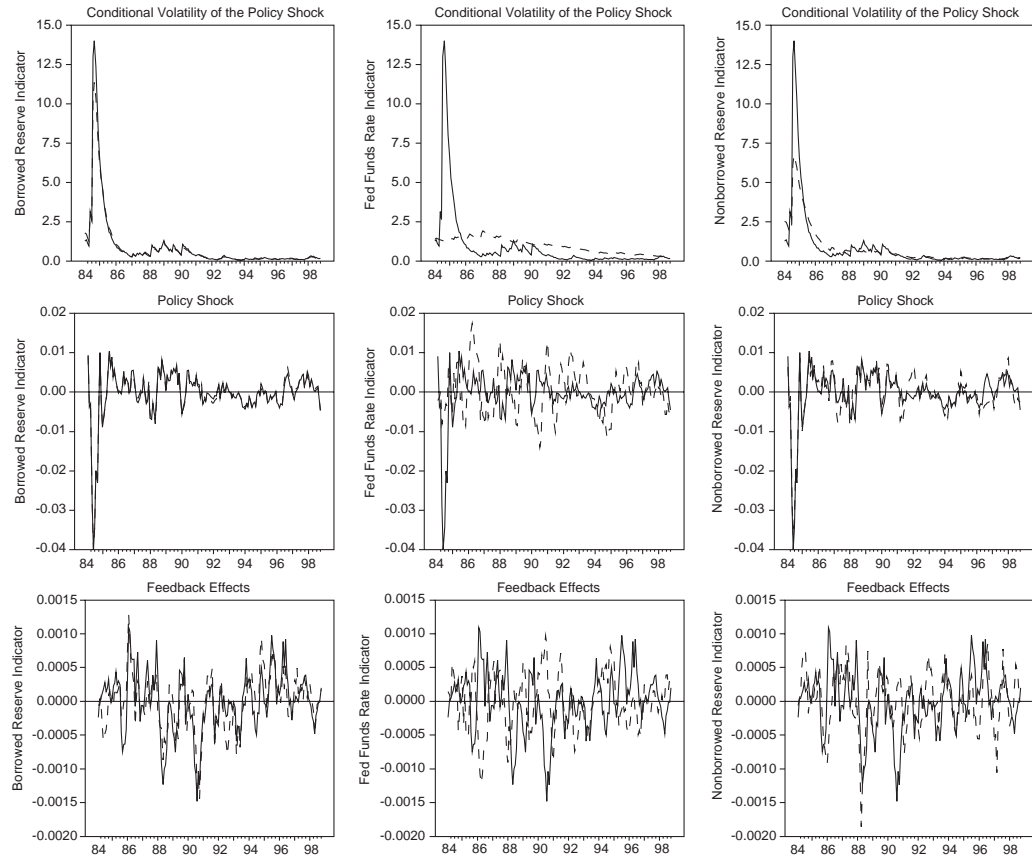
Fig. 1. Monetary policy measures. Note: The solid lines correspond to the valid monetary policy measures. The dotted lines are the monetary policy measures obtained by imposing the restrictions associated with either the borrowed reserve indicator, the federal funds rate indicator, or the non-borrowed reserve indicator, but without assuming the orthogonality conditions.

rule (8), this implies substantial declines in the policy indicator (i.e. a combination of the innovations of the three reserve variables) and negative values for policy shocks.

In addition, our valid smoothed policy shocks display a high volatility for the period 1988:04–1991:03 which seems to result from a pronounced unanticipated contractionary policy from 1988:01 to 1988:05, an expansionary policy between 1988:06 and 1989:11, a severe monetary tightening from 1989:12 to 1990:04, and an easier policy from 1990:05 to 1991:03. Interestingly, the dating of the restrictive policy recorded in 1988 from our measure is quite close to the tight policy action in 1988:12 reported by Romer and Romer (1994), based on their reading of the minutes of the Federal Open Market Committee. Moreover, the post-1988 pattern is consistent with some common observations about changes in monetary policy that occurred through the business cycle phases (e.g. Strongin, 1995). In particular, there was a severe monetary contraction before the business cycle peak recorded in 1990:07, followed by easing policy actions until the trough in 1991:03, and by a somewhat tighter policy in the months that followed.

According to our valid measure of the smoothed feedback effects, the Fed has often responded to fluctuations in non-reserve variables. The most important downward movements are recorded in 1988:05 and 1990:08, while pronounced upward spikes are observed in 1986:02, 1987:12, 1995:07, and 1996:06. Also, the feedback component was positive during the Continental Illinois episode, negative during the 1988 unanticipated contractionary policy, and negative during the 1990–1991 recession. Moreover, it was progressively smaller (in absolute values) from peak to trough.

Comparing the valid measures reported above with alternative ones, we find that the measures derived from the restrictions identifying the borrowed-reserve targeting procedure coincide almost perfectly with their valid counterparts. For instance, the correlations between the BR-induced and valid measures are 0.987 for the conditional volatilities, 0.995 for the smoothed policy shocks, and 0.781 for the smoothed feedback effects. These high correlations strongly suggest that the valid restrictions associated with the borrowed-reserve targeting procedure allow an adequate disentanglement of the monetary authority's reaction function (8) in terms of policy shock and feedback effects.

In contrast, the measures corresponding to the interest-rate targeting procedure always differ sharply from their valid counterparts. For example, the FFR indicator produces a flatter conditional volatility that substantially understates the pronounced fluctuations recorded in 1984. Also, this indicator yields measures of policy shocks and feedback effects that often display the wrong signs. This translates into weak correlations between the FFR-based and valid measures of 0.306 for the conditional volatilities, 0.162 for the smoothed policy shocks, and -0.251 for the smoothed feedback effects. Hence, the invalid restrictions behind the interest-rate targeting procedure produce highly misleading results regarding policy shocks and feedback effects associated with the monetary policy.

The measures derived from the non-borrowed-reserve targeting track some of the valid measures quite well. For instance, the correlations between the NBR-policy and valid measures are respectively 0.893 and 0.923 for the conditional volatilities

and the smoothed policy shocks. However, it is only 0.323 for the smoothed feedback effects. Hence, the invalid restrictions identifying the NBR indicator yield a reasonable measure of policy shocks, but a misleading measure of feedback effects.

Finally, the measures obtained by adding the orthogonality conditions to the sets of targeting restrictions differ more sharply from the valid measures. This is because these conditions constrain the current non-reserve variables and policy shocks to be orthogonal. Consequently, the correlation between feedback effects and policy shocks in (8) is fixed to zero. In contrast, the correlations between these components are −0.125 and −0.106 for the smoothed and unsmoothed valid measures. Thus, imposing the false orthogonality restrictions distorts the decomposition of the monetary authority's reaction function into policy shocks and feedback effects.

Taken together, these findings have important implications for the specification and estimation of the Fed's reaction function. First, the econometric specification must be consistent with the valid restrictions leading to the MIX, ANBR, or BR indicator. This means that valid policy indicators need to combine either the three reserve variables, or a mix of the non-borrowed reserves and total reserves. This differs sharply with the practice of approximating the policy indicator by a single variable such as the federal funds rate or the non-borrowed reserves. Second, the estimation method must relax the orthogonality conditions. In this sense, an instrumental-variable approach is appropriate to estimate the coefficients of the monetary authority's reaction function. In contrast, the common practice of applying the OLS technique is inadequate, given that it assumes the orthogonality between the non-reserve variables and policy shocks. In sum, it is only by meeting these econometric requirements that it is possible to adequately decompose the monetary authority's reaction function into policy shocks and feedback effects, and to distinguish between the Fed's exogenous changes in policy and systematic responses to fluctuations in non-reserve variables.

7. Dynamic responses

To analyze the temporal effects of the identified fundamental disturbances, we report the dynamic responses of the variables to monetary policy shocks, as well as to shocks to the demand for total reserves and borrowed reserves. For reasons explained above, we refer to the responses computed from the ML estimates of the parameters of system (4) and of the GARCH(1,1) processes (6) as the valid responses.

Fig. 2 displays the valid responses with their (possibly asymmetric) 68% probability intervals.[5] First we examine the response of the non-reserve and reserve variables to a positive, one unconditional standard-deviation policy shock. These are presented in the first two columns. An expansionary policy shock generates a

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[5]The intervals are computed using Sims and Zha's (1999) bayesian procedure based on unconditional moments.
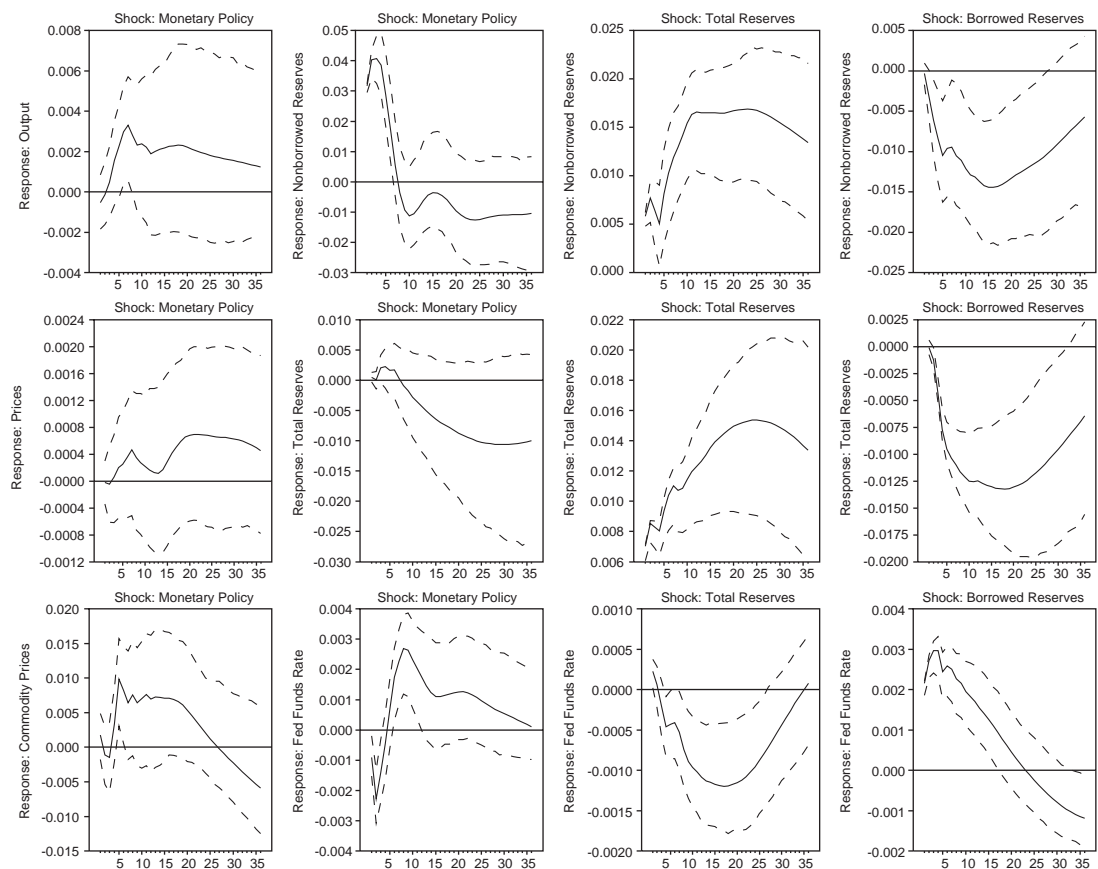
Fig. 2. Dynamic responses: unrestricted policy indicators without orthogonality conditions. Note: The solid lines correspond to the valid responses. The dotted lines represent the error bands associated with the 68% probability intervals.

persistent, hump-shaped increase in output, with the response peaking seven months after the shock. The price level also increases, but its response is imprecisely estimated. The commodity prices increase sharply. There is also a significant decline in the federal funds rate, or liquidity effect, over a period of six months after the shock. The non-borrowed reserves increase during the first five months and then decline after. Finally, the total reserves increase initially and fall after.

The third column shows how the reserve variables respond to a positive, one unconditional standard-deviation, shock to total reserves while the fourth column displays the responses of the reserve variables to a negative, one unconditional standard-deviation shock to borrowed reserves. A positive shock to total reserves triggers a sharp, persistent increase both in the non-borrowed reserves and total reserves. The federal funds rate initially rises and then falls. A negative shock to borrowed reserves produces a large, persistent decline in the non-borrowed reserves and total reserves, and a persistent increase in the federal funds rate. These dynamic responses are generally consistent with the identifying assumptions associated with the MIX, ANBR, and BR indicators. In contrast, they are inconsistent with the FFR indicator which requires that the monetary authority smooths the federal funds rate by increasing the non-borrowed reserves after a negative shock to borrowed reserves, and with the NBR indicator, where the Fed does not alter the non-borrowed reserves after a non-policy shock.

Comparing the valid responses obtained from system (4) with those estimated under the various identification conditions helps to evaluate the consequences of imposing the invalid restrictions. For the valid MIX, BR and ANBR indicators, we present only the findings obtained with the BR indicator since the results are very similar for all these indicators.

Fig. 3 provides the responses corresponding to the borrowed reserve indicator. We report three sets of responses: the valid responses obtained from system (4), those obtained by imposing only the valid restrictions identifying the borrowed-reserve targeting procedure, and the responses generated by further imposing the false orthogonality restrictions.

The responses obtained by imposing only the valid restrictions identifying the BR indicator are very similar to those of the valid system. In particular, the signs, magnitudes and shapes of responses match very closely. In contrast, adding the invalid orthogonality restrictions significantly distorts many responses. Specifically, these false restrictions substantially overstate the response of output to a policy shock. Furthermore, the reserve variables respond very differently to a shock to total reserves or to borrowed reserves. In particular, both the responses of the non-borrowed reserves and total reserves to a shock to borrowed reserves have the wrong sign. These findings corroborate our conclusions based on formal tests that the restrictions associated with borrowed-reserve targeting are empirically valid, while the orthogonality conditions are not. Also, these results show that the invalid orthogonality restrictions tend to considerably reduce the effects of the shifts in the borrowing function. As explained previously, it becomes more difficult in this context to discriminate between the borrowed-reserve and interest-rate targeting procedures.
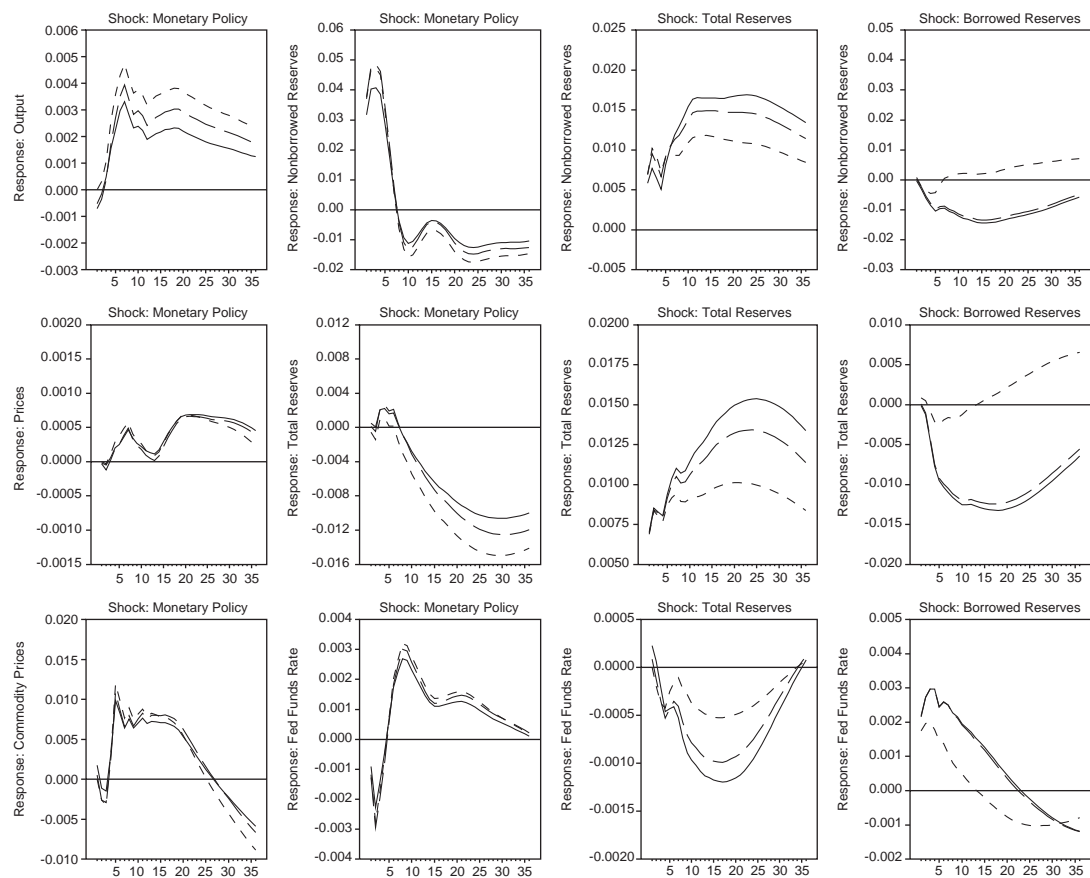
Fig. 3. Dynamic responses: borrowed reserve indicator with and without orthogonality conditions. Note: The solid lines correspond to the valid responses. The dashed lines represent the responses obtained by imposing only the restrictions associated with the borrowed reserve indicator. The dotted lines are the responses obtained by further imposing the restrictions related to the orthogonality conditions.

Fig. 4 compares the valid responses with those obtained under the interest-rate targeting procedure, with and without the orthogonality restrictions. A striking feature is the large difference in these responses. A notable example is the response of prices to a policy shock. While system (4) generates a rise in prices following an expansionary policy shock, the invalid restrictions lead to a decline in prices. This anomalous response of prices, often called the price puzzle, has previously been noted in the literature (e.g. Eichenbaum, 1992; Sims, 1992; Sims and Zha, 1995; Christiano et al., 1996). Unlike the explanations that have been offered for its existence in the past literature, our findings suggest that it may be an artifact of imposing the false identifying restrictions. Apart from the price puzzle, the false restrictions also overstate the response of output to a policy shock by a significant amount. They further imply a much sharper and persistent decline in the federal funds rate or liquidity effect than with the valid system. Imposing only the invalid restrictions identifying the FFR indicator does not significantly alter the responses of the reserve variables to a shock to total reserves. However, imposing the orthogonality restrictions under-predicts these responses substantially. Finally, the false restrictions produce highly misleading responses of the reserve variables to a shock to borrowed reserves.

Fig. 5 contrasts the responses implied by the NBR indicator with their valid counterparts. Without the orthogonality conditions, the two output responses match fairly well, although the invalid restrictions identifying the NBR indicator somewhat underestimate the rise in output after the first twelve months. Adding the false orthogonality conditions has the opposite effect: it significantly overestimates the response of output following an expansionary policy shock. Unlike the FFR indicator, the NBR-policy shock produces a rise in nominal prices, but the invalid restrictions identifying the NBR targeting procedure substantially overstate the price response. The liquidity effects obtained under the false restrictions and with system (4) are very similar. Therefore, although the orthogonality conditions and the restrictions identifying the NBR indicator are jointly invalid, they do not generate the price puzzle or overestimate the liquidity effect. Finally, the invalid restrictions greatly affect the responses of the reserve variables to a shock to total reserves or to borrowed reserves.

These findings have important implications for evaluating the effects of monetary policy. First, an accurate description of the dynamic impacts of policy shocks requires the use of the valid restrictions identifying the MIX, ANBR, or BR targeting procedure. We have shown that compared to the valid restrictions, the false restrictions associated with the FFR indicator substantially overpredict the response of output, underpredict the response of prices, and overestimate the liquidity effect. Also, the invalid restrictions associated with the NBR targeting procedure greatly underestimate the increase in output and overstate the rise in prices. Second, an analysis of the dynamic impacts of policy shocks must relax the orthogonality conditions. These invalid restrictions always substantially overstate the magnitude and persistence of the response of output.
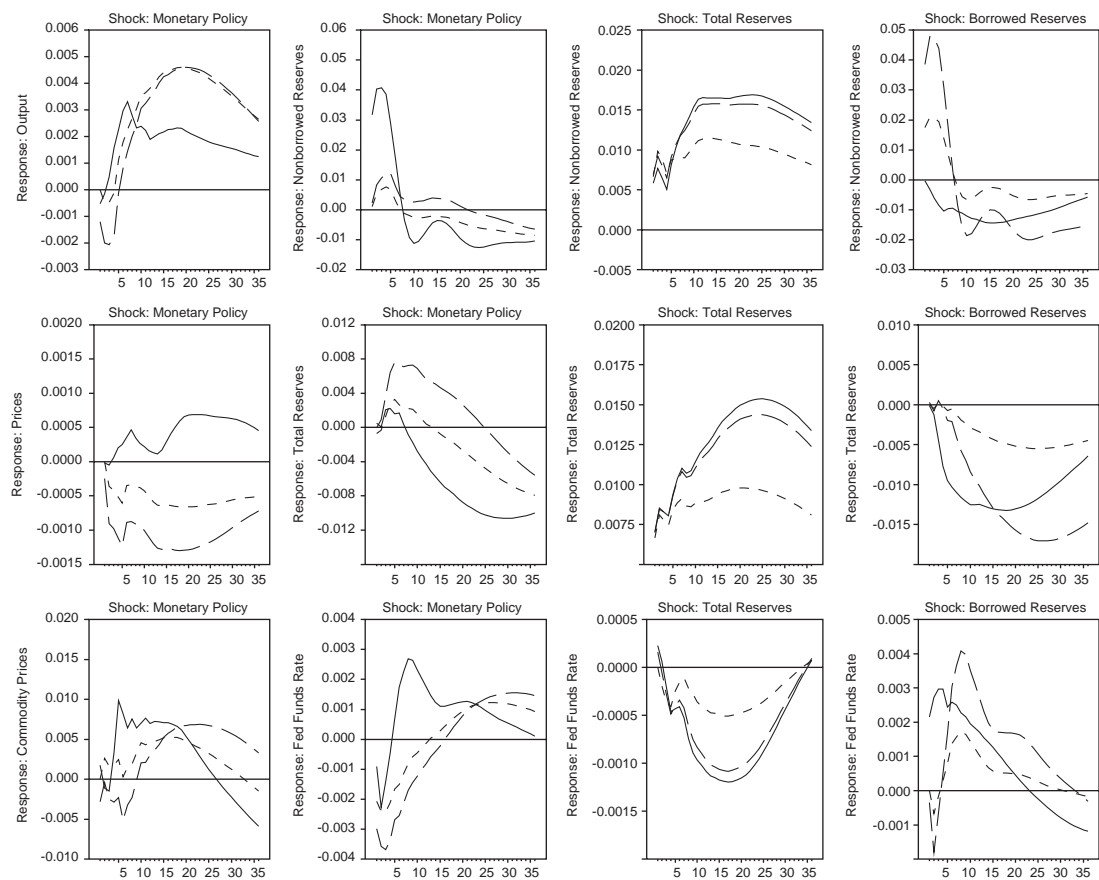
Fig. 4. Dynamic responses: federal funds rate indicator with and without orthogonality conditions. Note: The solid lines correspond to the valid responses. The dashed lines represent the responses obtained by imposing only the restrictions associated with the federal funds rate indicator. The dotted lines are the responses obtained by further imposing the restrictions related to the orthogonality conditions.
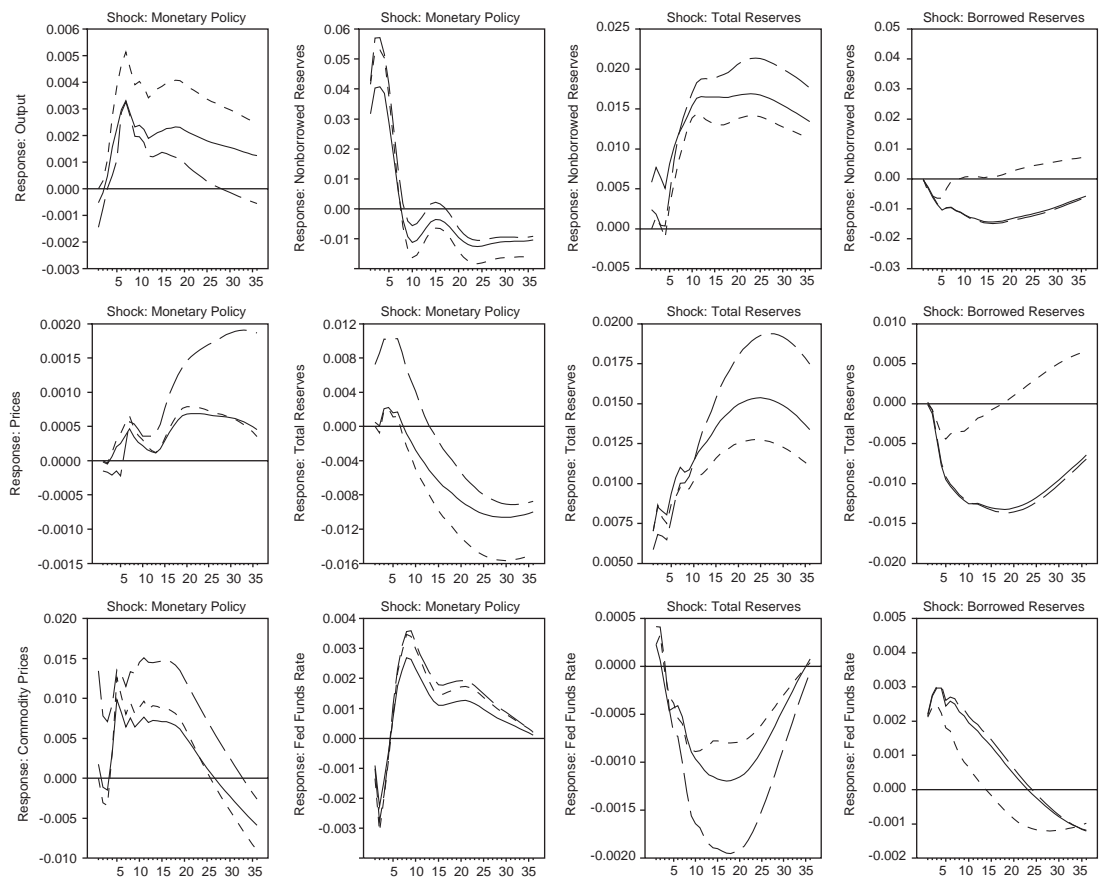
Fig. 5. Dynamic responses: non-borrowed reserve indicator with and without orthogonality conditions. Note: The solid lines correspond to the valid responses. The dashed lines represent the responses obtained by imposing only the restrictions associated with the non-borrowed reserve indicator. The dotted lines are the responses obtained by further imposing the restrictions related to the orthogonality conditions.

8. Conclusion

In this paper, we proposed a procedure to test the targeting and orthogonal restrictions traditionally imposed to identify monetary policy shocks. The novel aspect of this approach is that it accounts for the time-varying conditional volatility of fundamental disturbances. In this context, the SVAR becomes over-identified, so that the restrictions can be tested individually and jointly.

Our estimates indicate that all, but one, structural innovations display time-varying conditional variances. Interestingly, the pronounced movements in these variances coincide with specific events, such as the Continental Illinois incident and the 1990–1991 recession. Also, the major volatility shifts allow the identification of the policy shocks.

The test results reveal that the targeting restrictions associated with the interest-rate or non-borrowed-reserve indicator are strongly rejected, while those behind the other policy indicators are not. Also, the orthogonality conditions are strongly rejected, given that the policy shocks contemporaneously affect output and prices mainly through current adjustments of interest rates.

These findings have important implications for policy. Specifically, the policy shocks and their dynamic effects on the economy are adequately measured from the valid targeting restrictions. In contrast, misleading policy measures and dynamic responses are obtained from the invalid restrictions associated with interest-rate targeting, non-borrowed-reserve targeting, or orthogonality conditions. Finally, policy indicators combining several reserve variables and estimation techniques relaxing the orthogonality conditions are required to appropriately decompose the monetary authority's reaction function into policy shocks and feedback effects, and to distinguish between the Fed's exogenous changes in policy and systematic responses to fluctuations in output and prices.

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