The Timing of Monetary Policy Shocks[1]

Giovanni Olivei
Federal Reserve Bank of Boston

Silvana Tenreyro
London School of Economics

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Abstract

A vast empirical literature has documented delayed and persistent effects of monetary policy shocks on output. We show that this finding results from the aggregation of output impulse responses that differ sharply depending on the timing of the shock: When the monetary policy shock takes place in the first two quarters of the year, the response of output is quick, sizable, and dies out at a relatively fast pace. In contrast, output responds very little when the shock takes place in the third or fourth quarter. We propose a potential explanation for the differential responses based on uneven staggering of wage contracts across quarters. Using a stylized dynamic general equilibrium model, we show that a very modest amount of uneven staggering can generate differences in output responses similar to those found in the data. *JEL Codes*: E1, E52, E58, E32, E31.

1 Introduction

An important branch of the macroeconomics literature is motivated by the questions of whether, to what extent, and why monetary policy matters. As concerns the first two questions, substantial empirical work has led to a broad consensus that monetary shocks do have real effects on output. Moreover, the output response is persistent and occurs with considerable delay: The typical impulse-response has output peaking six to eight quarters after a monetary policy shock (see, for example, Christiano, Eichenbaum, and Evans 1999). As for the third question, a large class of theories points to the existence of contractual rigidities to explain why monetary policy might cause real effects on output. Theoretical models usually posit some form of nominal or real rigidity in wages or prices that is constant over time. For example, wage contracts are assumed to be staggered uniformly over time or subject to change with a constant probability at each point in time (Taylor 1980 and Calvo 1983).[1]

This convenient simplification, however, may not be a reasonable approximation of reality. As a consequence of organizational and strategic motives, wage contract renegotiations may occur at specific times in the calendar year. While there is no systematic information on the timing of wage contracts, anecdotal evidence supports the notion of "lumping" or uneven staggering of contracts. For example, evidence from firms in manufacturing, defense, information technology, insurance, and retail in New England surveyed by the Federal Reserve System in 2003 for the "Beige Book" indicates that most firms take decisions regarding compensation changes (base-pay and health insurance) during the fourth quarter of the calendar year. Changes in compensation then become effective at the very beginning of the next year. The Radford Surveys of compensation practices in the information

[1] State-dependent versions of price- and wage-setting behavior have been developed in the literature (see Dotsey, King, and Wolman 1999). However, as we argue in the text, the probability of changing prices and wages over time may change for reasons not captured by changes in the state of the economy.

technology sector reveals that more than 90 percent of the companies use a focal base-pay administration, with annual pay-change reviews; pay changes usually take place at the beginning of the new fiscal year. According to the same survey, 60 percent of the IT companies close their fiscal year in December.[2] To the extent that there is a link between pay changes and the end of the fiscal year, it is worth noting that 64 percent of the firms in the Russel 3,000 index end their fiscal year in the fourth quarter, 16 percent in the first, 7 percent in the second, and 13 percent in the third quarter.[3] Finally, reports on collective bargaining activity compiled by the Bureau of Labor Statistics show that the distribution of expirations and wage reopening dates tends to be tilted towards the second semester of the year.[4]

If the staggering of wage contracts is not uniform, as the anecdotal evidence suggests, in principle monetary policy can have different effects on real activity at different points in time. Specifically, monetary policy should have, other things equal, a smaller impact in periods of lower rigidity – that is, when wages are being reset. This paper provides an indirect test for the presence and the importance of the lumping or uneven staggering of contracts by examining the effect of monetary policy shocks at different times in the calendar year. In order to do so, we introduce quarter-dependence in an otherwise standard VAR model. Our goal is to assess whether the effect of a monetary policy shock differs according to the quarter in which the shock occurs and, if so, whether such a difference can be reconciled with uneven staggering.

We find that there are significant differences in output impulse-responses depending on the timing of the shock. In particular, after a monetary shock that takes place in the first quarter, the response of output is fairly rapid, with output reaching a level close to the peak effect 4 quarters after the

[2]We thank Andy Rosen of Aon Consulting's Radford Surveys for providing us with the information.

[3]This information is for the year 2003 and is available from Standard and Poor's COMPUSTAT. To compute the percentages, we have weighted each firm in the Russel 3,000 index by the firm's number of employees.

[4]See *Current Wage Developments*, various issues, Bureau of Labor Statistics.

shock. The response is even more front-loaded and dies out faster when the shock takes place in the second quarter. In this case, the peak effect is attained 3 quarters after the shock. In both cases, the response of output to a monetary policy shock is economically relevant. An expansionary shock in either the first or the second quarter with an impact effect on the federal funds rate of -25 basis points raises output in the following 8 quarters by an average of about 25 basis points. In contrast, the response of output to a monetary shock occurring in the second half of the calendar year is small, both from a statistical and from an economic standpoint. A 25 basis points unexpected monetary expansion in either the third or fourth quarter raises output in the 8 quarters following the shock by less than 10 basis points on average, with the effect not statistically different from zero at standard confidence levels. The well-known finding that output takes a long time to respond and is quite persistent may be interpreted as the combination of these sharply different quarterly responses.

The dynamics of output in response to a monetary policy shock at different times of the year is mirrored by the dynamics of prices and wages. The price- and wage-response is delayed when the shock occurs in the first half of the year, whereas prices and wages respond more quickly when the shock occurs in the second half of the year.

We interpret the differential responses across quarters in the context of a stochastic dynamic general equilibrium model that builds on Christiano, Eichenbaum, and Evans (2005). To represent uneven staggering, the model features a variant of the mechanism proposed by Calvo (1983). The crucial difference is that the probability of changing wages is not constant across quarters. We show that a modest amount of uneven staggering can lead to significantly different output responses. This happens even if the cumulative effect of the monetary policy shock on wages and prices is not strikingly different across quarters, a feature also present in the data.

The remainder of the paper is organized as follows. Section 2 presents the empirical methodology and introduces the data. Section 3 presents the dynamic effects of monetary policy on different macroeconomic aggregates and performs a set of robustness tests. Section 4 illustrates the theoretical model and discusses its implications in light of the empirical findings. Section 5 offers some concluding remarks.

2 Methodology

2.1 Empirical Model

Our empirical analysis for measuring the effect of monetary policy shocks relies on a very general linear dynamic model of the macroeconomy whose structure is given by the following system of equations:

$$\mathbf{Y}_t = \sum_{s=0}^{S} \mathbf{B}(q_t)_s \mathbf{Y}_{t-s} + \sum_{s=1}^{S} \mathbf{C}(q_t)_s \; p_{t-s} + \mathbf{A}^y(q_t)\mathbf{v}_t^y \tag{1}$$

$$p_t = \sum_{s=0}^{S} \mathbf{D}_s \mathbf{Y}_{t-s} + \sum_{s=1}^{S} \mathbf{g}_s \; p_{t-s} + v_t^p. \tag{2}$$

Boldface letters are used to indicate vectors or matrices of variables or coefficients. In particular, $\mathbf{Y}_t$ is a vector of non-policy macroeconomic variables (e.g., output, prices, and wages), and p_t is the scalar variable that summarizes the policy stance. We take the federal funds rate as our measure of policy, and use innovations in the federal funds rate as a measure of monetary policy shocks. Federal Reserve operating procedures have varied in the past 40 years, but several authors have argued that funds-rate targeting provides a good description of Federal Reserve policy over most of the period (see Bernanke and Blinder, 1992, and Bernanke and Mihov, 1998). Equation (1) allows the non-policy variables $\mathbf{Y}_t$ to depend on both current and lagged values of $\mathbf{Y}$, on lagged values of p, and on a vector of uncorrelated disturbances $\mathbf{v}^y$.[5] Equation (2) states that the policy variable p_t depends on both

[5] Note that the vector of disturbances $\mathbf{v}^y$, composed of uncorrelated elements, is pre-multiplied by the matrix $\mathbf{A}^y(q)$ to indicate that each element of $\mathbf{v}^y$ can enter into any of the non-policy equations. This renders the assumption of

current and lagged values of $\mathbf{Y}$, on lagged values of p, and on the monetary policy shock v^p.[6] As such, the system embeds the key restriction for identifying the dynamic effects of exogenous policy shocks on the various macro variables $\mathbf{Y}$: Policy shocks do not affect macro variables within the current period. Although debatable, this identifying assumption is standard in several recent VAR analyses.[7]

The model in equations (1) and (2) replicates the specification of Bernanke and Blinder (1992), with the crucial difference that we allow for time-dependence in the coefficients. Specifically, $\mathbf{B}(q_t)_s$ and $\mathbf{C}(q_t)_s$ are coefficient matrices whose elements, the coefficients at each lag, are allowed to depend on the quarter q_t that indexes the dependent variable, where $q_t = j$ if t corresponds to the j^{th} quarter of the year. The systematic response of policy takes the time-dependence feature of the non-policy variables into account: Substituting (1) into (2) shows that the coefficients in the policy equation are indirectly indexed by q_t through their impact on the non-policy variables, $\mathbf{Y}_t$.[8]

Given the identifying assumption that policy shocks do not affect macro variables within the current period, we can rewrite the system in a standard VAR reduced-form, with only lagged variables on the right-hand side:

$$\mathbf{X}_t = \mathbf{F}(L,q)\mathbf{X}_{t-1} + \mathbf{U}_t, \tag{3}$$

where $\mathbf{X}_t = [\mathbf{Y}_t, p(t)]'$, $\mathbf{U}_t$ is the corresponding vector of reduced-form residuals, and $\mathbf{F}(L,q)$ is a four-quarter distributed lag matrix of coefficients that allows for the coefficients at each lag to depend on the particular quarter q indexing the dependent variable. The system can then be estimated equation-

uncorrelated disturbances unrestrictive.

[6] Policy shocks are assumed to be uncorrelated with the elements of $\mathbf{v}^y$. Independence from contemporaneous economic conditions is considered part of the definition of an exogenous policy shock. The standard interpretation of v^p is a combination of various random factors that might affect policy decisions, including data errors and revisions, preferences of participants at the FOMC meetings, politics, etc. (See Bernanke and Mihov 1998).

[7] See, among others, Bernanke and Blinder (1992), Bernanke and Mihov (1998), Christiano, Eichenbaum and Evans (1999) and (2005), Boivin and Giannoni (2003), and Rotemberg and Woodford (1997).

[8] In this specification, the coefficients $\mathbf{D}_s$ and $\mathbf{g}_s$ are constant across seasons, neglecting differential policy responses in different seasons beyond the indirect effect through $\mathbf{Y}_t$ we already mentioned. We are unaware of any evidence suggesting that policy responses to given outcomes vary by season.

by-equation using ordinary least squares. The effect of policy innovations on the non-policy variables is identified with the impulse-response function of $\mathbf{Y}$ to past changes in v^p in the unrestricted VAR (3), with the federal funds rate placed last in the ordering.[9] An estimated series for the policy shock can be obtained via a Choleski decomposition of the covariance matrix of the reduced-form residuals.

One important implication of quarter dependence is that the effects of monetary policy shocks vary depending on the quarter in which the shock takes place. Denote by $\mathbf{X}(T)$ the skip-sampled matrix series, with $\mathbf{X}(T) = (\mathbf{X}_{1,T}, \mathbf{X}_{2,T}, \mathbf{X}_{3,T}, \mathbf{X}_{4,T})$, where $\mathbf{X}_{j,T}$ is the vector of variables in quarter j in year T, and $j = 1, 2, 3, 4$.[10] Then we can rewrite the quarter-dependent reduced-form VAR (3) as follows:

$$\boldsymbol{\Xi}_0 \mathbf{X}(T) = \boldsymbol{\Xi}_1(L)\mathbf{X}(T-1) + \mathbf{U}(T), \tag{4}$$

where $\boldsymbol{\Xi}_0$ and $\boldsymbol{\Xi}_1(L)$ are parameter matrices containing the parameters in $\mathbf{F}(L,q)$ in (3), and $\mathbf{U}(T) = (\mathbf{U}_{1,T}, \mathbf{U}_{2,T}, \mathbf{U}_{3,T}, \mathbf{U}_{4,T})$, with $\mathbf{U}_{j,T}$ the vector of reduced-form residuals in quarter j of year T. The system in (4) is simply the reduced-form VAR (3) rewritten for annually observed time series. As such, the reduced-form (4) does not contain time-varying parameters. Moreover, because the matrix $\boldsymbol{\Xi}_0$ can be shown to be lower-triangular, it can be inverted to yield:

$$\mathbf{X}(T) = \boldsymbol{\Xi}_0^{-1}\boldsymbol{\Xi}_1(L)\mathbf{X}(T-1) + \boldsymbol{\Xi}_0^{-1}\mathbf{U}(T), \tag{5}$$

with $\boldsymbol{\Xi}_0^{-1}$ still being a lower-triangular matrix. The system (5) illustrates that when a monetary policy shock occurs in the first quarter, the response of the non-policy variables in the next quarter will be governed by the reduced-form dynamics of the non-policy variables in the second quarter.

[9] The ordering of the variables in $\mathbf{Y}_t$ is irrelevant. Since identification of the dynamic effects of exogenous policy shocks on the macro variables $\mathbf{Y}$ only requires that policy shocks do not affect the given macro variables within the current period, it is not necessary to identify the entire structure of the model.

[10] If $t = 1,...,n$, then the observations in $\mathbf{X}_{1,T}$ are given by $t = 1, 5, 9,...,n-3$, the observations in $\mathbf{X}_{2,T}$ are given by $t = 2, 6, 10,...,n-2$, and so on.

The response two quarters after the initial shock will be governed by the reduced-form dynamics of the non-policy variables in the third quarter, and so on.

2.2 Testing

The quarter-dependent VAR in (3) generates four different sets of impulse-responses to a monetary policy shock, according to the quarter in which the shock occurs. It is then important to assess whether the quarter-dependent impulse-response functions are statistically different from the impulse-responses of the nested standard VAR with no time-dependence. A first natural test for the empirical relevance of quarterly effects consists of simply comparing the estimates obtained from the quarter-dependent VAR (3) with those obtained from the restricted standard VAR using an F-test, equation by equation. A rejection of the null hypothesis of no seasonal dependence would imply that the system generates four different sets of impulse-responses. The F-tests on the linear reduced-form VAR, however, do not map one-for-one into a test on the corresponding impulse-responses because the impulse-response functions are nonlinear combinations of the estimated coefficients in the VAR. To assess the significance of quarter-dependence directly on the impulse-response functions, we develop a second test that complements the F-test on the linear VAR equations. Specifically, we consider the maximum difference, in absolute value, between the impulse-responses of variable x in the quarter-dependent VAR and in the standard non-time-dependent VAR, to obtain the following statistic:

$$D = \sup_{k} |x_k^q - x_k|$$

where x_k^q denotes the period k response in the quarter-dependent model and x_k the response in the standard non-time-dependent model.[11] We resort to simulation methods for inference. Using a bootstrap procedure, we calculate the distribution of the D statistic under the assumption that the there is no quarter-dependence. The bootstrap algorithm involves generating a random sample by sampling (with replacement) from the residuals of the estimated non-time-dependent reduced-form VAR. Using fixed initial conditions,[12] we recursively generate a new data set using the estimated parameters from the standard non-time-dependent VAR. We then estimate new impulse-responses from both the quarter-dependent and the standard VAR, and compute a new value D^{S}, where the superscript S denotes a simulated value. The procedure is repeated 2,000 times to obtain a bootstrap p-value, which is the percentage of simulated D^{S} exceeding the observed D.

2.3 Data and Estimation

Our benchmark analysis is based on quarterly data covering the period 1966:Q1 to 2002:Q4. The beginning of the estimation period is dictated by the behavior of monetary policy. Only after 1965 did the federal funds rate, the policy variable in our study, exceed the discount rate and hence acted as the primary instrument of monetary policy. We use seasonally adjusted data, but in the robustness section we also present results based on non-seasonally adjusted data. The non-policy variables in the system include real GDP, the GDP deflator, and an index of spot commodity prices.[13] As is now standard in the literature, the inclusion of the commodity price index in the system is aimed at mitigating the "price puzzle," whereby a monetary tightening initially leads to a rising rather than

[11] We compute the supremum of the difference in impulse-response functions over 20 quarters following a monetary policy shock.

[12] The fixed initial conditions are given by the values that the variables included in the VAR take over the period 1965:Q1 to 1965:Q4.

[13] The source for real GDP and the GDP deflator is the Bureau of Economic Analysis, Quarterly National Income and Product Accounts. The source for the spot commodity price index is the Commodity Research Bureau.

falling price level. In the robustness section we consider alternative specifications where we replace the GDP deflator by core CPI and by an index for wages, given by compensation per-hour in the nonfarm business sector.[14]

We estimate each equation in the VAR (3) separately by OLS, using four lags of each variable in the system. In our benchmark specification, all the variables in the vector $\mathbf{Y}$ are expressed in log levels. The policy variable, the federal funds rate, is expressed in levels. We formalize trends in the non-policy variables as deterministic, and allow for a linear trend in each of the equations of the VAR (3). In the robustness section we discuss findings when GDP is expressed as the (log) deviation from a segmented deterministic trend, while the GDP deflator and the commodity price index are expressed in (log) first-differences.

3 The Dynamic Effects of Monetary Policy Shocks

3.1 Results from the VAR Specification

In this section we present the estimated dynamic effects of monetary policy shocks on real GDP, the GDP deflator, and the federal funds rate. Impulse-responses are depicted in Figures 1 through 5, together with 95 percent and 80 percent confidence bands around the estimated responses.[15] We consider a monetary policy shock that corresponds to a 25-basis point decline in the funds rate on impact. For ease of comparison, the response of the variables to the shock are graphed on the same scale across figures. Figure 1 displays impulse-responses to the policy shock when we do not allow for quarter-dependence in the reduced-form VAR, as is customary in the literature. The top panel

[14] The source for both core CPI and compensation per-hour in the nonfarm business sector is the Bureau of Labor Statistics.

[15] While much applied work uses 95 percent confidence intervals, Sims and Zha (1999) note that the use of high-probability intervals camouflages the occurrence of large errors of over-coverage and advocate the use of smaller intervals, such as intervals with 68 percent coverage (one standard error in the Gaussian case). An interval with 80 percent probability corresponds to about 1.3 standard error in the Gaussian case.

shows that the output response to the policy shock is persistent, peaking 7 quarters after the shock and slowly decaying thereafter. The response of output is still more than half of the peak response 12 quarters after the shock. The center panel shows that prices start to rise reliably 3 quarters after the shock, although it takes about one year and a half for the increase to become significant. The bottom panel, which displays the path of the federal funds rate, illustrates that the impact on the funds rate of a policy shock is less persistent than the effect on output.

Figures 2 to 5 display impulse-responses when we estimate the quarter-dependent reduced-form VAR (3). The responses to a monetary policy shock occurring in the first quarter of the year are shown in Figure 2. Output rises on impact and reaches a level close to its peak response 4 quarters after the shock. The output response dies out at a faster pace than in the non-time-dependent VAR: 12 quarters after the shock, the response of output is less than a third of the peak response, which occurs 7 quarters after the shock as in the non-time-dependent VAR. Moreover, the peak response is now more than twice as large as in the case with no quarter-dependence. The center panel shows that, despite controlling for commodity prices, there is still a "price puzzle," although the decline in prices is not statistically significant. It takes about 7 quarters after the shock for prices to start rising. The fed funds rate, shown in the bottom panel, converges at about the same pace as in Figure 1.

Figure 3 displays impulse-responses to a shock that takes place in the second quarter. It is apparent that the response of output is fast and sizable. Output reaches its peak 3 quarters after the shock, and the peak response is more than three times larger than the peak response in the case with no quarter-dependence. Moreover, the response wanes rapidly, becoming insignificantly different from zero 8 quarters after the shock. The center panel shows that prices start rising 3 quarters after the shock. The bottom panel illustrates that the large output response occurs despite the fact that the policy shock exhibits little persistence.

The responses to a monetary policy shock in the third and the fourth quarter of the year contrast sharply with the responses to a shock taking place in the first half of the calendar year. Figure 4 shows the impulse-responses to a shock that occurs in the third quarter. The response of output in the top panel is now small and insignificant, both from a statistical and from an economic standpoint. Interestingly, as the center panel illustrates, prices start to increase reliably immediately after the shock. The output and price responses to a shock in the fourth quarter are qualitatively similar. As Figure 5 illustrates, the response of output is fairly weak, while prices respond almost immediately following the shock.

The differences in output responses are substantial from a policy standpoint. The policy shock raises output in the following 8 quarters by an average of almost 25 basis points in either the first or the second quarter. In contrast, the increase in output is less than 10 basis points on average in both the third and the fourth quarter. Moreover, the differences documented in figures 1 to 5 are corroborated by formal tests on the importance of quarter-dependence. Equation-by-equation F-tests in the reduced-form VAR (3) yield p-values of 0.18 for the output equation, 0.04 for the price equation, 0.03 the for the commodity prices equation, and 0.006 for the federal funds rate equation.

While indicative of the existence of seasonal dependence, these relatively low p-values do not necessarily translate into statistically different impulse-responses for the corresponding variables. For this purpose, we evaluate the D-statistic described in Section 2.2, which assesses whether the maximum difference between the impulse-response of a given variable in the quarter-dependent VAR and the corresponding response of that variable in the standard non-time-dependent VAR is statistically different. Table 1 reports the bootstrapped p-values for the D-statistic in each quarter for GDP, the GDP deflator, and the federal funds rate. The table shows that according to this test, the output response in the first, second, and third quarter of the calendar year is statistically different from the non-time dependent output impulse-response at better than the asymptotic 5 percent level. The null hypothesis of an output response equal to the non-time dependent response is rejected at the asymptotic 10 percent level in the fourth quarter. As may be inferred from Figures 1 through 5, the table shows that the evidence in favor of quarter-dependent price impulse-responses is weaker than for output. Still, the test identifies statistical differences in the third and fourth quarters: In the third quarter, the null hypothesis of a price response equal to the non-time dependent response is rejected at the asymptotic 1 percent level and in the fourth quarter the null is rejected at the 5 percent level.

3.2 The Distribution of Monetary Policy Shocks and the State of the Economy

An important issue to consider is whether the different impulse-responses we obtain across quarters are the result of different types of shocks. In principle, differences in the intensity and direction (expansionary versus contractionary) of shocks could produce different impulse-responses. To explore this hypothesis, we test for the equality of the distributions of shocks across quarters by means of a Kolmogorov-Smirnov test. The test consists of a pairwise comparison of the distributions of shocks between every 2 quarters, with the null hypothesis of identical distributions. We find that we cannot reject the null hypothesis in any 2 quarters: The smallest p-value corresponds to the test for the equality of the distributions of shocks between the third and fourth quarters and is equal to 0.31; the largest p-value corresponds to the test between the second and third quarters and is equal to 0.97. These findings suggest that differences in the type of monetary policy shocks across quarters are unlikely to provide an explanation for the quarterly differences in impulse-responses documented in Figures 2 through 5.

Another issue is whether our findings are driven by the state of the economy. In principle, a theoretical argument can be made that an expansionary monetary policy shock has a larger impact on output and a smaller impact on prices when the economy is running below potential, and, vice-versa, a smaller impact on output and a larger impact on prices when the economy is running above potential. To explore this issue, we partitioned the data according to whether the output gap was positive or negative and estimated two different reduced-form VARs. The impulse-responses for output and prices to a monetary policy shock from the VAR estimated using observations corresponding to a negative output gap were similar to the impulse-responses obtained from the VAR estimated using observations corresponding to a positive output gap.[16] These results suggest that the stage of the business cycle is unlikely to be a candidate for explaining the different impulse-responses across quarters.

There is, however, a more subtle way in which the state of the economy could influence our findings. Barsky and Miron (1989) trace a parallel between seasonal and business cycles, and note that in seasonally unadjusted data the first and third quarters resemble a recession (the third quarter being milder), whereas the second and fourth quarters resemble an expansion (with the fourth being stronger). Our use of seasonally adjusted data should in principle control for the seasonal component of output. And even if such a control were imperfect, the pattern of impulse-responses in Figures 2 to 5 cannot be easily reconciled with the seasonal cycle. The response of output is in fact large when the policy shock occurs in the first (recession) and second (expansion) quarters, and the response is weak when the shock occurs in the third (recession) and fourth (expansion) quarters. It is still possible, though, that the seasonal pattern of some activities that are particularly sensitive to interest rate movements, such as (consumption and producer) durables and structures, could affect some of our findings. In particular, Barsky and Miron show that in the first quarter of the year there is a pronounced seasonal slowdown in spending for both durables and structures. A potential interpretation for our fourth-quarter results would then be that at that time of the calendar year a policy

[16] These findings are available upon request. There is no established evidence in the extant empirical literature that monetary shocks have different effects according to the stage of the business cycle.

shock has little impact on output because the transmission mechanism is impaired by the low level of interest-sensitive activities in the subsequent quarter. This interpretation, however, is problematic because a policy shock occurring in the fourth quarter persists over the next two quarters, as the estimated impulse-response for the funds rate in Figure 5 shows.[17] We thus view our findings as difficult to reconcile with an explanation that relies mainly on seasonal fluctuations in output or in the interest-sensitive components of output.

3.3 Robustness

We here summarize results on the robustness of our baseline specification along several dimensions.[18] Because the quarter-dependent reduced-form VAR (3) requires the estimation of a fairly large number of parameters, we investigated whether our findings are sensitive to outliers. For this purpose, we re-estimated the VAR equation-by-equation using Huber (1981) robust procedure. The Huber estimator can be interpreted as a weighted least squares estimator that gives a weight of unity to observations with residuals smaller in absolute value than a predetermined bound, but downweights outliers (defined as observations with residuals larger than the predetermined bound).[19] With this procedure, estimated impulse-responses (not shown) turn out to be very similar to the ones in Figures 2 through 5. A notable byproduct of the robust estimation procedure is that p-values for the F-tests on quarter-dependence are now well below 0.05 for all the equations in the VAR.

[17] When the policy shock occurs in the third quarter, it is still difficult to argue for a breakdown of the transmission mechaninsm induced by the seasonal pattern of some interest-sensitive components of output. This is because, as Barsky and Miron show, the seasonal level of spending on consumer and producer durables is very high in the fourth quarter.

[18] For reasons of space, we do not provide pictures of the estimated impulse-responses in most cases. The pictures not shown in the paper are available from the authors upon request.

[19] Denote by σ the standard deviation of the residuals in any given equation of the VAR (3). For the given equation, the Huber estimator gives a weight of unity to obervations with residuals smaller in absolute value than $c\sigma$, where c is a parameter usually chosen in the range $1 \leq c \leq 2$, while outliers, defined as observations with residuals larger than $c\sigma$, receive a weight of $\frac{c\sigma}{|u_i|}$, where u_i is the residual for observation i. The estimator is farly insensitive to the choice of c.

Since our proposed explanation for the different impulse-responses relies on uneven staggering of wage contracts across quarters, we considered an alternative specification where the GDP deflator is replaced by a wage index in the vector of non-policy variables $\mathbf{Y}$. Using wages in lieu of final prices does not alter our main findings. The estimated output responses (not shown) are virtually the same as in the benchmark specification, and the response of wages closely mimics the response of prices across different quarters. Similarly, the results are not affected by including both the GDP deflator and the wage index in the vector of non-policy variables $\mathbf{Y}$.

In our benchmark specification we control for seasonal effects by using seasonally adjusted data. Still, because we are exploiting a time-dependent feature of the data, it is of interest to check whether our results are driven by the seasonal adjustment. To this end, we estimate impulse-responses to a monetary shock from the quarter-dependent reduced-form VAR (3) using seasonally unadjusted data for the non-policy variables $\mathbf{Y}$.[20] The results from this exercise are illustrated in Figures 6 through 9, which show the responses of output, prices, and the federal funds rate to a 25 basis-point decline in the funds rate. The responses of output and prices using seasonally unadjusted data are remarkably similar to the responses obtained in the benchmark specification using seasonally adjusted data, although the estimated responses with seasonally unadjusted data are less precise.

The results continue to hold under a different treatment of the low-frequency movements in output and prices. Specifically, we considered a specification for the quarter-dependent reduced-form VAR (3) in which variables in $\mathbf{Y}$ are not expressed in log-levels, but rather GDP is expressed as a deviation from a segmented deterministic trend,[21] and prices are expressed in log first-differences. Such a specification is used in several papers in the literature (see, e.g., Boivin and Giannoni 2003). The

[20] Since we do not have data on the seasonally unadjusted GDP deflator, we replace the GDP deflator with the seasonally unadjusted CPI. The CPI index is also used to deflate the seasonally unadjusted data for nominal GDP.

[21] Specifically, we consider the deviation of log real GDP from its segmented deterministic linear trend, with break-points in 1974 and 1995.

estimated impulse-responses (not shown) are qualitatively similar to those reported in the benchmark specification. In particular, output responds more strongly and more quickly to a monetary policy shock in the first than in the second half of the year, while the opposite occurs for inflation.

3.4 Interpretation of the Evidence

Overall, Figures 2 through 5 and the supporting statistics uncover considerable differences in the response of output across quarters. The slow and persistent response of output to a policy shock typically found in the literature and reported in Figure 1 is the combination of different quarter-dependent responses. The difference in the behavior of prices across quarters is slightly less striking, given the imprecision with which the responses are estimated. It is interesting, though, that when the policy shock occurs in the third and fourth quarters, prices rise more quickly than when the shock takes place in either the first or the second quarter.

Together with the reported VAR results, the rejection of the hypotheses that the distirbution of monetary policy shocks is different across quarters and that the state of the economy is triggering the differences in the impulse responses lends itself to the following interpretation in the context of models with contractual rigidities. If a large number of firms sign wage contracts at the end of the calendar year then, on average, monetary policy shocks in the first half of the year will have a large impact on output, with little effect on prices. In contrast, monetary policy shocks in the second half of the year will be quickly followed by wage and price adjustments. The policy shock will be "undone" by the new contracts at the end of the year; and as a result the effect on output will be smaller on average. We show next that this intuition can be formalized in a dynamic stochastic general equilibrium setup that allows for uneven staggering of wage contracts.

4 A Model of Uneven Staggering

This section discusses a simple form of contractual rigidities based on a variant of the mechanism proposed by Calvo (1983). The critical difference is that we allow for the probability of changing wages to differ across quarters in a calendar year. This modelling device is a simple way of introducing clustering of wage contracts at certain times of the calendar year, and it nests the standard Calvo-style sticky-wage framework as a special case when the probability of resetting wages is equal across quarters. The uneven staggering of wage contracts in a calendar year is then embedded into a general equilibrium macro model that closely follows Christiano et al. (2005). Our version of their model is slightly simpler in that, consistent with our empirical setup, monetary policy targets a short-term interest rate by means of a Talyor-type reaction function. Since interest-rate targeting by the monetary authority makes money demand irrelevant in determining the equilibrium evolution of the other variables in the model,[22] we consider a cashless version of the model.

The model's key propagation mechanism in response to a temporary shock to the nominal interest rate is very simple. The nominal wage rigidity in the labor market is transmitted to prices. Because of this inherited rigidity, inflation does not respond immediately to changes in the nominal interest rate. Consequently, in the short run changes in the nominal interest rate translate into changes in the real interest rate, and hence into changes in aggregate demand conditions. Monetary policy, however, is neutral in the long run. As it is now standard in the literature, the model features habit formation in consumption and investment adjustment costs. These features attenuate the initial impact of a monetary policy shock on the economy, and make the effects of the shock long lasting.

In what follows, we model the evolution of nominal wages in the presence of uneven staggering. Uneven staggering of wages is the crucial element for the model to generate quarter-dependence

[22] See Woodford (2003).

in impulse responses. We then calibrate the model parameters and compare the model-generated impulse-responses with the empirical responses from our quarter-dependent benchmark VAR specification. We leave the description of the other equations and features of the model, which follow Christiano et al. (2005), to the Appendix (in particular, section A.1.1 describes the behaviour of firms, and A.1.2 describes the preferences and constraints of the households).

4.1 Wage Setting with Nominal Rigidities and Staggering

Our model economy features a continuum of households. At each time t, each household $i \in (0, 1)$ enjoys monopoly power over its differentiated labor service, $h_{i,t}$, and sells this service to a representative competitive firm with demand for labor-type i given by

$$h_{i,t} = \left(\frac{W_t}{W_{i,t}}\right)^{\frac{\lambda_w}{\lambda_w - 1}} L_t,\ \lambda_w \in [1, \infty).$$

In the equation, L_t denotes aggregate labor while W_t is the aggregate wage level, which takes the following form

$$W_t = \left[\int_0^1 W_{i,t}^{\frac{1}{1-\lambda_w}} di\right]^{1-\lambda_w}.$$

Households take W_t and L_t as given and set wages following the mechanism proposed by Calvo (1983). However, instead of facing a constant probability of resetting wage in any given period, households face (potentially) different probabilities over the course of a calendar year. For simplicity and to keep a close parallel with the empirical exercise, we divide the year into four quarters and assume that for any labor type the probability of resetting wages in quarter k is $(1 - \alpha_k)$, with $k = 1,..., 4$. When a household receives the signal to change its wage, the new wage is set optimally by taking into account the probability of future wage changes. In particular, if a contract is negotiated in the first quarter, the probability that it is *not* renegotiated in the second quarter will be α_2; the probability that it is *not* renegotiated in the next two quarters will be $\alpha_2\ \alpha_3$. Subsequent probabilities will be, correspondingly, $(\alpha_2\alpha_3\alpha_4)$, $(\alpha_2\alpha_3\alpha_4\alpha_1)$, $(\alpha_2^2\alpha_3\alpha_4\alpha_1)$, and so on. If a household cannot reoptimize its wage at time t, it uses a simple automatic rule of the form $W_{i,t} = \pi_{t-1}\ W_{i,t-1}$, where $\pi_{t-1} = P_t/P_{t-1}$ and P_t is the price level for the consumption good. The optimal wage for labor-type i resetting the contract in the first quarter is then

$$\tilde{W}_{i,t} = \arg\max_{\{W_{i,t}\}} E_{t-1} \left\{ \begin{array}{c} \sum\limits_{j=0}^{\infty} \prod\limits_{k=1}^{4} \alpha_k^j \beta^{4j} \{ \left[\psi_{t+4j} \frac{X_{t,4j} W_{i,t} h_{i,t+4j}}{P_{t+4j}} - z\left(h_{i,t+4j}\right) \right] + \\ +\alpha_2 \beta \left[\psi_{t+4j+1} \frac{X_{t,4j+1} W_{i,t} h_{i,t+4j+1}}{P_{t+4j+1}} - z(h_{i,t+4j+1}) \right] + \\ +\alpha_2\alpha_3\beta^2 \left[\psi_{t+4j+2} \frac{X_{t,4j+2} W_{i,t} h_{i,t+4j+2}}{P_{t+4j+2}} - z(h_{i,t+4j+2}) \right] + \\ +\alpha_2\alpha_3\alpha_4\beta^3 \left[\psi_{t+4j+3} \frac{X_{t,4j+3} W_{i,t} h_{i,t+4j+3}}{P_{t+4j+3}} - z(h_{i,t+4j+3}) \right] \} \end{array} \right\}, \tag{6}$$

where

$$\begin{aligned} X_{t,l} &= \pi_t \cdot \pi_{t+1} \cdot \pi_{t+2} \cdot \ldots \cdot \pi_{t+l-1} \text{ if } l \geqslant 0 \\ &= 1 \qquad\qquad\qquad\qquad\quad \text{if } l = 0, \end{aligned}$$

and ψ_t is the marginal utility of income at time t (the Lagrange multiplier for the household's budget constraint at time t). The optimal wage in the first quarter maximizes the expected stream of discounted utility from the new wage, defined as the difference between the gain derived from the hours worked at the new wage, $X_{t,4j}W_{i,t}h_{i,t+j}$ (expressed in *utils*) and the disutility $z(h)$ of working.[23] This expression is only valid for wages set in the first quarter, but expressions for the optimal wage

[23] Labor income is expressed in real terms terms (by dividing by the price level) and converted into utils using the marginal utility of income ψ.

in the other quarters of the calendar year can be derived in a similar fashion.[24] Note that since all labor-types resetting their wages at a given quarter will choose the same wage, we can drop the index i and simply refer to the optimal wage in period t as $\tilde{W}_t$.

Denoting log-linearized variables with a hat, defining $\widehat{\tilde{w}}_t$ and $\hat{w}_t$ as

$$\begin{aligned}\widehat{\tilde{w}}_t &= \widehat{\tilde{W}}_t - \hat{P}_t \\ \hat{w}_t &= \hat{W}_t - \hat{P}_t,\end{aligned}$$

and introducing the dummy variables q_{kt}, with $k = 1,\ldots 4$, which take the value of 1 in quarter k and 0 otherwise, we show in the Appendix that wage maximization in a given quarter leads to the following recursive log-linearized expression for the optimal wage rate

$$\widehat{\tilde{w}}_t + \hat{\pi}_t = \frac{1 - \prod_{k=1}^{4} \alpha_k \beta^4}{\Gamma_{(q,\alpha,\beta)}} \left[\hat{\pi}_t + \frac{\lambda_w - 1}{2\lambda_w - 1} \left(\frac{\lambda_w}{\lambda_w - 1} \hat{w}_t + \hat{L}_t - \hat{\psi}_t \right) \right] + \beta \sum_{k=1}^{4} q_{kt} \alpha_{k+1} \frac{\Phi_{(q,\alpha,\beta)}}{\Gamma_{(q,\alpha,\beta)}} E_{t-1}(\widehat{\tilde{w}}_{t+1} + \hat{\pi}_{t+1}), \tag{7}$$

with the expressions for the parameters $\Gamma_{(q,\alpha,\beta)}$ and $\Phi_{(q,\alpha,\beta)}$ provided in the Appendix. According to this expression, the optimal (real) wage is an average between a constant markup λ_w over the marginal rate of substitution between consumption and leisure, and the optimal wage expected to prevail in the next period. The weights on the two terms vary according to the quarter in which the wage is reset. In particular, the weight on next-period wage is larger the smaller the probability of changing wage in the next period. The dynamics for the aggregate wage level W_t is given by the weighted average between the optimal wage of the labor types that receive the signal to change and the wages of those that did not get the signal. By the law of large numbers, the proportion of labor

[24] The corresponding expression for workers setting wages in the second quarter can be obtained by subtituting α_{k+1} for α_k , for $k = 1, 2, 3$ and substituting α_4 for α_1 in expression (6). Appropriate substitutions lead to the formulae for the optimal wage in the third and fourth quarters.

types renegotiating wages at t will be equal to $(1-\alpha_j)$. Therefore, as shown in the Appendix, the quarter-dependent law of motion for the aggregate wage in log-deviations from the steady state is given by

$$\hat{w}_t = \left[1 - \left(\sum_{k=1}^{4} q_{kt}\alpha_k\right)\right]\widehat{\widetilde{w}}_t + \left(\sum_{k=1}^{4} q_{kt}\alpha_k\right)(\hat{w}_{t-1} + \hat{\pi}_{t-1} - \hat{\pi}_t). \tag{8}$$

4.2 Model Solution and Calibration

The wage equations (7) and (8), together with conditions (18) through (27) in the Appendix, characterize the model dynamics for the non-policy variables. To close the model, we assume that the monetary authority follows a Taylor-type reaction function:

$$\hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)(a_\pi E_{t-1}\hat{\pi}_{t+1} + a_y\hat{y}) + \varepsilon_t, \tag{9}$$

where $\hat{R}_t = \ln R_t - \ln \bar{R}$ is the nominal interest rate in deviation from its steady state level, and $\hat{y}_t$ is the output gap. The term ε_t is the policy shock whose effect we want to evaluate.

Because of the presence of the time-varying indicators q_{jt} in the equations describing the wage dynamics, the system is non-linear. To solve the model, we use the non-linear algorithm proposed by Fuhrer and Bleakley (1996).

Table 2 summarizes the benchmark values used to calibrate the model. The parameters in the policy reaction function (9) are consistent with the estimates in Fuhrer (1994). For the remaining parameters, our calibration closely follows Christiano et al. (2005). In particular, we maintain the same degree of habit persistence in consumption, with the parameter governing the degree of habit persistence η set at 0.63. The parameter governing the costs of adjusting investment (the inverse of the elasticity of investment with respect to the price of installed capital, denoted by κ) is calibrated at 2.0, a value that falls within the range of estimates provided by Christiano et al. (2005). The discount factor β is set at 0.993, the capital share α at 0.36, and the depreciation rate δ at 0.025. The parameter governing exogenous price rigidity, ξ_p, is set at 0.1. Christiano et al. (2005) show that their results are fairly insensitive to the values of this parameter; in particular, they show that the main results hold when prices are fully flexible ($\xi_p = 0$). This is because wage contracts, not price contracts, are the important nominal rigidity for imparting empirically-consistent dynamics to the model.[25]

In calibrating the values for the probability of resetting wages in a given quarter, we follow an approach consistent with the parametrization in Christiano et al. (2005). In their setup the probability of wage changes across quarters is identical and such that the average frequency of wage changes is approximately 3 quarters. Our way of calibrating the α_k's ensures that the average frequency of wage changes is still about 8 months.[26] To capture the seasonal effects, we set the values of α_k so that $\alpha_4 < \alpha_3 < \alpha_1 < \alpha_2$. This corresponds to a situation in which a larger fraction of wages is changed during the course of the fourth and third quarters, a smaller fraction is changed in the first quarter, and an even smaller fraction during the second quarter. This assumption is in line with anecdotal evidence suggesting that wages are reset in the later months or at the very beginning of the calendar year, with fewer changes taking place during the second quarter. The calibrated probabilities ($\alpha_1 = 0.7$; $\alpha_2 = 0.9$; $\alpha_3 = 0.5$; $\alpha_4 = 0.4$) imply that 20 percent of the wage changes take place in the first quarter, 7 percent in the second quarter, 33 percent in the third quarter and 40 percent in the fourth quarter.[27] These frequencies are consistent with wage-setting practices of New England firms

[25] Card (1990) also provides empirical evidence on the importance of nominal wage rigidities in the link between aggregate demand shocks and real economic activity.

[26] In other words, $\alpha^4 = \prod_{k=1}^4 \alpha_k$, where α is the constant probability value used in Christiano et al. (2005), equal to the geometric average of the quarter-dependent probabilities. Given our calibrated values for the α_k's in Table 2, this implies an average frequency of wage adjustment of 2.4 ($= 1/(1 - \sqrt[4]{\prod_{k=1}^4 \alpha_k}$) quarters, or about seven and a half months .

[27] In each quarter k, the proportion of wage changes relative to the total number of changes in a given calendar year is $(1 - \alpha_k)/(4 - \sum_{k=1}^4 \alpha_k)$.

surveyed in the Federal Reserve System's "Beige Book."[28,29]

The results of the simulations are displayed in Figures 10 through 12, and show the impulse-responses of output, inflation, and the nominal interest rate to a 25-basis point decline in the nominal interest rate on impact. To make the results comparable to the identifying assumption underlying our empirical exercise, we assume that the shock occurs at the end of period t, when all the period t non-policy variables have been already set. The figures also plot the corresponding empirical responses and 95 percent confidence bands from the estimation of the quarter-dependent VAR in the previous section.

Overall, the model is able to generate impulse-responses to monetary policy shocks in different quarters that are qualitatively consistent with the empirical patterns we have documented. Policy shocks in the first and second quarter have a large effect on output, since few households are allowed to reset their wages optimally and those who do are limited in their adjustment by strategic complementarities in wage-setting decisions. In the third and fourth quarter, the response of output is less than half the size of the response in the first half of the year. This difference in the response of output occurs even though our model features the same degree of real rigidities as in Christiano et al. (2005). In the model, real rigidities work in the direction of dampening the effect of uneven staggering of wages, but our calibrated values for the α_k's still imply relevant differences in the response of output across quarters. At the same time, real rigidities help to generate persistent responses to the policy shock. Consistent with Christiano et al. (2005), the model-generated impulse-response for output peaks 3 to 4 quarters after the shock, depending on the quarter in which the shock occurs. This matches the response of output to a policy shock in the second quarter, but the output response to

[28]Findings about wage-setting practices of New England firms surveyed in the Federal Reserve System's "Beige Book" over the course of 2003 are available from the authors upon request. Firms are identified by sector, but the identity of the firms is kept confidential.

[29]The remaining parameters are set as in Christiano et al's benchmark model: $\chi = 0$ and $\sigma_a = 0.01$.

a policy shock in the first quarter is not as persistent as in the data. As for inflation, the model produces impulse-responses that are not strikingly different across quarters. In the two quarters after the shock, prices increase somewhat faster when the shock occurs in the third or in the fourth quarter – a feature we also observe in the data. The response of the federal funds rate is consistent with the empirical exercise, though in the second quarter the theoretical response is somewhat weaker than its empirical counterpart.

5 Concluding Remarks

The paper documents novel findings regarding the impact of monetary policy shocks on real activity. After a monetary expansion that takes place in the first quarter of the year, output picks up quickly and tends to die out at a relatively fast pace. This pattern is even more pronounced when the monetary policy expansion takes place in the second quarter of the year. In contrast, output responds little when the monetary expansion takes place in the third and fourth quarters of the year. The conventional finding that monetary shocks affect output with long delays and that the effect is highly persistent may be interpreted as the combination of these different output impulse-responses.

We argue that the differential responses are not driven by different types of monetary policy interventions, nor by different "states" of the economy across quarters. Encouraged by anecdotal evidence on the timing of wage changes, which suggests that a large fraction of wages are reset towards the end of each calendar year, we propose a potential explanation for the differential responses based on contractual lumping and develop a theoretical general equilibrium model based on Christiano et al. (2005) featuring uneven staggering of nominal wage contracts. The model generates impulse-responses that qualitatively match those found in the data.

While our model assumes uneven staggering, there are studies in the literature addressing the optimality of uniform staggering versus synchronization of price (or wage) changes. The general finding of this literature is that synchronization is the equilibrium timing in many simple Keynesian models of the business cycle.[30] Yet, the new generation of Keynesian models has glossed over this finding and assumed uniform staggering as both a convenient modeling tool and an essential element in the transmission mechanism of monetary policy shocks. This paper provides an empirical setting to test the hypothesis of uniform versus uneven staggering of wage changes, and in so doing argues for the empirical and theoretical relevance of models in which wage changes are less staggered and more synchronized.

We have addressed the robustness of our findings along several dimensions, but additional evidence could corroborate our results. Other shocks, such as technology shocks, should also have a different impact across the calendar year if wage staggering is not uniform. Identification of technology shocks, however, is contentious and would require additional variables in our VAR, thus reducing degrees of freedom at the estimation stage. A more promising avenue, in our view, is the examination of international evidence. Other countries likely exhibit uneven staggering of wage contracts, and the transmission mechanism of monetary shocks should be affected accordingly. In this respect, Japan is particularly relevant, because a large fraction of Japanese firms set wages in the spring season (during the wage setting process known as Shunto, or "spring offensive"). Preliminary findings for Japan indicate that monetary policy shocks that take place in the third quarter (after the Shunto) have a large impact on output, whereas monetary policy shocks occurring in the second quarter (during the Shunto) have virtually no output effect.

[30] Ball and Cecchetti (1988) show that staggering can be the equilibrium outcome in some settings with imperfect information, but even then such a result is not necessarily pervasive, since it depends on the structure of the market in which firms compete and on firms setting prices for a very short period of time.

In other settings staggering can be the optimal outcome for wage negotiations if the number of firms is veyr small (see Fethke and Policano 1986). The incentive for firms to stagger wage negotiation dates, however, diminishes the larger the number of firms in an economy .

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A Appendix

The first part of this Appendix introduces the model, based on Christiano et al. (2005). In particular, we describe the firms' behaviour, households' preferences and constraints, and the equilibrium conditions. The second part presents the derivation of the equations governing the wage dynamics. The final part presents the set of equations that summarize the model's dynamics around its steady state.

A.1 Review of the Model

A.1.1 Firms

There are three classes of firms: The first class consists of a representative, competitive firm that buys the differentiated labor service h_{it} from the households and transforms it into an aggregate labor input L_t using the CES technology:

$$L_t = \left(\int h_{it}^{1/\lambda_W} di \right)^{\lambda w}, \lambda_{\ w} \in [1, \infty).$$

The second class consists of a representative, competitive firm that produces the final consumption good Y_t using a continuum of intermediate goods Y_{jt} combined through the CES technology:

$$Y_t = \left(\int Y_{jt}^{1/\lambda_f} dj \right)^{\lambda_f}, \lambda_{\ f} \in [1, \infty),$$

The third class of firms produces intermediate goods $j \in (0,1)$. Each intermediate j is produced by a monopolist using the technology:

$$\begin{aligned} Y_{jt} &= k_{jt}^{\alpha} L_{jt}^{1-\alpha} - \phi, \alpha \;\in (0,1) \text{ if } k_{jt}^{\alpha} L_{jt}^{1-\alpha} \geq \phi \\ &= 0 \text{ otherwise,} \end{aligned}$$

where L_{jt} and k_{jt} are the labor and capital services used in the production of intermediate j. Intermediate good firms rent capital at the rental rate R_t^k and labor at the average rate W_t in perfectly competitive factor markets and profits are distributed to households at the end of each period. Workers are paid in advance of production, hence the jth firm borrows its wage bill $W_t L_{jt}$ from the financial intermediary at the beginning of the period, repaying at the end of the period at the gross interest rate R_t. The intermediate good firm's real marginal cost is given by

$$s_t = \left(\frac{1}{1-\alpha}\right)^{1-\alpha} \left(\frac{1}{\alpha}\right)^{\alpha} \left(\frac{R_t^k}{P_t}\right)^{\alpha} \left(\frac{W_t}{P_t} R_t\right)^{1-\alpha},$$

Firm j sets price $P_{j,t}$ following a Calvo-type rule, facing a probability $(1-\xi_p)$ of being able to reoptimize its nominal price at each period. The ability to reoptimize is independent across firms and time. Firms that cannot reoptimize index their price to lagged inflation:

$$P_{j,t} = \pi_{t-1} P_{j,t-1}$$

The optimal price $\tilde{P}_t$ (which in equilibrium is constant across reoptimizing firms) is given by

$$\tilde{P}_t = \arg\max E_{t-1} \sum_{j=0}^{\infty} (\beta \xi_p)^j \psi_{t+j} (\tilde{P}_t X_{tj} - s_t P_{t+j}) Y_{j,t+j},$$

where ψ_t is the marginal value of a dollar to the household (which is constant across households in equilibrium).

A.1.2 Households

There is a continuum of infinitely-lived households i, with $i \in (0,1)$ who derive utility from consumption and disutility from labor effort, and own the physical capital of the economy. Every period each household makes the following sequence of decisions. First, he decides how much to consume and invest in physical capital, and how much capital service to supply. Second, he purchases securities that are contingent on whether he can reoptimize his wage.[31] Third, he sets its wage after finding out whether it can reoptimize or not.

Household i's expected utility is given by:[32,33]

$$E_{t-1}^{i}\left\{\sum_{j=0}^{\infty}\beta^{t+j}\left[u(c_{t+j}-be_{t+j})-z(h_{i,t+j})\right]\right\}, \tag{10}$$

where $\beta \in (0,1)$ is the intertemporal discount factor, c_t is consumption at time t; u is the period utility derived from consumption, with $u' > 0$ and $u'' < 0$; $e_{t+j} = \chi e_{t+j-1} + (1-\chi)c_{t+j-1}$ represents habit formation in consumption, with $b,\chi \in [0,1)$;[34] $h_{i,t}$ is the number of hours worked at t and z is the disutility of labor effort, with $z' > 0$ and $z'' \geqslant 0$.

[31] As in Christiano et al., this is assumed for analytical convenience. Because the uncertainty over whether one can reoptimize wages is idiosyncratic, households work different number of hours and earn different wage rates; this in turn could lead to potentially heterogeneous levels of consumption and asset holdings. Following Woodford (1996), it can be shown that, in equilibrium, the existence of state-contingent securities ensures that households are homogeneous with respect to consumption choice and asset holdings, though heterogeneous with respect to the wage rate and the supply of labor.

[32] Given the assumptions above, the formula anticipates the result that all households consume the same, despite working different hours. Hence the corresponding omission of the corresponding subscript i.

[33] Unlike CEE, money does not enter the utility function. Monetary policy will be introduced as innovations to an interest-rate rule which will affect consumption and investment.

[34] See Fuhrer (2000) for a thorough explanation of habit formation in consumption, as represented in this functional form, and CEE's technical appendix.

The household's dynamic budget constraint is given by

$$V_{t+1} + P_t[c_t + i_t + a(u_t)\bar{k}_t] = R_t V_t + R_t^k u_t \bar{k}_t + D_t + A_{i,t} + W_{i,t} h_{i,t} - T_t, \qquad \forall t,$$

where V_t is the household's beginning of period t financial wealth, deposited with a financial intermediary where it earns the gross nominal interest rate R_t. The term $R_t^k u_t \bar{k}_t$ represents the household's earnings from supplying capital services, where $u_t \bar{k}_t$ denotes the physical stock of capital, $\bar{k}_t$, adjusted by the capital utilization rate u_t, which is decided by the household at time t, and R_t^k denotes the corresponding return. D_t denotes firm profits and $A_{i,t}$ denotes the net cash inflow from participating in state-contingent security markets at time t. $W_{i,t} h_{i,t}$ is labor income and T_t is a lump-sum tax used to finance government expenditures, $P_t g_t$; the government budget is always balanced.[35] Finally, P_t is the price of one unit of the consumption good, and i_t and $a(u_t)\bar{k}_t$ represent, respectively, the purchases of investment goods and the cost of setting the utilization rate to u_t, in units of consumption goods.

The evolution of the stock of physical capital, which, as said, is owned by the households, is given by:

$$\bar{k}_{t+1} = (1-\delta)\bar{k}_t + F(i_t, i_{t-1}) \tag{11}$$

where δ is the depreciation rate and the function F represents the technology transforming current and past investment into installed capital for use in the following period. The properties of F and u are discussed below. Capital services k_{jt} are related to the stock of capital $\bar{k}_{jt}$ through $k_t = u_t \bar{k}_t$.

Financial intermediaries receive V_t from households and lend all their money to intermediate-good firms, which use it to buy labor services L_t. Loan market clearing implies $W_t L_t = V_t$.

[35] Having a mechanic government sector makes the calibration of consumption and investment shares in the model, s_c and s_i, more accurate.

A.1.3 Functional Forms

The following functions are assumed to characterize utility and investment adjustment costs:

$$\begin{aligned} u(\cdot) &= \log(\cdot) \\ z(\cdot) &= \vartheta_0(\cdot)^2 \\ F(i_t, i_{t-1}) &= \left[1 - S\left(\frac{i_t}{i_{t-1}}\right)\right] i_t,\ S'(1) = 0, \kappa \ \equiv S''(1) > 0 \end{aligned}$$

For the capital utilization function, $a(u_t)$ it is assumed that $u_t = 1$ in steady state, and $a(1) = 0$. We define $\sigma_a = a''(1)/a'(1)$. Both κ and σ_a affect the dynamics of the model but not its steady state.

A.2 Wage Setting Process

Let us assume for the moment that period t corresponds to a first quarter (and hence, so does $t + 4j$, $\forall j$) while $t + 1 + 4j$, $\forall j$ corresponds to the second quarter, $t + 2 + 4j$, $\forall j$ corresponds to the third and $t + 3 + 4j$, $\forall j$ corresponds to the fourth quarter. Since all labor-types resetting their wages at a given quarter will choose the same wage, we can get rid of the i's and simply refer to the optimal wage in period t as $\tilde{W}_t$. The first order condition for the optimal wage $\tilde{W}_t$ in the first quarter satisfies:

$$E_{t-1} \left\{ \begin{array}{c} \sum\limits_{j=0}^{\infty} \prod\limits_{i=1}^{4} \alpha_i^j \beta^{4j} h_{t+4j} \psi_{t+4j} \{ \left[\frac{\tilde{W}_t \cdot X_{t,4j}}{P_{t+4j}} - \lambda_w \frac{z_{h,t+4j}}{\psi_{t+4j}} \right] + \\ \alpha_2 \beta h_{t+4j+1} \psi_{t+4j+1} \left[\frac{\tilde{W}_t \cdot X_{t,4j+1}}{P_{t+4j+1}} - \lambda_w \frac{z_{h,t+4j+1}}{\psi_{t+4j+1}} \right] + \\ \alpha_2 \alpha_3 \beta^2 h_{t+4j+2} \psi_{t+4j+2} \left[\frac{\tilde{W}_t \cdot X_{t,4j+2}}{P_{t+4j+2}} - \lambda_w \frac{z_{h,t+4j+2}}{\psi_{t+4j+2}} \right] + \\ \alpha_2 \alpha_3 \alpha_4 \beta^3 h_{t+4j+3} \psi_{t+4j+3} \left[\frac{\tilde{W}_t \cdot X_{t,4j+3}}{P_{t+4j+3}} - \lambda_w \frac{z_{h,t+4j+3}}{\psi_{t+4j+3}} \right] \} \end{array} \right\} = 0$$

where, $z_{h,t+l}$ is the derivative of of z with respect to h_{t+l} and

$$X_{t,l} = \left\{ \begin{array}{lr} \pi_t \cdot \pi_{t+1} \cdot \pi_{t+2} \cdot ...\pi_{t+l-1} & \text{for } l \geq 0 \\ 1 & \text{for } l = 0 \end{array} \right\} \text{ and } \pi_t = \frac{P_t}{P_{t-1}}$$

Log-linearizing this expression around its steady state, we obtain:

$$\begin{aligned} \widehat{\tilde{W}}_t = \hat{P}_{t-1} + \Theta E_{t-1} \{ \sum_{j=0}^{\infty} \prod_{i=1}^{4} \alpha_i^j \beta^{4j} \cdot \{ & \left[\hat{\pi}_{t+4j} + \tfrac{\lambda_w - 1}{2\lambda_w - 1} (\tfrac{\lambda_w}{\lambda_w - 1} (\hat{W}_{t+4j} - \hat{P}_{t+4j}) + \hat{L}_{t+4j} - \hat{\psi}_{t+4j}) \right] \\ & + \alpha_2 \beta \left[\hat{\pi}_{t+4j+1} + \tfrac{\lambda_w - 1}{2\lambda_w - 1} (\tfrac{\lambda_w}{\lambda_w - 1} (\hat{W}_{t+4j+1} - \hat{P}_{t+4j+1}) + \hat{L}_{t+4j+1} - \hat{\psi}_{t+4j+1}) \right] \\ & + \alpha_2 \alpha_3 \beta^2 \left[\hat{\pi}_{t+4j+2} + \tfrac{\lambda_w - 1}{2\lambda_w - 1} (\tfrac{\lambda_w}{\lambda_w - 1} (\hat{W}_{t+4j+2} - \hat{P}_{t+4j+2}) + \hat{L}_{t+4j+1} - \hat{\psi}_{t+4j+2}) \right] \\ & + \alpha_2 \alpha_3 \alpha_4 \beta^3 \left[\hat{\pi}_{t+4j+3} + \tfrac{\lambda_w - 1}{2\lambda_w - 1} (\tfrac{\lambda_w}{\lambda_w - 1} (\hat{W}_{t+4j+3} - \hat{P}_{t+4j+3}) + \hat{L}_{t+4j+3} - \hat{\psi}_{t+4j+3}) \right] \} \end{aligned}$$

where $\hat{x}_t = \frac{x_t - x}{x}$ and x is the non-stochastic steady state level of x and

$$\Theta^{-1} = \sum_{j=0}^{\infty} \prod_{i=1}^{4} \alpha_i^j \beta^{4j} (1 + \alpha_2 \beta + \alpha_2 \alpha_3 \beta^2 + \alpha_2 \alpha_3 \alpha_4 \beta^3) = \frac{(1 + \alpha_2 \beta + \alpha_2 \alpha_3 \beta^2 + \alpha_2 \alpha_3 \alpha_4 \beta^3)}{1 - \alpha_1 \alpha_2 \alpha_3 \alpha_4 \beta^4}$$

We can write $\widehat{\tilde{W}}_t$ in recursive form as:

$$\begin{aligned} \widehat{\tilde{W}}_t &= \hat{P}_{t-1} + \Theta \left[\hat{\pi}_t + \frac{\lambda_w - 1}{2\lambda_w - 1} (\frac{\lambda_w}{\lambda_w - 1} (\hat{W}_t - \hat{P}_t) + \hat{L}_t - \hat{\psi}_t) \right] + \\ & + \beta \alpha_2 \frac{1 + \beta \alpha_3 \left[1 + \beta \alpha_4 + \beta^2 \alpha_4 \alpha_1 \right]}{1 + \beta \alpha_2 (1 + \beta \alpha_3 + \beta^2 \alpha_3 \alpha_4)} E_{t-1} (\widehat{\tilde{W}}_{t+1} - \hat{P}_t) \end{aligned} \quad (12)$$

The aggregate wage level is a weighted average of the optimal wage set by workers that received the signal to reoptimize wages and the wages of those who did not get the signal. As stated before, those who do not reoptimize, set their wages the previous period's wage rate, adjusted by past inflation. If we keep our convention that t (and $\{t + 4j\}$) corresponds to the first quarter, the proportion of workers changing wages at t will be equal to $(1-\alpha_1)$, by the law of large numbers is:

$$\hat{W}_t = (1-\alpha_1)\widehat{\tilde{W}}_t + \alpha_1(\hat{W}_{t-1} + \hat{\pi}_{t-1}) \tag{13}$$

Equations (12) and (13) give us the laws of motions when wages are set in the first quarter. More generally, for wages set in any quarter of the calendar year, we introduced the dummy variables q_{jt}, with $j = 1, \ldots 4$, which take on the value 1 in the jth quarter and 0 otherwise. We can then write the equations governing the wage dynamics as:

$$\widehat{\tilde{W}}_t = \hat{P}_{t-1} + \frac{1-\prod_{j=1}^{4}\alpha_j\beta^4}{\Gamma_{(q,\alpha,\beta)}}\left[\hat{\pi}_t + \frac{\lambda_w - 1}{2\lambda_w - 1}\left(\frac{\lambda_w}{\lambda_w - 1}(\hat{W}_t - \hat{P}_t) + \hat{L}_t - \hat{\psi}_t\right)\right] + \beta\sum_{k=1}^{4} q_{kt}\alpha_{k+1}\frac{\Phi_{(q,\alpha,\beta)}}{\Gamma_{(q,\alpha,\beta)}}E_{t-1}(\widehat{\tilde{W}}_{t+1} - \hat{P}_t), \tag{14}$$

and

$$\hat{W}_t = \left[1 - \left(\sum_{k=1}^{4} q_{kt}\alpha_k\right)\right]\widehat{\tilde{W}} + \left(\sum_{k=1}^{4} q_{kt}\alpha_k\right)(\hat{W}_{t-1} + \hat{\pi}_{t-1}) \tag{15}$$

where

$$\begin{aligned}
\Gamma_{(q,\alpha,\beta)} &= 1 + \beta\{q_{1t}\alpha_2\left[1 + \beta\alpha_3 + \beta^2\alpha_3\alpha_4\right] + q_{2t}\alpha_3\left[1 + \beta\alpha_4 + \beta^2\alpha_4\alpha_1\right] + \\
&\quad + q_{3t}\alpha_4\left[1 + \beta\alpha_1 + \beta^2\alpha_1\alpha_2\right] + q_{4t}\alpha_1\left[1 + \beta\alpha_2 + \beta^2\alpha_2\alpha_3\right]\} \\
\Phi_{(q,\alpha,\beta)} &= 1 + \{\beta q_{1t}\alpha_3\left[1 + \beta\alpha_4 + \beta^2\alpha_4\alpha_1\right] + q_{2t}\alpha_4\left[1 + \beta\alpha_1 + \beta^2\alpha_1\alpha_2\right] + \\
&\quad + q_{3t}\alpha_1\left[1 + \beta\alpha_4 + \beta^2\alpha_4\alpha_3\right] + q_{4t}\alpha_2\left[1 + \beta\alpha_3 + \beta^2\alpha_3\alpha_4\right].
\end{aligned}$$

Defining $\widehat{\widetilde{w}}_t$, and $\hat{w}_t$ as

$$
\begin{aligned}
\widehat{\widetilde{w}}_t &= \widehat{\widetilde{W}}_t - \hat{P}_t \\
\hat{w}_t &= \hat{W}_t - \hat{P}_t
\end{aligned}
$$

equations (14), (15) become, respectively:

$$
\widehat{\widetilde{w}}_t + \hat{\pi}_t = \frac{1 - \prod_{j=1}^{4} \alpha_j \beta^4}{\Gamma_{(q,\alpha,\beta)}} \left[\hat{\pi}_t + \frac{\lambda_w - 1}{2\lambda_w - 1} \left(\frac{\lambda_w}{\lambda_w - 1} \hat{w}_t + \hat{L}_t - \hat{\psi}_t \right) \right] + \beta \sum_{k=1}^{4} q_{kt} \alpha_{k+1} \frac{\Phi_{(q,\alpha,\beta)}}{\Gamma_{(q,\alpha,\beta)}} E_{t-1} (\widehat{\widetilde{w}}_{t+1} + \hat{\pi}_{t+1}), \tag{16}
$$

$$
\hat{w}_t = \left[1 - \left(\sum_{k=1}^{4} q_{kt} \alpha_k \right) \right] \widehat{\widetilde{w}}_t + \left(\sum_{k=1}^{4} q_{kt} \alpha_k \right) (\hat{w}_{t-1} + \hat{\pi}_{t-1} - \hat{\pi}_t) \tag{17}
$$

A.3 The Model's equations

Solving the model's steady state as in Christiano et al. (2005) and linearizing the system around the steady state, leads to the following set of equations, which, together with equations (16) and (17) characterize the dynanmics of the model:

Marginal cost equation:[36]

$$
\hat{s}_t = \alpha (\hat{w}_t + \hat{R}_t + \hat{L}_t - \hat{k}_t) + (1 - \alpha)(\hat{w}_t + \hat{R}_t) \tag{18}
$$

Inflation equation:

$$
\hat{\pi}_t = \frac{1}{1+\beta} \hat{\pi}_{t-1} + E_{t-1} \left\{ \frac{\beta}{1+\beta} \hat{\pi}_{t+1} + \frac{(1 - \beta\xi_p)(1 - \xi_p)}{(1+\beta)\xi_p} \hat{s}_t \right\} \tag{19}
$$

Capital-price (P_t^k) equation:

$$
\hat{P}_t^k = E_{t-1} \left\{ \hat{\psi}_{t+1} - \hat{\psi}_t + [1 - \beta(1-\delta)](\hat{w}_{t+1} + \hat{R}_{t+1} + \hat{L}_{t+1} - \hat{k}_{t+1}) + \beta(1-\delta)\hat{P}_{t+1}^k \right\} \tag{20}
$$

[36] This makes use of the equilibrium condition: $\hat{R}_t^k - \hat{P}_t = \hat{w}_t + \hat{R}_t + \hat{l}_t - \hat{k}_t$

Aggregate resource-constraint equation[37]:

$$s_c\hat{c}_t + s_g\hat{g}_t + s_i\left\{\hat{\imath}_t + \left[\frac{1}{\beta} - (1-\delta)\right]\frac{1}{\delta}(\hat{k}_t - \hat{\bar{k}}_t)\right\} = \alpha\hat{k}_t + (1-\alpha)\hat{L}_t \tag{21}$$

Habit-formation equation:

$$\hat{e}_{t+1} = \chi\hat{e}_t + (1-\chi)\hat{c}_t \tag{22}$$

Marginal-Utility-of-Income Equation:

$$\hat{\psi}_{t+1} = \hat{\psi}_t - (\hat{R}_{t+1} - \hat{\pi}_{t+1}) \tag{23}$$

Euler Equation:

$$E_{t-1}\left\{\beta\chi\hat{\psi}_{t+1} + \sigma_c\left(\hat{c}_t - \frac{b}{1-\chi}\hat{e}_t\right) + (b+\chi)\beta\sigma_c\left(\hat{c}_{t+1} - \frac{b}{1-\chi}\hat{e}_{t+1}\right)\right\} = \hat{\psi}_t \tag{24}$$

where $\sigma_c = \frac{1-\chi}{1-\chi-b}\frac{1-\beta\chi}{1-\beta\chi-\beta b}$
Price-of-Capital Equation:

$$P_t^k = \kappa\left[\hat{\imath}_t - \hat{\imath}_{t-1} - \beta(\hat{\imath}_{t+1} - \hat{\imath}_t)\right] \tag{25}$$

Optimal-Capital Equation:

$$\hat{\bar{k}}_t = (1-\delta)\hat{\bar{k}}_{t-1} + \delta\hat{\imath}_t \tag{26}$$

Output Equation:

$$\hat{y}_t = \alpha\hat{k}_t + (1-\alpha)\hat{L}_t$$

Investment Equation:

$$\hat{k}_t - \hat{\bar{k}}_t = \frac{1}{\sigma_a}(\hat{w}_t + \hat{R}_t + \hat{L}_t - \hat{k}_t) \tag{27}$$

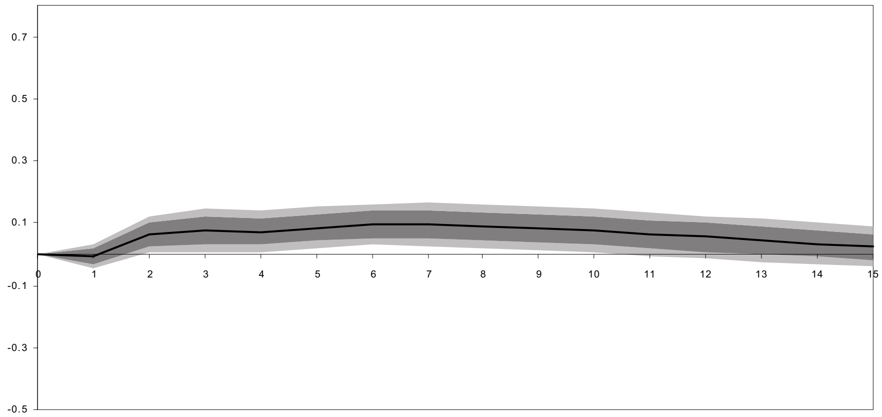
Taylor-Rule Equation:

$$\hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)(a_\pi E_{t-1}\hat{\pi}_t + a_y\hat{y}_t) + \varepsilon_t$$

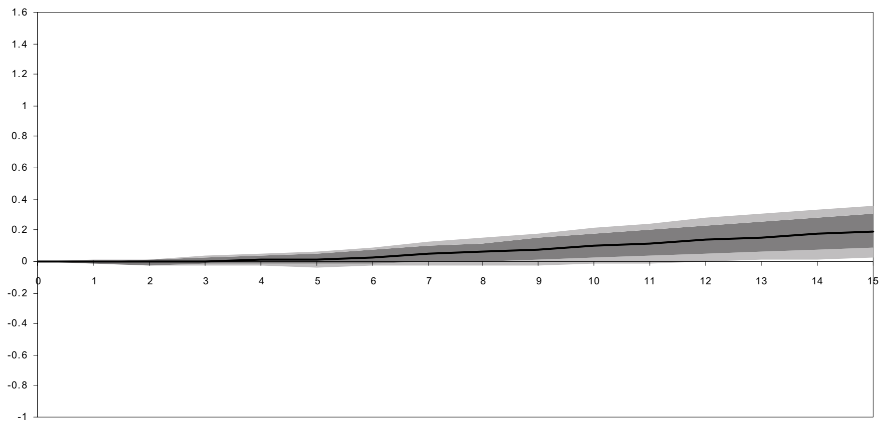
[37] See details for this derivation in Christiano et al. (2005) technical Appendix.

FIGURE 1

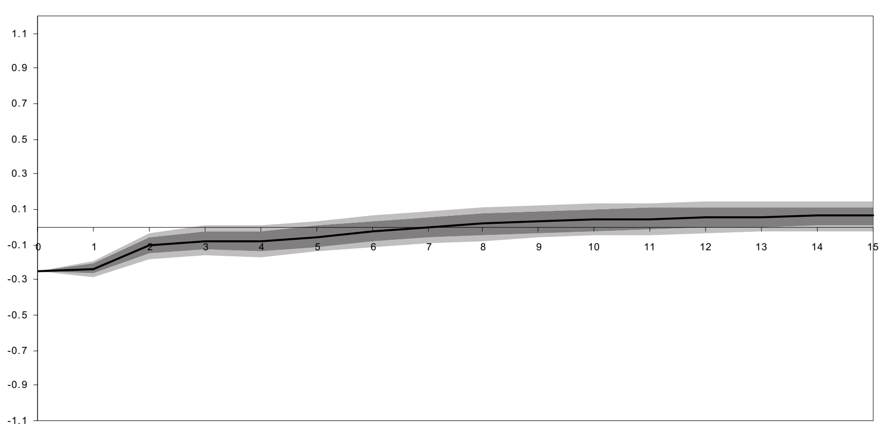
25-Basis Point Decline in Fed Funds Rate
No Quarterly Dependence. 1966:Q1 to 2002:Q4



Response of GDP



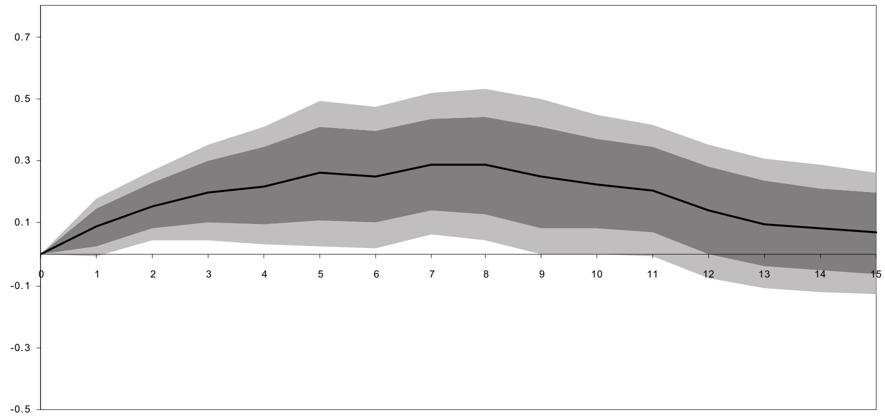
Response of PGDP



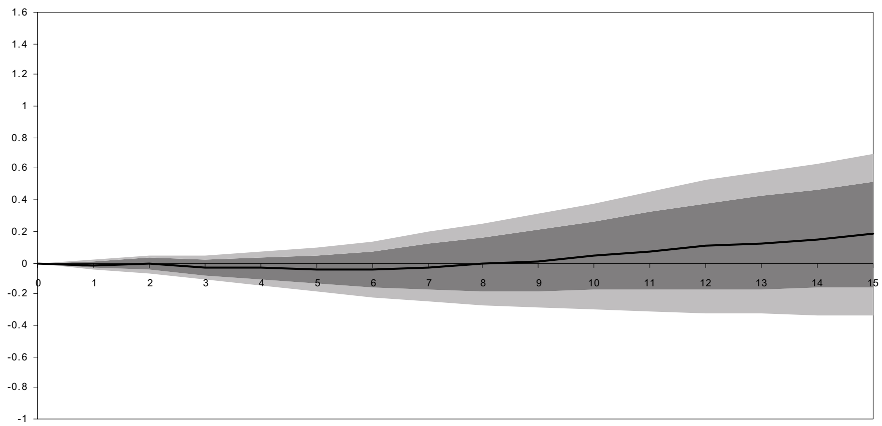
Response of FFR

FIGURE 2

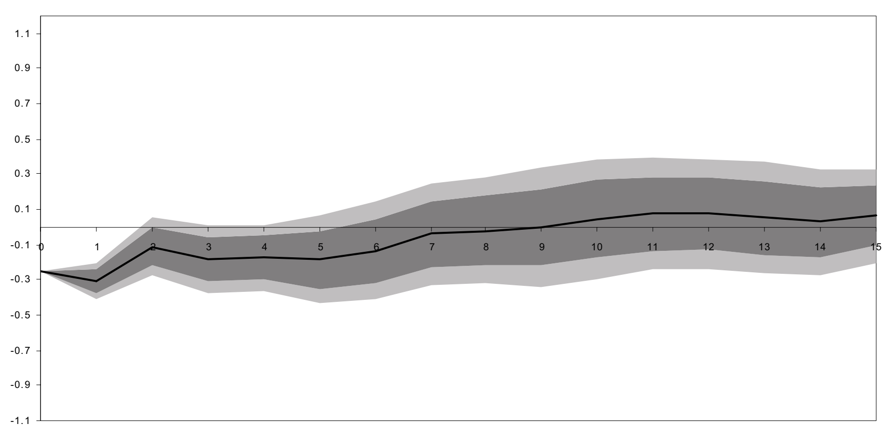
25-Basis Point Decline in Fed Funds Rate in Q1
Quarterly Dependence. Benchmark Model 1966:Q1 to 2002:Q4



Response of GDP



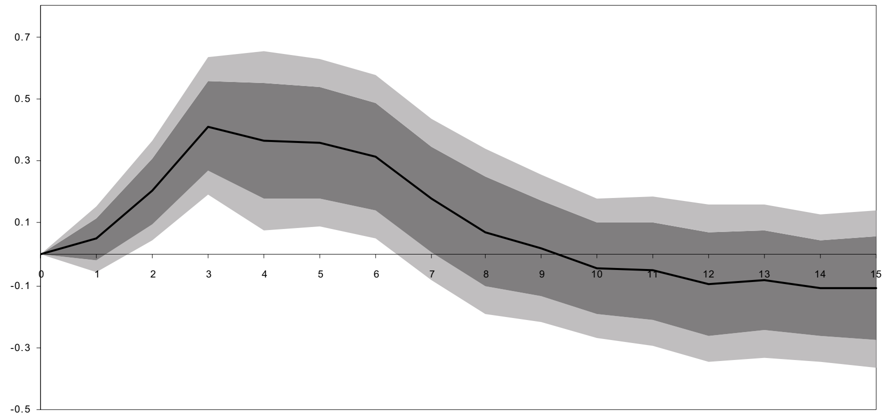
Response of PGDP



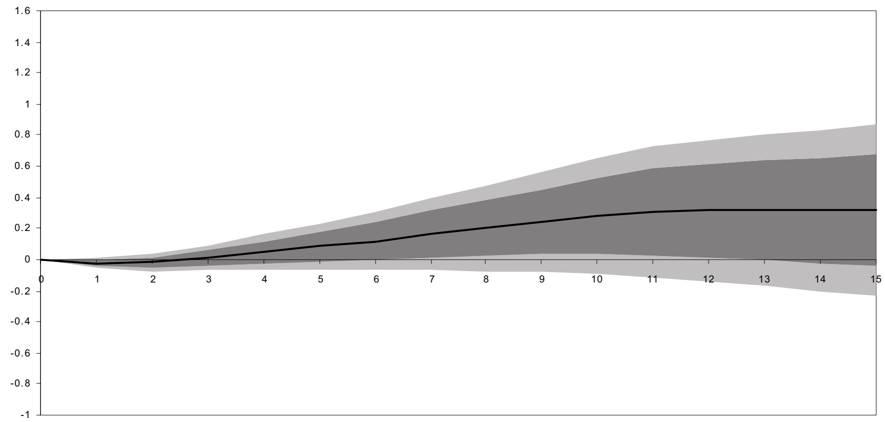
Response of FFR

FIGURE 3

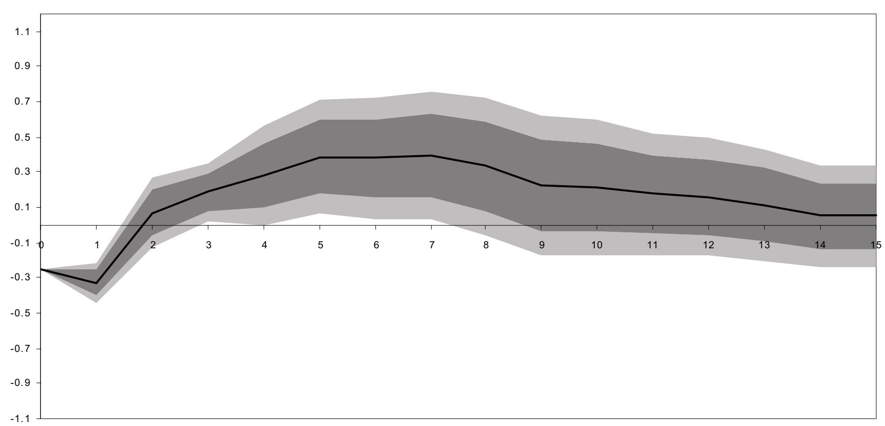
25-Basis Point Decline in Fed Funds Rate in Q2
Quarterly Dependence. Benchmark Model 1966:Q1 to 2002:Q4



Response of GDP



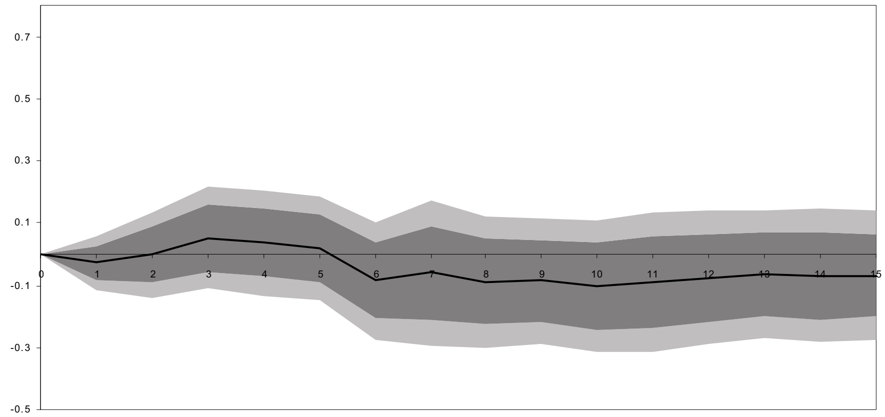
Response of PGDP



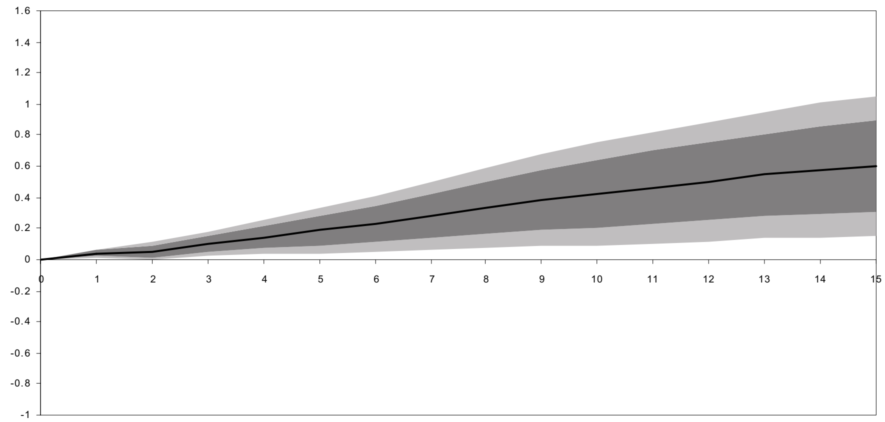
Response of FFR

FIGURE 4

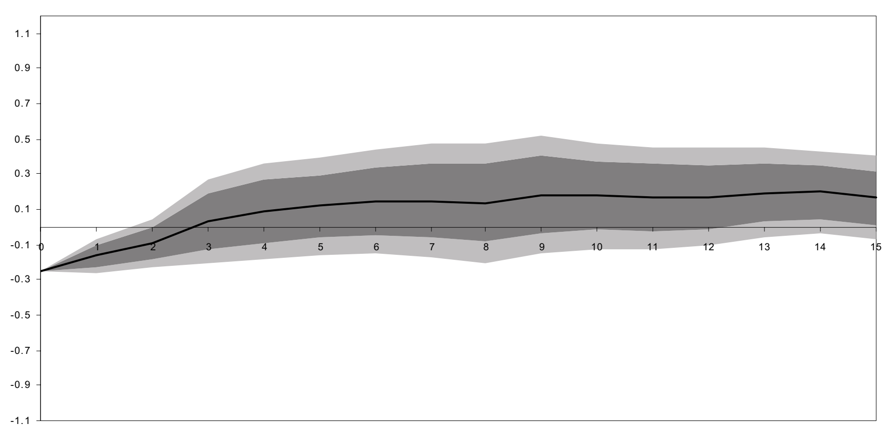
25-Basis Point Decline in Fed Funds Rate in Q3
Quarterly Dependence. Benchmark Model 1966:Q1 to 2002:Q4



Response of GDP



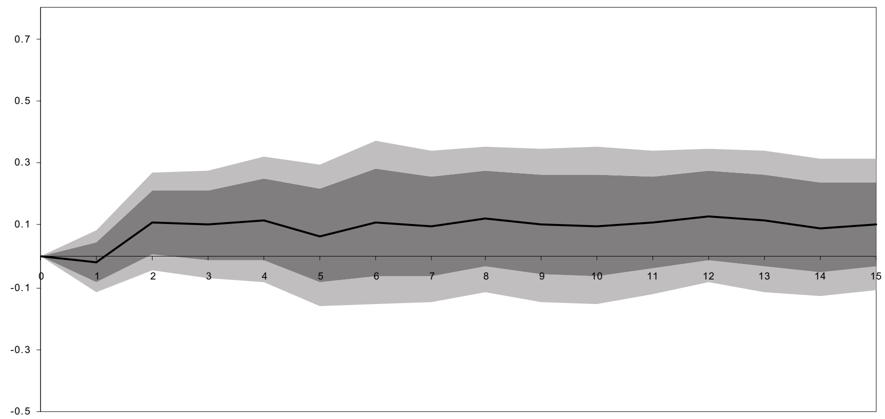
Response of PGDP



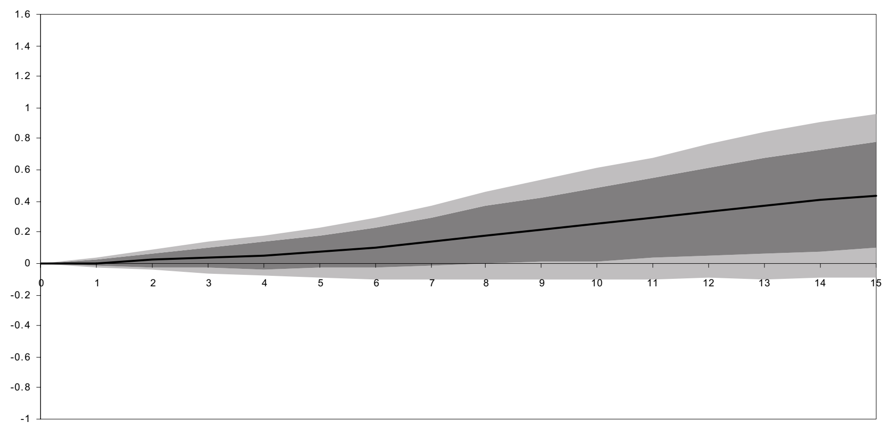
Response of FFR

FIGURE 5

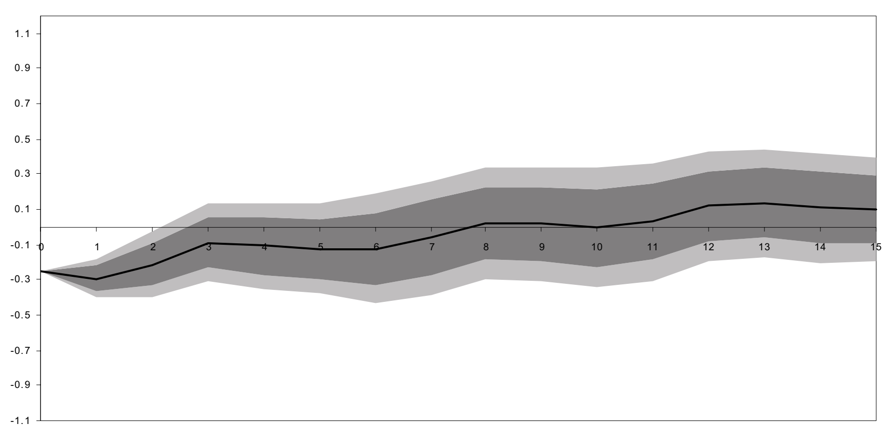
25-Basis Point Decline in Fed Funds Rate in Q4
Quarterly Dependence. Benchmark Model 1966:Q1 to 2002:Q4



Response of GDP



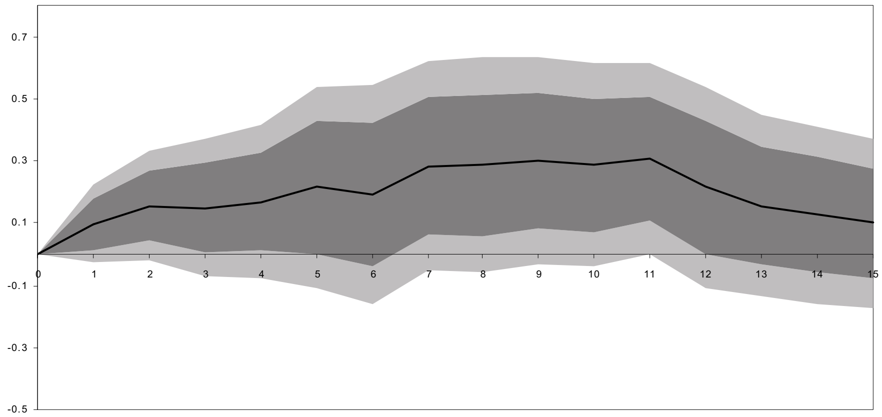
Response of PGDP



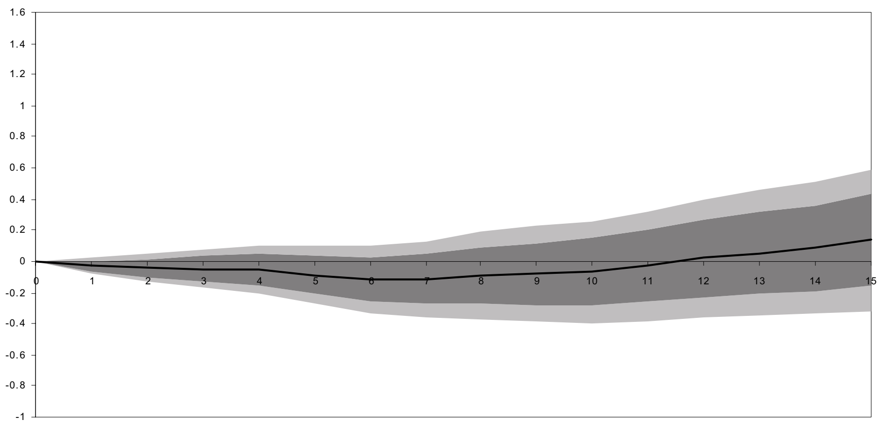
Response of FFR

FIGURE 6

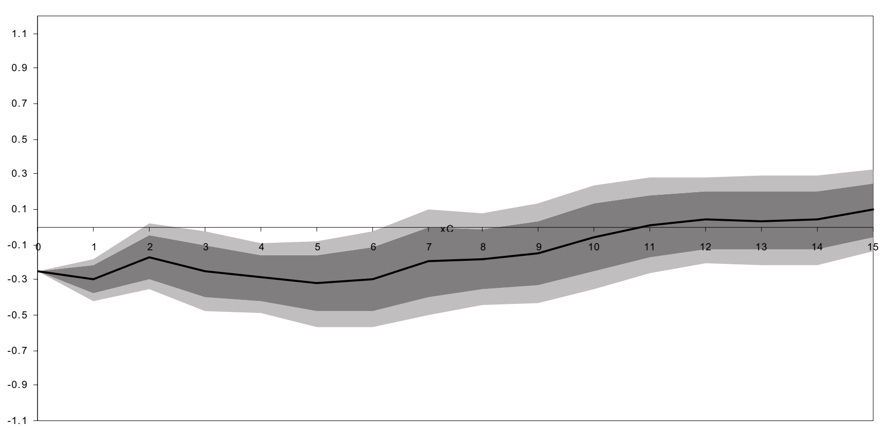
25-Basis Point Decline in Fed Funds Rate in Q1
Quarterly Dependence. NSA Data-System 1966:Q1 to 2002:Q4



Response of GDP



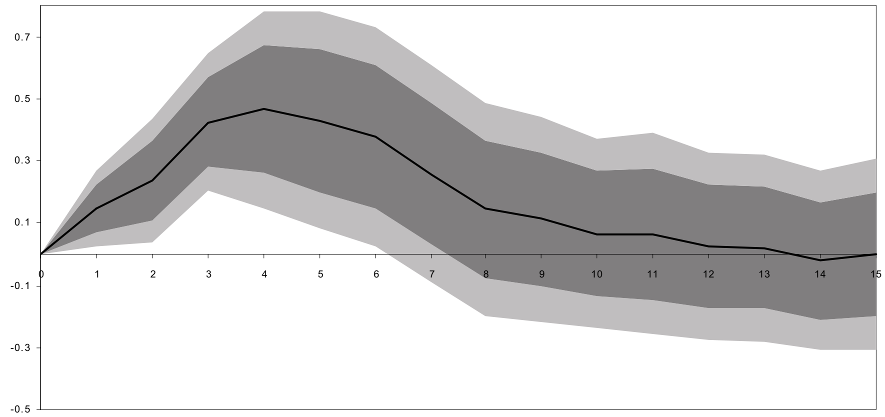
Response of CPI



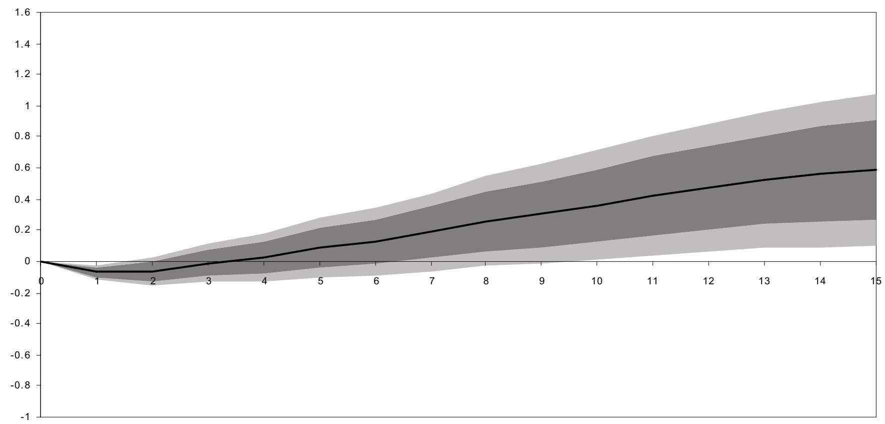
Response of FFR

FIGURE 7

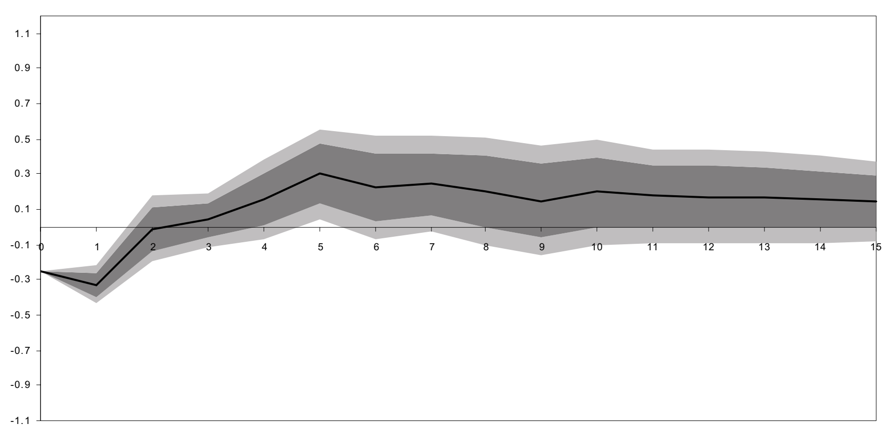
25-Basis Point Decline in Fed Funds Rate in Q2
Quarterly Dependence. NSA Data-System 1966:Q1 to 2002:Q4



Response of GDP



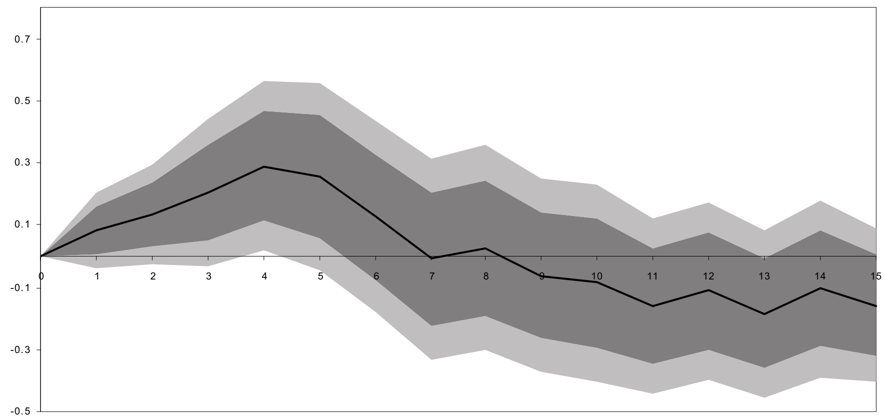
Response of CPI



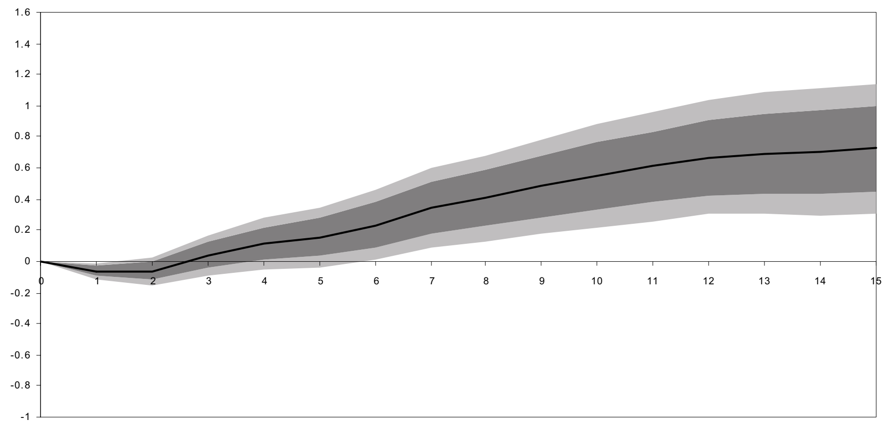
Response of FFR

FIGURE 8

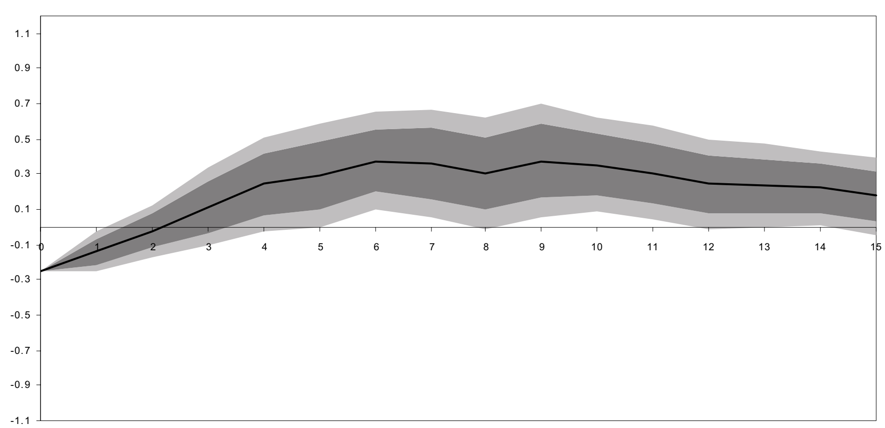
25-Basis Point Decline in Fed Funds Rate in Q3
Quarterly Dependence. NSA Data-System 1966:Q1 to 2002:Q4



Response of GDP



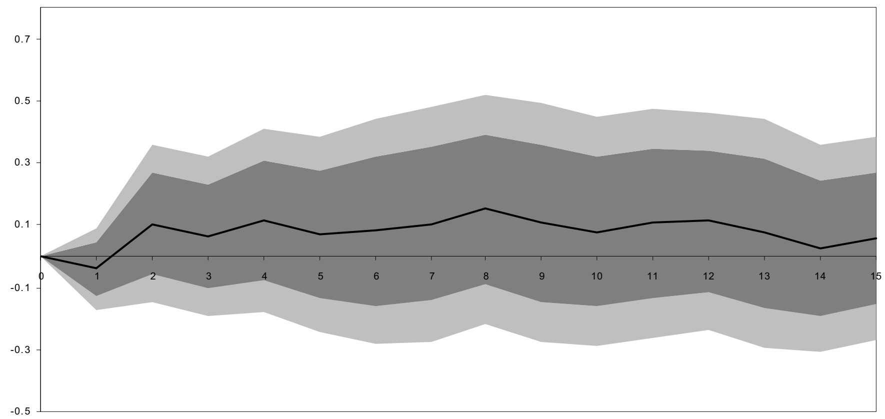
Response of CPI



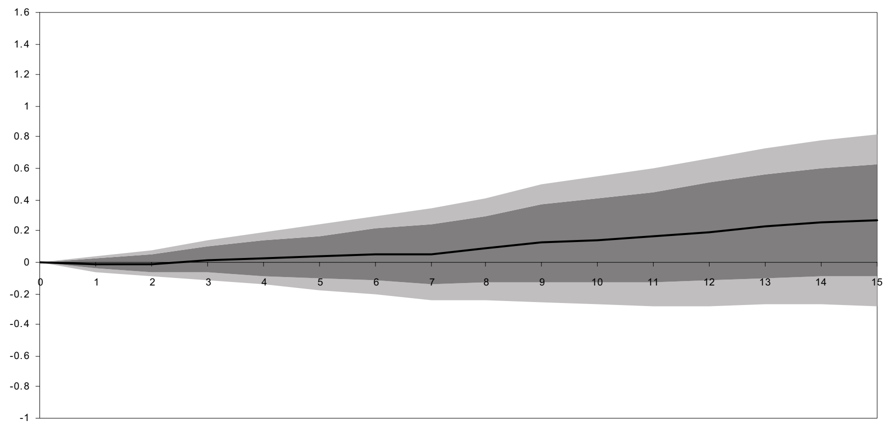
Response of FFR

FIGURE 9

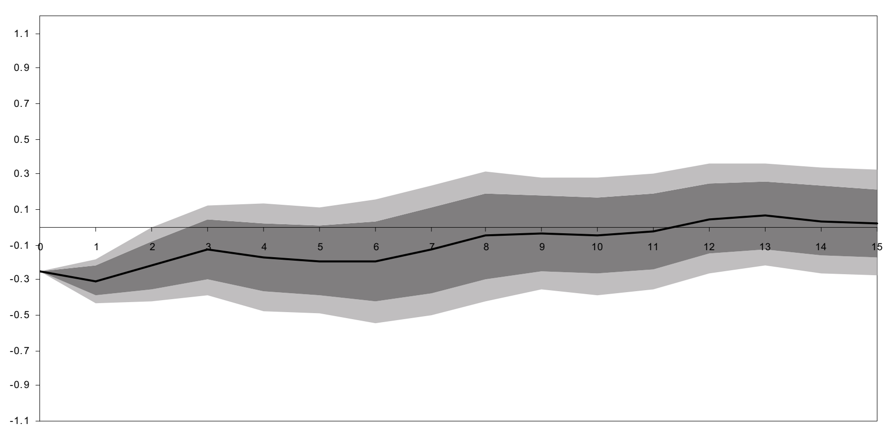
25-Basis Point Decline in Fed Funds Rate in Q4
Quarterly Dependence. NSA Data-System 1966:Q1 to 2002:Q4



Response of GDP



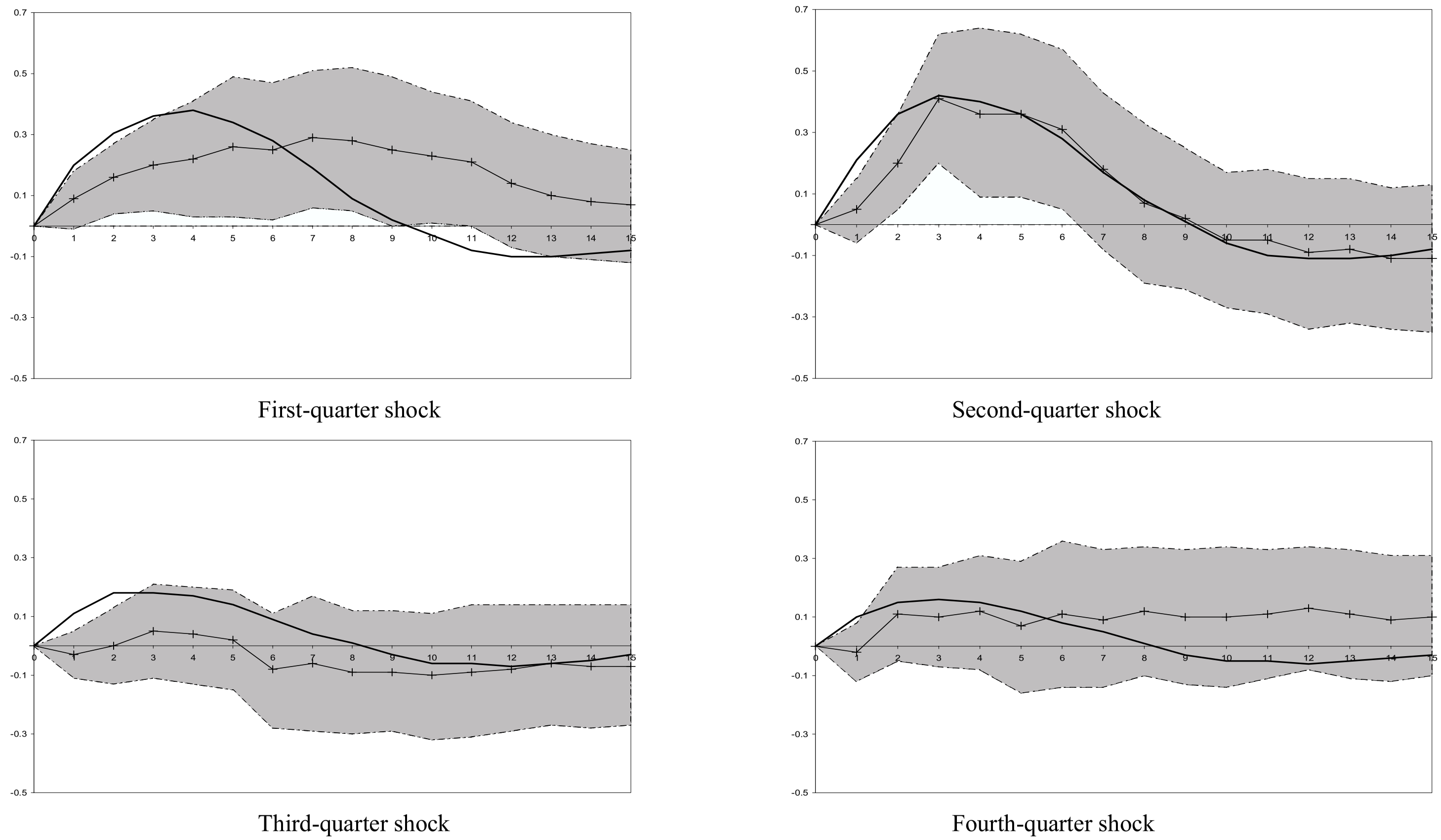
Response of CPI



Response of FFR

FIGURE 10

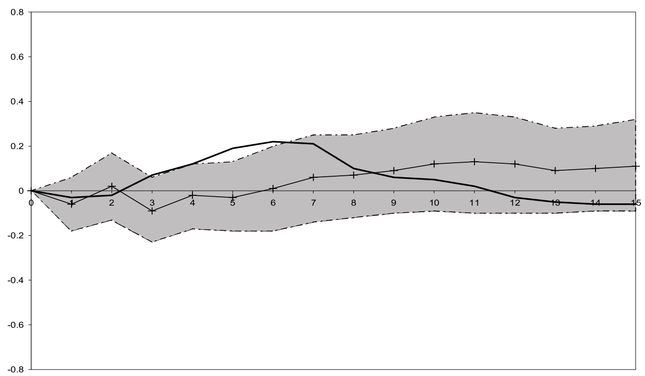
Model and VAR impulse responses of output to a 25-Basis Point Decline in Fed Funds Rate.



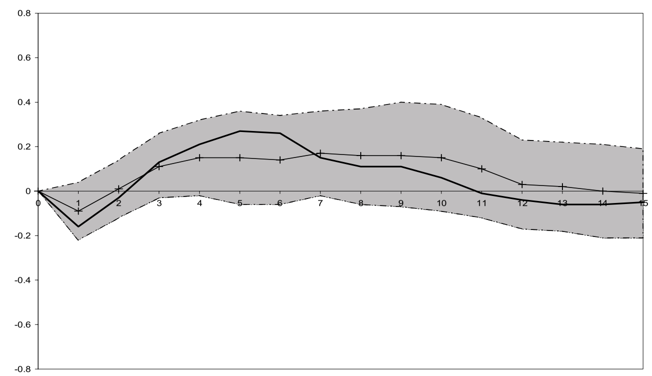
Note: Bold solid lines are the theoretical responses and solid lines-plus sign are the VAR responses. Broken lines indicate the 95 percent confidence intervals around VAR estimates. Vertical axis units are deviations from the steady state path.

FIGURE 11

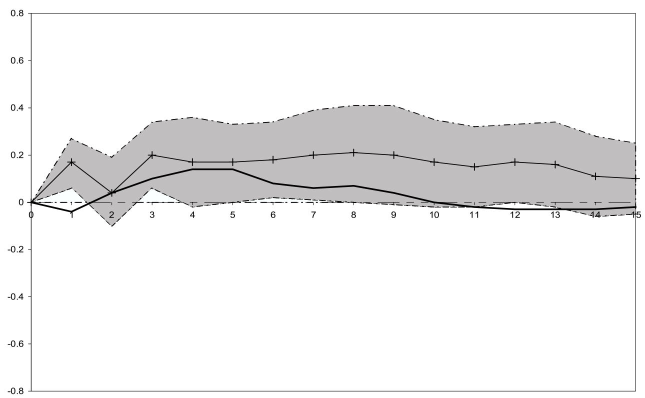
Model and VAR impulse responses of inflation to a 25-Basis Point Decline in Fed Funds Rate.



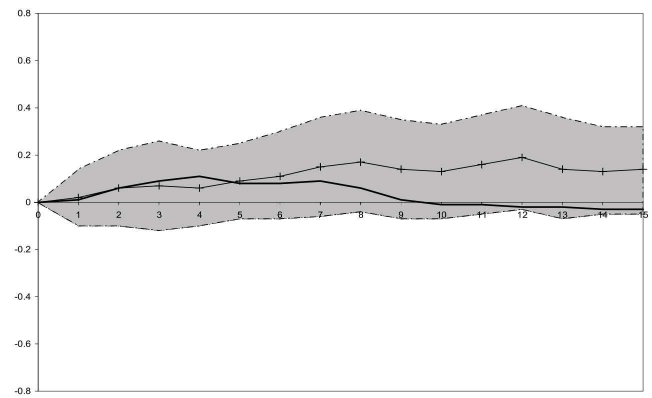
First-quarter shock



Second-quarter shock



Third-quarter shock

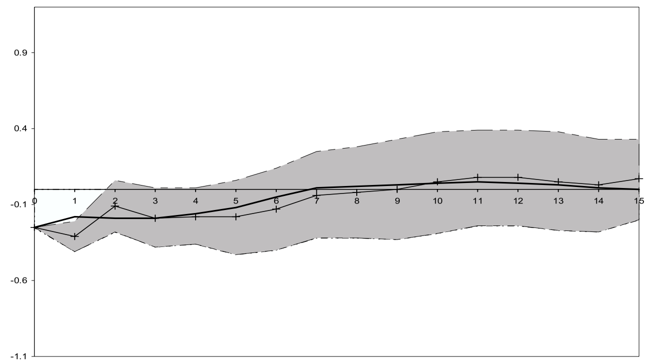


Fourth-quarter shock

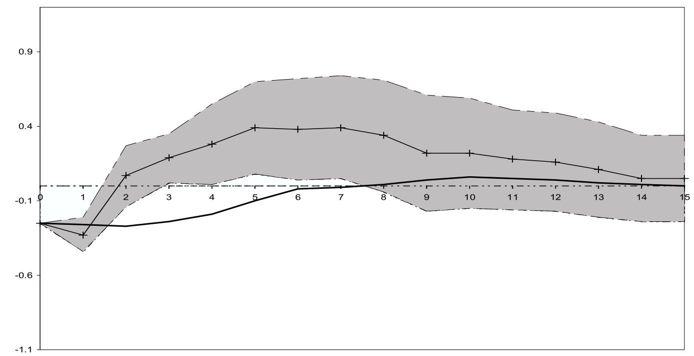
Note: Bold solid lines are the theoretical responses and solid lines-plus sign are the VAR responses. Broken lines indicate the 95 percent confidence intervals around VAR estimates. Vertical axis units are deviations from the steady state path (annualized percentage points).

FIGURE 12

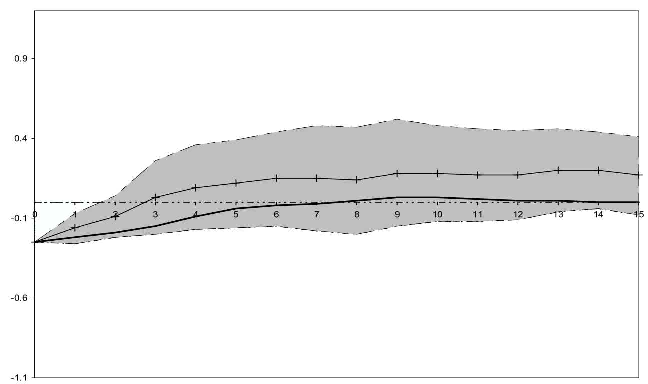
Model and VAR impulse responses of the Fed Funds Rate to a 25-Basis Point Decline in Fed Funds Rate.



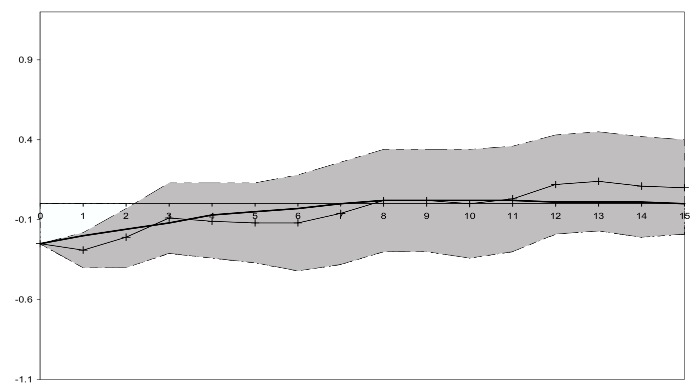
First-quarter shock



Second-quarter shock



Third-quarter shock



Fourth-quarter shock

Note: Bold solid lines are the theoretical responses and solid lines-plus sign are the VAR responses. Broken lines indicate the 95 percent confidence intervals around VAR estimates. Vertical axis units are deviations from the steady state path (annualized percentage points).

Table 1. Differences in Impulse-Responses Across Quarters
p-values for D-Statistic

Variable	Quarter			
	First	Second	Third	Fourth
GDP	0.02	0.00	0.04	0.08
GDP Deflator	0.41	0.15	0.01	0.05
Fed Funds Rate	0.22	0.00	0.13	0.09

Table 2. Parameter Calibration

Parameter Values	
β	0.993
α_{κ}	0.360
δ	0.025
λ_w	1.200
ξ_p	0.100
κ	2.000
η	0.630
σ_a	0.010
α_1	0.700
α_2	0.900
α_3	0.500
α_4	0.400
a_{π}	1.500
a_y	0.100
ρ	0.825