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HIGH FREQUENCY IDENTIFICATION OF MONETARY NON-NEUTRALITY

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ABSTRACT

We provide new evidence on the responsiveness of real interest rates and inflation to monetary shocks. Our identifying assumption is that the increase in the volatility of interest rate news in a 30-minute window surrounding scheduled Federal Reserve announcements arises from news about monetary policy. Real and nominal yields and forward rates at horizons out to 3 years move close to one-for-one at these times implying that changes in expected inflation are small. At longer horizons, the response of expected inflation grows. Accounting for "background noise" in interest rates is crucial in identifying the effects of monetary policy on interest rates, particularly at longer horizons. We use structural macroeconomic models to show that the impact of changes in real interest rates on output is small or the impact of changes in output on prices is small or both. Furthermore, our evidence points towards substantial inflation inertia.

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1 Introduction

A fundamental question in macroeconomics is how monetary policy affects the economy. The key empirical challenge in answering this question is that most changes in interest rates happen for a reason. For example, the Fed might lower interest rates to counteract the effects of an adverse shock to the financial sector. In this case, the effect of the Fed's actions are confounded by the financial shock, making it difficult to identify the effects of monetary policy. Two sources of existing evidence are structural vector autoregressions (e.g. Christiano, Eichenbaum, and Evans, 1999) and Romer and Romer's (2004) approach of looking at the effects of changes in the intended federal funds rate that are orthogonal to the Fed's information set as measured by its staff forecast. The concern remains, however, that not all endogenous variation has been purged from these measures of monetary shocks.

An alternative approach—the one we pursue in this paper—is to focus on movements in bond prices in a narrow window around scheduled Federal Open Market Committee (FOMC) meetings. Key to this approach is that, while interest rates are continually being affected by many factors, monetary news is revealed in a lumpy fashion, with a disproportionate fraction of news revealed at the time of FOMC announcements. Since bond prices adjust in real-time to news about the macroeconomy, movements in bond prices at the time of an FOMC announcement reflect the effect of news about current and future monetary policy. This is important for identification since it strips out endogenous variation in interest rates associated with other shocks than monetary shocks. For example, a positive employment announcement that occurs several days or even hours before an FOMC announcement will already have been factored into bond prices when the Fed makes its announcement.

This approach to identifying monetary shocks was pioneered by Cook and Hahn (1989), Kuttner (2001), and Cochrane and Piazzesi (2002). They use a one-day window surrounding FOMC announcements and implicitly assume that monetary shocks are the dominant source of variation in bond prices during these days. More recently, Hanson and Stein (2012) apply this identifying assumption to study the impact of monetary shocks on long-term real interest rates. We show, however, that assuming that no other shocks occur on FOMC announcement days is too strong an assumption. Interest rates exhibit substantial fluctuations on non-FOMC days. This suggests that other shocks than the FOMC announcement affect interest rates on FOMC days and it is unlikely that these other fluctuations arise purely from monetary shocks. Accounting for this "background noise" in interest rates is crucial in accurately assessing the effects of monetary shocks, particularly at longer horizons.[1]

To control for other shocks that occur on FOMC days, we use a heteroskedasticity-based estimator pioneered by Rigobon (2003) and Rigobon and Sack (2004). Like the earlier literature, we make use of the discontinuous increase in the volatility of interest rates at the time of FOMC announcements. Our identifying assumption is, however, weaker. We allow for the possibility that some movements in interest rates in a narrow window around FOMC announcments are associated with non-monetary shocks (we consider a 30- minute window and a 1-day window). The key assumption is that there is nothing special about these windows of time around FOMC announcement when it comes to other shocks than the FOMC announcement. As a consequence, the increase in the volatility of interest rates at the time of FOMC announcements, relative to its baseline level on non-FOMC days, is assumed to arise purely from monetary shocks.[2]

We use this approach to provide a new measure of the magnitude of monetary non-neutrality. In conventional monetary models, the Federal Reserve stimulates the economy by lowering nominal interest rates. The power of monetary policy arises because prices respond only sluggishly to such a monetary stimulus. The sluggish response of prices implies that a change in nominal interest rates translates into a change in real interest rates. The greater is the degree of rigidity of prices, the larger is the response of real interest rates relative to the response of inflation. In this sense, the relative size of the response of inflation and real interest rates to a monetary shock can be used to gauge the extent of monetary non-neutrality in the economy.

In recent years, FOMC announcements have not revealed much surprise news about contemporaneous changes in the Federal Funds rate. For the most part, the Fed's actions at a given meeting are anticipated in advance. FOMC announcements, however, frequently reveal substantial amounts of news about the future path of nominal interest rates (Gurkaynak, Sack, and Swanson, 2005). We therefore study the effects of a "policy news shock" equal to the first principal component of unexpected changes at the time of FOMC announcements in nominal interest rates over the year following an FOMC meeting.[3] By construction, the policy news shock has large effects on nominal

[1] Gurkaynak, Sack, and Swanson (2005) and Fleming and Piazzesi (2005) use intra-day data to assess the impact of FOMC actions on nominal interest rates. This sharply reduces the amount of background noise in interest rates.

[2] Wright (2012) uses Rigobon's identification by heteroskedasticity approach to identify the effects of unconventional monetary policy on interest rates during the recent period over which short-term nominal interest rates have been at their zero lower bound.

[3] Our policy news shock is closely related to the "path factor" studied by Gurkaynak, Sack, and Swanson (2005).

yields. For example, a 1% policy news shock leads to an 86 basis point increase in the 2-year nominal yield.

More interestingly, the policy news shock also has a large and statistically significant effect on the real yield curve. Data on real interest rates are available from the market for Treasury Inflation Protected Securities (TIPS). The impact of a 1% policy news shock on the 2-year real yield is 85 basis points, and the impact on the 3-year real yield is 77 basis points. It is easier to interpret the time-path of the effects of the policy news shock on instantaneous real forward rates. The effect of a 1% policy news shock on the 2-year real forward rate is 68 basis points. It falls monotonically at longer horizons to 56 basis points at 3 years, 35 basis points at 5 years, and 1 basis point at 10 years.[4]

While our policy news shocks lead to substantial movements in the real interest rate, they lead to quite modest changes in expected inflation as measured by the breakeven inflation rate implied by TIPS. Recall that we would expect a contractionary monetary policy shock that raises real interest rates to lower inflation. In fact, the effect of our policy news shock on inflation is close to zero and statistically insignificant at the 2 and 3 year horizons. At longer horizons, the inflation effect is negative and grows to 29 basis points at a 5 year horizon.

An important question is whether some of the effects on longer-term real interest rates we estimate reflect risk premia as opposed to changes in expected future short-term real interest rates. A key point is that constant risk premia do not affect our results, since our identification is based on changes in bond yields at the time of FOMC announcements. To address the possibility that risk premia may change at the time of FOMC announcements, we study the effect of our monetary shocks on expected real rates using direct measures of expectations from the *Blue Chip Economic Indicators*, which surveys professional forecasters on their beliefs about future interest rates and inflation. Since these data are direct measures of expectations, they are immune from risk premium effects. While our estimates based on this approach are less precise than those based on asset prices, they support a similar time-pattern of effects on real interest rates and a small inflation response. Furthermore, we find no evidence that the interest rate effects we identify dissipate quickly after the announcement, as would be predicted by some models of liquidity premia.[5]

[4]In this regard, our results differ significantly from Hanson and Stein (2012) who find that their measure of monetary shocks has a significant effect on instantaneously real forwards even at the 10-year horizon. A key difference is our heteroskedasticity-based estimation approach, which accounts for"background noise" in interest rates. We discuss this issue further in section 3.

[5]Hanson and Stein (2012) present a behavioral model in which "search for yield" generates significant risk premium

What can be learned about the structure of the economy from these empirical results? The relative size of the real interest rate and inflation response to the monetary shock can be thought of as being governed by the combination of two forces. First, the Euler equation dictates that an increase in the real interest rate leads to a decrease in output. The strength of this force is governed by the intertemporal elasticity of substitution (IES). Second, the resulting decrease in output leads firms to reduce their prices, generating a fall in inflation. The strength of this force is governed by the extent of nominal and real rigidities, which determine how often firms adjust their prices and by how much they change their prices when they change them. The modest size of the response of inflation to our monetary shock relative to the size of the response of real interest rates implies that our empirical evidence points to some combination of output not responding much to changes in real interest rates (a small IES) and prices not responding much to a change in output (substantial nominal and real rigidities).

In addition, simple New Keynesian models imply that inflation is purely forward looking. This means that the largest response of inflation should be immediately following the monetary shock, when all the high real interest rates are in the future. The response of inflation should then dissipate as the response of real interest rates dies out. In contrast to this, the response of inflation that we estimate in the data builds over time. This suggests a model with a substantial degree of inflation inertia.

Using a simulated method-of-moments estimation approach we quantify the extent to which our empirical evidence can inform us about the structural parameters discussed above in the context of a New Keynesian business cycle model. This exercise is analogous to efforts to estimate monetary models to match evidence from structural VARs (e.g., Christiano, Eichenbaum, and Evans (2005)). We show that the evidence we present identifies the product of the IES, the degree of nominal rigidities and the degree of real rigidities. Assuming a conventional value of the degree of nominal rigidities, our estimates imply a lower IES or larger degree of real rigidities than is typically assumed in the monetary economics literature (or both). Furthermore, we find that it is crucial to include a large "backward-looking" term in the Phillips curve to match the growing response of inflation that we observe in the data.

Finally, we investigate whether the low IES and/or large degree of real rigidities we estimate can be explained by the frictions emphasized by Christiano et al. (2005, CEE) , Altig et al. (2011,

effects of monetary shocks.

ACEL), and Smets and Wouters (2007). We find that the CEE/ACEL model can match the response of nominal and real interest rates and inflation to our monetary shock if we assume somewhat larger values of price and wage rigidities and a lower value of the elasticity of investment to the price of capital than the authors of those papers estimate. For relatively transitory shocks to monetary policy such as those analyzed in CEE, these alternative parameters yield a somewhat smaller effect of monetary shocks on output than the parameter values estimated in CEE. The greater nominal and real rigidities amplify the effects of monetary shocks, while the lower investment elasticity reduces these effects. For our much more persistent monetary shock, our alternative parameterization yields a somewhat larger effect of monetary shocks on output.

In the above discussion, we have implicitly assumed that FOMC announcements change the private sector's beliefs about current and future monetary policy without providing the private sector with new information about the state of the economy. In other words, we have been assuming that the Fed does not have an informational advantage over the private sector. In this case, FOMC announcements may provide the private sector with information about the preferences of the Fed—i.e., how tough they are on inflation—but it may also provide the private sector with information about the Fed's beliefs about the current and future state of the economy. Even if the Fed and the private sector have the same information set, they may hold different beliefs about the future path of the natural rate of output if they interpret the information differently (perhaps due to believing in somewhat different models).

A potential alternative interpretation of our results to the one we emphasize above is that FOMC announcements reveal information to the private sector about the state of the economy. If this is the case and the private sector believes that the Fed will conduct monetary policy in such a way as to make sure the real interest rate tracks the "natural rate of interest"—i.e., the real interest that would prevail if prices were fully flexible—then FOMC announcements may affect the expected path of real interest rates without affecting output and inflation. Our empirical evidence is consistent with this interpretation at the short end of the term structure, but not at the long end. In addition, for this effect to be important, the Fed must have a considerable informational advantage relative to private markets arising either from superior data or superior analytical capacities.

The paper proceeds as follows. Section 2 describes the data we use in our analysis. Section 3 describes the construction of our policy news shock and presents our main empirical results regarding the response nominal and real interest rates and inflation to the policy news shock. Section 4 presents the theoretical model that we use to map our estimates into measures of monetary non-neutrality. In section 5 we use our empirical estimates to make inference about structural parameters. Section 6 concludes.

2 Data

We use data on interest rates from several sources. First, we use tick-by-tick data on Fed Funds futures and Eurodollar futures from the CME Group (owner of the Chicago Board of Trade and Chicago Mercantile Exchange). Fed Fund futures have been traded since 1989, while Eurodollar futures began trading in the early 1980's. For each month, we make use of the current month's Fed Funds futures contract, the next month's Fed Funds futures contract and the Fed Funds futures contract for the month of the next FOMC meeting (which typically occurs in one or two months). And we make use of the Eurodollar futures that expire in two, three and four quarters.

The Federal Funds futures contract for a particular month (say April 2004) trades at price p and pays off $100 - \bar{r}$ where $\bar{r}$ is the average of the effective Federal Fund Rate over the month. The effective Federal Fund Rate is the rate that is quoted by the Federal Reserve Bank of New York on every business day. This rate is computed as a weighted average rate from trades that day. The price of the futures contract can, thus, be used to construct market based expectations of the average Fed Funds rate over the month in question.[6]

A Eurodollar futures contract expiring in a particular quarter (say 2nd quarter 2004) is an agreement to exchange, on the second London business day before the third Wednesday of the last month of the quarter (typically a Monday near the 15th of the month), the price of the contract p for 100 minus the then current three-month US dollar BBA LIBOR interest rate. The contract thus provides market-based expectations of three month nominal interest rates on the expiration date.[7]

To measure movements in Treasuries at horizons of 1 year or more, we use daily data on zero-coupon nominal treasury yields and instantaneous forward rates constructed by Gurkaynak, Sack, and Swanson (2007). These data are available on the Fed's website at `http://www.federalreserve.`

[6]See the Chicago Board of Trade Reference guide `http://www.jamesgoulding.com/Research_II/FedFundFutures/FedFunds(FuturesReferenceGuide).pdf` for a detailed description of Fed futures contracts. On a trading day in March (say), the April Federal Funds futures contract is labels as 2nd expiration nearby and also as 1st beginning nearby, in reference to the month over which $\bar{r}$ is computed.

[7]See the CME Group Eurodollar futures reference guide `http://www.cmegroup.com/trading/interest-rates/files/eurodollar-futures-reference-guide.pdf` for more details about how Eurodollar futures are defined.

gov/pubs/feds/2006/200628/200628abs.html. We also use the yields on 3M and 6M Treasury bills. We retrieve these from the Federal Reserve Board's H.15 data release.

To measure movements in real interest rates, we use zero-coupon yields and instantaneous forward rates constructed by Gurkaynak, Sack, and Wright (2010) using data from the TIPS market. These data are available on the Fed's website at http://www.federalreserve.gov/pubs/feds/2008/200805/200805abs.html. TIPS are "inflation protected" because the coupon and principal payments are multiplied by the ratio of the reference CPI on the date of maturity to the reference CPI on the date of issue.[8] The reference CPI is a moving average of the CPI two and three months prior to the maturity or issue month, to allow for the fact that the Bureau of Labor Statistics publishes these data with a lag.

TIPS were first issued in 1997 and were initially sold at maturities of 5, 10 and 30 years, but only the 10-year bonds have been issued systematically throughout the sample period. Other maturities have been issued more sporadically. While liquidity in the TIPS market was initially poor, TIPS now represent a substantial fraction of outstanding Treasury securities. We start our analysis in 2000 to avoid relying on data from the period when TIPS liquidity was limited.

We obtain the dates and times of FOMC meetings up to 2004 from the appendix to Gurkaynak, Sack, and Swanson (2005). We obtain the dates of the remaining FOMC meetings from the Federal Reserve Board website at http://www.federalreserve.gov/monetarypolicy/fomccalendars.htm. For the latter period, we verified the exact times of the FOMC announcements using the first news article about the FOMC announcement on *Bloomberg*.

We use data on inflation swaps from *Bloomberg*. An inflation swap is a financial instrument designed to help investors hedge inflation risk. As is standard for swaps, nothing is exchanged when an inflation swap is first executed. However, at the maturity date of the swap, the counterparties exchange $R_t^x - \Pi_t$, where R_t is the x-year inflation swap rate and Π_t is the reference inflation over that period. If agents were risk neutral, therefore, R_t would be expected inflation over the x year period.

Finally, we use data on expectations of future nominal interest rates and inflation from the *Blue Chip Economic Indicators*. *Blue Chip* carries out a survey during the first few days of every month soliciting forecasts of these variables for up to the next 8 quarters.

[8]This holds unless inflation is negative, in which case no adjustment is made for the principle payment.

3 Empirical Analysis

Our goal in this section is to identify the effect of the monetary news contained in scheduled FOMC announcements on nominal and real interest rates and inflation. Our identification approach makes use of the discontinuous increase in the volatility of monetary shocks at the time of FOMC announcements. We therefore consider changes in interest rates in a narrow window around FOMC announcements. We consider two time intervals. The first is a 30 minute window from 10 minutes before the FOMC announcement to 20 minutes after it. The second is a 1 day window from the close of markets the day before the FOMC meeting to the close of markets the day of the FOMC meeting.

In their post-meeting announcements, the FOMC conveys information not only about immediate changes in the Federal Funds Rate but also about likely changes in monetary policy at later dates. In fact, over the last 15 years, changes in the Federal Funds Rate have often been largely anticipated by markets once they occur, while FOMC announcements have come to focus more and more on guiding expectations about future changes in the Federal Funds Rate (Gurkaynak, Sack, and Swanson, 2005). Motivated by these developments, we construct a measure of monetary policy news Δi_t by taking the first principle component of changes in five interest rates of maturity less than one year which can be inferred from futures data. We use Federal Funds futures and Eurodollar futures to infer changes in the market's expectations about the Federal Funds rate immediately following the FOMC meeting, the Federal Funds rate immediately following the next FOMC meeting, and the 3-month Eurodollar interest rate at horizons of two, three and four quarters.[9] We refer to Δi_t the "policy news shock."[10] The scale of the policy news shock is arbitrary. For convenience, we rescale it such that an OLS regression of the 1-year Treasury yield on the policy news shock yields a coefficient of one. Appendix A provides details about the construction of the policy news shock.

3.1 Identification

If we were confident that movements in the policy news shock Δi_t over the windows of time we consider around FOMC announcements were due to monetary shocks and nothing else, then this

[9] More precisely, the expiraction date of the "two quarter" Eurodollar future is between one and two quarters in the future at any given point in time. See our discussion in section 2 on the exact expiration dates of Eurodollar futures.

[10] Our policy news shock variable is closely related to the path factor considered by Gurkaynak, Sack, and Swanson (2005). The five interest rate futures that we use to construct our policy new shock are the same five futures as Gurkaynak, Sack, and Swanson (2005) use. They motivate the choice of these particular futures by liquidity considerations.

variable would constitute a pure measure of monetary shocks. We could thus regress any other variable of interest on the policy news shock to assess the effect of monetary shocks on that variable. This is the approach taken by Cook and Hahn (1989), Kuttner (2001) and Cochrane and Piazzesi (2002) (with a one-day window) and more recently by Hanson and Stein (2012) (with a two-day window). A potential concern with this approach is that other shocks may occur over the course of FOMC days. Interest rates fluctuate substantially on non-FOMC days. This suggests that other shocks than FOMC announcements affect interest rates on FOMC days. There is no way of knowing whether these other shocks are monetary shocks or non-monetary shocks.

We would, therefore, like to allow for "background noise" in interest rates on both FOMC and non-FOMC announcement days. To this end we adopt a heteroskedasticity-based estimator of monetary shocks developed by Rigobon (2003) and Rigobon and Sack (2004). Let ϵ_t denote a pure monetary shock and suppose that movements in the policy news shock we measure in the data is governed both by monetary and non-monetary shocks:

$$\Delta i_t = \alpha_i + \epsilon_t + \beta_i \eta_t, \tag{1}$$

where η_t is a vector of all other shocks that affect Δi_t. Here α_i and β_i are constants and we normalize the impact of ϵ_t on Δi_t to one. We wish to estimate the effects of the monetary shock ϵ_t on an outcome variable s_t. This variable is also affected by both the monetary and non-monetary shocks:

$$\Delta s_t = \alpha_s + \gamma \epsilon_t + \beta_s \eta_t. \tag{2}$$

Our objective is to estimate γ, which should be interpreted as the impact of the pure monetary shock ϵ_t on s_t relative to its effect on i_t. Our identifying assumption is that the variance of monetary shocks increases at the time of FOMC announcements, while the variance of other shocks is unchanged. Define $R1$ as a sample of narrow time intervals around FOMC announcements, and define $R2$ as a sample of equally narrow time intervals that do not contain FOMC announcements but are comparable on other dimensions (e.g., same time of day, same day of week, etc.). We refer to $R1$ as our "treatment" sample and $R2$ as our "control" sample. Our identifying assumption is that $\sigma_{\epsilon,R1} > \sigma_{\epsilon,R2}$, while $\sigma_{\eta,R1} = \sigma_{\eta,R2}$.

We show in Appendix B that given these assumptions γ is given by

$$\gamma = \frac{\mathrm{cov}_{R1}(\Delta i_t, \Delta s_t) - \mathrm{cov}_{R2}(\Delta i_t, \Delta s_t)}{\mathrm{var}_{R1}(\Delta i_t, \Delta s_t) - \mathrm{var}_{R2}(\Delta i_t, \Delta s_t)}. \tag{3}$$

Notice that if we set the variance of the "background noise" η_t to zero, then this estimator reduces to the coefficient from an OLS regression of Δs_t on Δi_t. Intuitively, the full heteroskedasticity-based estimator can be thought of as the simple OLS estimator, adjusted for the "normal" covariance between Δs_t and Δi_t.

As we discuss above, we present results where the policy news shock is constructed using 30-minute and 1-day time intervals surrounding FOMC announcements. Our control samples are then 30-minute or 1-day intervals that are chosen to be as comparable as possible except that they do not include FOMC announcements. Specifically, in the case of 30-minute windows, we choose the same 30-minute window (from 2:05pm to 2:35pm) on all non-FOMC Tuesdays and Wednesdays as our control sample (since scheduled FOMC meetings tend to occur on Tuesdays and Wednesdays), and in the case of 1-day windows, we choose all non-FOMC Tuesdays and Wednesdays as our control sample. For our treatment sample, we focus on only scheduled FOMC meetings, since unscheduled meetings may occur in reaction to other shocks and thus be endogenous. In all cases, the outcome variables are measured over a 1-day window. Our sample period starts on January 1st 2000 and extends to January 25th 2012. We drop data before 2000 because of concerns about liquidity or TIPS and because very few TIPS securities were trading at the time. In our baseline analysis, we drop the second half of 2008 and the first half of 2009 to avoid the period when disruption of financial markets in the Great Recession was most severe.

3.2 Main Estimates

Table 1 presents our baseline estimates of monetary shocks on nominal and real interest rates and inflation. The first column presents the effects of the policy news shock on nominal Treasury interest rates. By construction, the policy news shock has large effects on nominal yields. The effect of a 1% policy news shock on the zero-coupon 1-Year Treasury Yield is 98 basis points, and declines monotonically to 24 basis points at 10 years. Since longer-term yields reflect expectations about the average short-term interest rate over the life of the long bond, it is easier to interpret the time-path of the response of instantaneous forward rates. A 2-year instantaneous forward rate (say) is the short-term interest rate that the market expects to prevail in 2 years time. The impact of our policy news shock on forward rates is also monotonically declining in maturities. For maturities of 2, 3, 5, and 10 years, its effects on forward rates are 79, 45, 6 and -26 basis points, respectively. We show below that the negative effect on long-horizon nominal interest rates reflects a decline in long-horizon inflation expectations.

The second column of Table 1 presents the effects of the policy news shock on real interest rates measured using TIPS. While the effects on nominal rates are by construction, the impact of monetary shocks on real interest rates is not. In neoclassical models of the economy, the Fed controls the nominal interest rate but has no impact on real interest rates. Our estimate of the impact of a 1% the policy news shock on the 2-year real yield is 85 basis points, and the impact on the 3-year real yield is 77 basis points. Once again, the time-path of effects is easier to interpret using evidence on instantaneous forward rates. The effect of the shock on the 2-year real forward rate is 68 basis points. It falls monotonically at longer horizons to 56 basis points at 3 years, 35 basis points at 5 years, and 1 basis point at 10 years. Evidently, monetary policy shocks can affect real interest rates for substantial amounts of time. However, in the long-run, the effect of monetary policy shocks on real interest rates is zero as theory would predict.

The third column of Table 1 presents the effect of the monetary shock on break-even inflation, calculated as the difference between the nominal and real interest rate effects. The first several rows provide estimates based on bond yields, which indicate that the inflation response is small to start out with and grows over time. Again, it is helpful to consider instantaneous forward inflation rates to get estimates of inflation at points in time in the future. The inflation response implied by the 2 year forwards is actually slightly positive, though statistically insignificant. The inflation response is negative at longer horizons: for maturities of 3, 5 and 10 years, the effect is -11, -29 and -27 basis points. Our evidence thus points to inflation responding quite gradually to monetary shocks that have a substantial effect on real interest rates. In section 5 below, we discuss what we can infer about the structure of the economy from these estimates.

Our policy news shock captures the effects of FOMC meetings on expectations about nominal interest rates over the next year. An alternative approach would be to focus on the impact of FOMC announcements on market expectations about the level of the Federal Funds Rate immediately following the announcement. This is the approach taken by much of the early literature. For example, Cochrane and Piazzesi (2002) consider changes in one-month Eurodollar rates at the time of FOMC announcements as a proxy for changes in expectations about the Federal Funds Rate. The disadvantage of this approach, however, is that it captures less of the variation in interest rates in response to monetary shocks than the policy news shock we construct. The remaining columns of

Table 1, nevertheless, present estimates based on this approach. The conclusions are very similar. Nominal and real rates respond by roughly the same amount at horizons out to about 3 years. At longer horizons, the response of nominal rates is smaller than real rates, implying that inflation falls.[11]

3.3 Alternative Estimates

Table 2 compares our baseline methodology to alternative methods of identifying the monetary policy shock. The first two columns present our baseline results for nominal and real interest rates. These results are based on Rigobon's heterosketasticy-based estimator, and use a 30-minute interval to measure the policy news shock. The remaining columns compare these results to results using a one-day window to compute the monetary policy shock. Columns 3 and 4 present estimates based on applying the Rigobon estimator with a 1-day window. The standard errors on these estimates are extremely large. Intuitively, there is too much "background noise" in the policy news shock variable over a 1-day window to be able to estimate its effect on the term structure with any precision.

Columns 5 and 6 compare the results based on the Rigobon estimator and a 1-day window to those based on OLS and a 1-day window. The results based on OLS implicitly make the (much stronger) identifying assumption that *only* monetary shocks occur on the day of an FOMC announcement. A comparison of columns 3 and 4 and columns 5 and 5 shows that OLS massively underestimates the standard errors on the estimated effects of monetary policy shocks relative to the Rigobon estimator. The much larger Rigobon standard errors reflect the large amount of "background" noise in interest rates over an an entire day. These differences show that the OLS identifying assumption is too strong when a 1-day window is being used.[12]

These concerns loom even larger when longer-term interest rates are used as proxies for monetary shocks. Columns 7 and 8 present the results of applying the Rigobon estimator with the monetary shock measure Δi constructed as one-day changes in the two-year nominal yield. The standard errors are even larger than in the case of the policy-news shock, and are in most cases many times

[11] Beechey and Wright (2009) analyze the effect of Federal Funds rate shocks at the time of FOMC announcements on nominal and real 5-year and 10-year yields and the five-to-ten year forward for the sample period February 17th 2004 to June 13th 2008. Their results are similar to ours for the 5-year and 10-year yields.

[12] Interestingly, the Rigobon and OLS estimation approaches yield quite similar results when applied to the case where the policy news shock is measured over a 30-minute window. Intuitively, the relative volatility of monetary shocks in the 30-minute window surrounding an FOMC announcement is much larger than over the entire day, implying than the "background noise" effect is much smaller.

larger than the coefficient of interest. These results arise because of the large amount of background noise in longer-term interest rates. The increase in volatility associated with FOMC announcements is not large enough over a one-day horizon to accurately assess its impact on the term structure.

The analysis in tables 1 and 2 is for the sample period from Jan 1st 2000 to Jan 25th 2012, except that we drop the period spanning the height of the financial crisis in the second half of 2008 and the first half of 2009. Numerous well-documented asset pricing anomalies arose during this crisis period, and we wish to avoid the concern that our results are driven by these anomalies. We have, however, also carried out our analysis on the full sample including the crisis, as well as a more restrictive data sample ending at the beginning of 2008. Table A.1 presents the results of our analysis for these two alternative sample periods. All three sample periods yield similar results for nominal yields. The full sample yields somewhat larger effects on short-term real yields. In all three cases, the effect of the monetary shock on inflation is initially small and positive, but becomes increasingly negative at longer horizons.

3.4 Survey Measures of Interest Rates and Inflation

An important question when it comes to interpreting our results is to what extent the movements in long-term interest rates we identify reflect movements in risk premia as opposed to changes in expected future short-term interest rates. In this regard, it is important to keep in mind that constant risk premia will not affect our results, since our identification is based on changes in bond yields at the time of FOMC announcements. However, if risk premia change at the time of FOMC announcements this could confound our results.

To study this issue directly, we analyze the impact of our policy news shock on direct measures of expectations from the *Blue Chip Economic Indicators*. *Blue Chip* surveys professional forecasters on their beliefs about macroeconomic variables over the next two years in the first few days of every month. We study the impact of our policy news shock on survey expectations about future short-term interest rates and inflation. By construction, these effects reflect expected movements in rates, as opposed to risk premium effects.

We measure the change in expected interest rates for a particular quarter in the future by the change in the *Blue Chip* forecast about that quarter from one month to the next. We regress this measure on the the sum of the policy news shocks that occur over the month except for those that occur in the first week (because we do not know whether these occurred before or after the survey response). We use *Blue Chip* forecasts of the 3-month T-Bill rate and the GDP deflator in our analysis. We construct a measure of expected short-term real interest rates by taking the difference between the expected 3-month T-bill rate and the expected GDP deflator for a given quarter. Unfortunately, *Blue Chip* asks respondents only about the current and subsequent calendar year, so fewer observations are available for longer-term expectations, leading to larger standard errors.[13] The sample period for this analysis is January 1995 to January 2012, except that we exclude the apex of the 2008-2009 financial crisis as we do in the rest of our analysis.

Table 3 presents the results of this analysis. The table shows that the policy news shock has a persistent impact on expected short-term interest rates, both nominal and real. The interest rate effects are somewhat larger than in our baseline analysis, but rather noisily estimated. As in our analysis using financial variables, the effect on expected inflation is small and statistically insignificant at all horizons. The much larger standard errors on our estimates in this analysis arise from the fact that, unlike in our analysis of financial variables, the changes in survey variables are available only at a monthly as opposed to a daily frequency.

3.5 Inflation Swaps

We also consider an alternative measure of inflation expectations based on inflation swap data. Fleckenstein, Longstaff, and Lustig (2013) point out that measures of breakeven inflation from the TIPS and inflation swap markets are not equal and that this difference increases during the crisis. Table 4 compares our estimates of the effects of the policy news shock on breakeven inflation from TIPS to that on inflation from inflation swaps. The sample period for this analysis is limited by the availability of swaps data to beginning in January 1st 2005. The results are quite similar for these two variables at longer horizons. At shorter horizons the "price puzzle"—i.e., the positive inflation effect at the shortest horizons—is larger for the inflation swap data than the TIPS data, though statistically insignificant in both cases.

[13] For example, in the last quarter of the year, forecasters are only asked about their beliefs 1-year in advance; while in the first quarter they are asked about their beliefs for the next full 2-years.

3.6 Evidence of Mean Reversion

Finally, one additional question that merits attention is whether there is any evidence that the effects we identify on nominal and real yields tend to mean-revert over time, as some theories of liquidity premia might predict. Table 5 presents the effects of our policy news shock on nominal and real interest rates at horizons of 5, 10, 20, 60 , 125 and 250 trading days. While the estimates are extremely noisy, there is little evidence that the effects on interest rates tend to dissipate over time. Indeed, in most cases, the point estimates appear to grow over time (though, again, the standard errors are extremely large).

4 A Simple New Keynesian Model

To help interpret the implications of the empirical results we establish in section 3, we next build a simple New Keynesian business cycle model.[14]

4.1 Households

The economy is populated by a continuum of household types indexed by x. A household's type indicates the type of labor supplied by that household. Households of type x seek to maximize their utility given by

$$E_0 \sum_{t=0}^{\infty} \beta^t [u(C_t, \xi_t) + v(L_t(x), \xi_t)], \tag{4}$$

where β denotes the household's subjective discount factor, C_t denotes household consumption of a composite consumption good, $L_t(x)$ denotes household supply of differentiated labor input x, and ξ_t denotes a vector of preference shocks. There are an equal (large) number of households of each type. The composite consumption good in expression (4) is an index given by

$$C_t = \left[\int_0^1 c_t(z)^{\frac{\theta-1}{\theta}} dz \right]^{\frac{\theta}{\theta-1}}, \tag{5}$$

where $c_t(z)$ denotes consumption of products of variety z. The parameter $\theta > 1$ denotes the elasticity of substitution between different varieties.

Households have access to complete financial markets. Households of type x face a flow budget

[14] See Woodford (2003) and Gali (2008) for thorough expositions of New Keynesian models.

constraint given by

$$P_t C_t + E_t[M_{t,t+1} B_{t+1}(x)] \leq B_t(x) + W_t(x) L_t(x) + \int_0^1 \Xi_t(z) dz - T_t, \tag{6}$$

where P_t is a price index that gives the minimum price of a unit of the consumption good C_t, $B_{t+1}(x)$ is a random variable that denotes the state contingent payoff of the portfolio of financial securities held by households of type x at the beginning of period $t+1$, $M_{t,t+1}$ is the stochastic discount factor that prices these payoffs in period t,[15] $W_t(x)$ denotes the wage rate received by households of type x in period t, $\Xi_t(z)$ denotes the profits of firm z in period t, and T_t is a lump-sum tax levied by the government. To rule out Ponzi schemes, household debt cannot exceed the present value of future income in any state of the world.

Households face a decision in each period about how much to spend on consumption, how many hours of labor to supply, how much to consume of each differentiated good produced in the economy and what portfolio of assets to purchase. Optimal choice regarding the trade-off between current consumption and consumption in different states in the future yields the following consumption Euler equation:

$$\frac{u_c(C_{t+j}, \xi_{t+j})}{u_c(C_t, \xi_t)} = \frac{M_{t,t+j}}{\beta^j} \frac{P_{t+j}}{P_t} \tag{7}$$

as well as a standard transversality condition. Subscripts on the function u denote partial derivatives. Equation (7) holds state-by-state for all $j > 0$. Optimal choice regarding the intratemporal trade-off between current consumption and current labor supply yields a labor supply equation:

$$\frac{v_\ell(L_t(x), \xi_t)}{u_c(C_t, \xi_t)} = \frac{W_t(x)}{P_t}. \tag{8}$$

Households optimally choose to minimize the cost of attaining the level of consumption C_t. This implies the following demand curves for each of the differentiated products produced in the economy:

$$c_t(z) = C_t \left(\frac{p_t(z)}{P_t} \right)^{-\theta}, \tag{9}$$

where $p_t(z)$ denotes the price of product z and

$$P_t = \left[\int_0^1 p_t(z)^{1-\theta} dz \right]^{\frac{1}{1-\theta}}. \tag{10}$$

[15]The stochastic discount factor $M_{t,t+1}$ is a random variable over states in period $t+1$. For each such state it equals the price of the Arrow-Debreu asset that pays off in that state divided by the conditional probability of that state. See Cochrane (2005) for a detailed discussion.

4.2 Firms

There are a continuum of firms indexed by z in the economy. Firm z specializes in the production of differentiated good z, the output of which we denote $y_t(z)$. For simplicity, labor is the only variable factor of production used by firms. Each firm is endowed with a fixed, non-depreciating stock of capital. The production function of firm z is

$$y_t(z) = A_t f(L_t(z)), \tag{11}$$

where A_t denotes aggregate productivity. The function f is increasing and concave. It is concave because there are diminishing marginal return to labor given the fixed amount of other inputs employed at the firm. We follow Woodford (2003) in introducing heterogeneous labor markets. Firm belongs to an industry x. There are many firms in each industry. The goods in industry x are produced using labor of type x and all firms in industry x change prices at the same time. This heterogeneous labor market structure is a potentially strong source of real rigidities in price setting as we discuss in section 5.

Firm z acts to maximize its value,

$$E_t \sum_{j=0}^{\infty} M_{t,t+j}[p_{t+j}(z)y_{t+j}(z) - W_{t+j}(x)L_{t+j}(z)]. \tag{12}$$

Firm z must satisfy demand for its product given by equation (9). Firm z is therefore subject to the following constraint:

$$C_t \left(\frac{p_t(z)}{P_t}\right)^{-\theta} \leq A_t f(L_t(z)). \tag{13}$$

Firm z takes its industry wage $W_t(x)$ as given. Optimal choice of labor demand by the firm is given by

$$W_t(x) = A_t f_\ell(L_t(z))S_t(z), \tag{14}$$

where $S_t(z)$ denotes the firm's nominal marginal cost (the Lagrange multiplier on equation (13) in the firm's constrained optimization problem).

Firm z can reoptimize its price with probability $1-\alpha$ as in Calvo (1983). With probability α it must keep its price unchanged. Optimal price setting by firm z in periods when it can change its price implies

$$p_t(z) = \frac{\theta}{\theta-1} E_t \sum_{j=0}^{\infty} \frac{\alpha^j M_{t,t+j}y_{t+j}(z)}{\sum_{k=0}^{\infty} \alpha^k M_{t,t+k}y_{t+k}(z)} S_{t+j}(z). \tag{15}$$

Intuitively, the firm sets its price equal to a constant markup over a weighted average of current and expected future marginal cost.

4.3 Log-Linear Approximation of Private Sector Behavior

Appendix C shows that private sector behavior can be described up to a log-linear approximation around a zero-growth, zero-inflation steady state by an Euler equation and New Keynesian Phillips curve:

$$\hat{x}_t = E_t\hat{x}_{t+1} - \sigma(\hat{\imath}_t - E_t\hat{\pi}_{t+1} - \hat{r}^n_t), \tag{16}$$

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + \kappa\zeta\hat{x}_t. \tag{17}$$

Hatted variables denote percentage deviations from steady state. The variable $\hat{x} = \hat{y}_t - \hat{y}^n_t$ denotes the "output gap"—the difference between actual output and the "natural" level of output $\hat{y}^n_t$ that would prevail if prices were flexible, $\hat{\pi}_t$ denotes inflation, $\hat{\imath}_t$ denotes the gross return on a one-period, risk-free, nominal bond, and $\hat{r}^n_t$ denotes the "natural rate of interest." Both the natural rate of output and the natural rate of interest are functions of the exogenous shocks ξ_t and A_t. The parameter σ is the intertemporal elasticity of substitution.

We have split the slope of the Phillips curve into two parameters κ and ζ. The parameter $\kappa = (1-\alpha)(1-\alpha\beta)/\alpha$ governs the degree of nominal rigidity in the economy. The key parameter governing nominal rigidities is, of course, the frequency of price change α. The parameter $\zeta = (\omega + \sigma^{-1})/(1+\omega\theta)$, where the parameter ω is the elasticity of the marginal cost of firm z with respect to production of product z. The parameter ζ governs the degree of "real rigidity" in the economy. The numerator in ζ reflects the curvature of labor demand and labor supply which imply that marginal costs rise when production rises. The denominator is due to the heterogeneous nature of the the labor markets in the model. Intuitively, when firms in a particular industry raise their prices relative to the firms in other industries, this lowers demand which reduces the wage demands of workers in that industry implying that the firms don't want to raise their prices as much as they otherwise would.

4.4 Monetary Policy and Information Structure

In the simple model we have written down in this section, good monetary policy varies the short-term interest rate such that it tracks the natural rate of interest. If the monetary authority is able to vary the short-term interest rate in such a way that it perfectly tracks the natural rate of interest, it can achieve both a zero output gap and zero inflation (see Woodford, 2003, ch. 4).[16] With this in mind, we specify the following policy rule for the monetary authority:

$$\hat{\imath}_t - E_t\hat{\pi}_{t+1} = \bar{r}_t + \phi_\pi\hat{\pi}_t. \tag{18}$$

We have written this policy rule as a rule for the short term real interest rate. The first term in the rule is a time varying intercept term. We think of the monetary authority as using this term to track variation in the natural rate of interest r_t^n. The second term is a conventional endogenous feedback term implying that the monetary authority raises the real interest rate as inflation increases. If the monetary authority is successful at varying $\bar{r}_t$ so that it tracks r_t^n, inflation will be stable at zero and the endogenous feedback term will not come into play.

Our empirical results in section 3 suggest that news shocks about appropriate future monetary policy are important. To capture this in our model, we assume that the private sector and the central bank receive signals about future values of the natural rate of interest. The Fed periodically makes public statements where it conveys to the public its beliefs about the future path of the natural rate of interest.

How the private sector will react to these public statements by the Fed depends critically on how the public interprets the information content of these statements. For simplicity, we consider two polar cases. In the first case, which we refer to as *Fed's beliefs case*, we assume that the private sector and the central bank receive the same signals but hold different views about what these signals imply about future natural rates. The idea is that the private sector and the central bank have different priors about how to interpret signals (different models). Furthermore, we assume that the private sector is uncertain about how the central bank interprets new information. These assumptions imply that movements in the term structure of interest rates at the time of FOMC announcements should be interpreted as being due to updating by the private sector about what it thinks the Fed thinks the path for the natural rate of interest will be. Since the private sector and the Fed have the same information set, the private sector is not using the announcements of the Fed to update its own views about future natural rates. The private sector has already seen all the information that the Fed is basing its announcements on and has incorporated this information into its forecast about the natural rate if interest. This means there is nothing the private sector can learn from the Fed's

[16] Woodford (2003, ch. 4) shows that optimal monetary policy in the model presented above.

announcement about the natural rate. The private sector is only updating its beliefs about what the Fed thinks the natural rate will be. The difference in priors about how to interpret signals implies that the private sector and the Fed agree to disagree about the future path of the natural rate of interest. Nonetheless, the Fed's views about the natural rate of interest affect the private sector through future monetary policy.

In the second case, which we refer to as the *Fed information case*, we assume that the public and the central bank share the same model of the world and therefore agree about how to interpret new information. However, the central bank receives additional signals about economic fundamentals that the public does not receive directly. More specifically, there are two types of signals; signals that are seen by both the public and the central bank and signals that only the central bank receives. The central bank thus has an informational advantage. These assumptions imply that movements in the term structure of interest rates at the time of FOMC announcements should be interpreted as being due to the private sector using what the Fed says to update its own beliefs about the future path of the natural rate of interest. If the public believes that the Fed is committed to vary short term interest rates in such a way as to track the natural rate of interest, FOMC announcements will in this case not change the public's views about future deviations between interest rates and the natural rate.[17]

Let $\epsilon_{t,t+j}$ denote the time t shock to the private sector's expectations about the intercept term in the Fed's policy rule in period $t+j$. In other words, $\epsilon_{t,t+j} = E_t \bar{r}_{t+j} - E_{t-1} \bar{r}_{t+j}$. To capture the term structure of changes in interest rates that we estimate occurring at the time of FOMC announcements, we assume that

$$\epsilon_{t,t+j} = (\rho_1 + \rho_2)\epsilon_{t,t+j-1} - \rho_1 \rho_2 \epsilon_{t,t+j-2}. \tag{19}$$

This implies that the entire path of changes in private sector beliefs about Fed behavior at the time of an FOMC meeting can be characterized by three numbers: $\epsilon_{t,t}$, which gives the size and direction of the shock, and the parameters ρ_1 and ρ_2, which govern the term structure of news about future interest rates. We have chosen to parameterize equation (19) in terms of the roots of its lag polynomial for ease of interpretation. The difference between the two information structures discussed above is that in the Fed's beliefs case, the Fed's announcement does not change the private

[17] Our Fed's belief case and Fed information case are closely related to the notion of endogenous and exogenous monetary policy actions in Ellingsen and Soderstrom (2001).

sector's beliefs about the future evolution of the natural rate—i.e., $E_t r^n_{t+j} - E_{t-1} r^n_{t+j} = 0$—while in the Fed information case, the Fed's announcement implies a change in the private sector's beliefs about the future evolution of the natural rate that is equal to the change in beliefs about rates set by the Fed—i.e., $E_t r^n_{t+j} - E_{t-1} r^n_{t+j} = E_t \bar{r}_{t+j} - E_{t-1} \bar{r}_{t+j}$.

5 What Do We Learn About the Structure of the Economy?

Our goal in this section is to explain how the evidence from section 3 can be used to make inference about the structure of the economy. It is useful to consider the two cases discussed in section 4 regarding the interpretation the private sector gives to the FOMC announcement in turn.

5.1 Fed Information Case

Suppose first that we are in the Fed information case. In other words, suppose that the Fed's announcement causes an equally large adjustment to the private sector's beliefs about the interest rate path the Fed will set ($\bar{r}_{t+j}$) and its beliefs about path of the natural rate of interest (r^n_{t+j}). In this case, the Fed's announcement does not change the current or expected future "interest rate gap" ($\hat{\imath}_{t+j} - E_t \hat{\pi}_{t+j+1} - r^n_{t+j}$) and therefore also leaves the current and expected future level of the output gap and inflation unaffected. As a consequence, the response of nominal rates and real rates should be the same at all horizons.

The response of nominal and real interest rates we estimate in section 3 is consistent with this prediction at the short end of the term structure, but not at the long end. The response of nominal and real rates are very close to identical (and certainly not statistically significantly different from each other) at horizons out to 3 years. At the 5 and 10 year horizon, however, the nominal rate response is smaller than the real rate response implying that the response of inflation is significantly negative.

In addition, the plausibility of the Fed information case depends on how plausible it is to think that the Fed has a significant informational advantage over the private sector. To our knowledge, the Fed does not have access to a significant amount of information about the economy that is outside the public domain. Any informational advantage by the Fed about the natural rate of interest must thus be due to an advantage in processing information. Romer and Romer (2000) show that the Fed makes better forecasts than the private sector and argue that this is due to superior information processing. However, an alternative reason why the Fed might make better forecasts is that it has superior information about its future monetary policy ($\bar{r}_t$) rather than superior information about the natural rate of interest (r_t^n). This alternative reason falls under the Fed's beliefs case.

5.2 Fed's Beliefs Case

Now suppose that we are in the Fed's beliefs case. In other words, suppose that the Fed's announcement leads the private sector to change what it thinks the Fed thinks the path for the natural rate of interest will be, but without changing the private sector's own beliefs about the path of the natural rate. In this case, the shock leads to a change in the interest rate gap ($\hat{\imath}_{t+j} - E_t\hat{\pi}_{t+j+1} - r_{t+j}^n$). We can then use the relative size of the interest rate gap response and the response of inflation to make inference about the key parameters governing private sector behavior (σ, κ, and ζ).

For simplicity, in this case, we assume that the natural rate of interest and the natural rate of output are constant at their steady state values and that the economy starts in steady state. We then consider the response of the economy to a monetary shock that occurs in period t and is expected to affect the intercept in the monetary authority's policy rule over time as described by equation (19). This implies that below all hatted variables refer to the response to such a monetary shock holding the path for the natural rate constant at its steady state value.

Consider first the Euler equation—equation (16). If we assume that monetary shocks have no effect on output in the long run, we can solve the Euler equation forward and get that the response of output to a monetary shock is

$$\hat{y}_t = -\sigma \sum_{j=0}^{\infty} E_t \hat{r}_{t+j} = -\sigma \hat{r}_t^{\ell}. \tag{20}$$

where $\hat{r}_{t+j}$ denotes the response of the short-term real interest rate at time $t+j$—i.e., $\hat{r}_{t+j} = \hat{\imath}_{t+j} - E_t\hat{\pi}_{t+j+1}$—and $\hat{r}_t^{\ell}$ denotes the response of the long-run real interest rate.[18] This shows that the response of output to the shock is fully determined by the intertemporal elasticity of substitution and the path of the response of real interest rates or equivalently the response of the long-run real interest rate. In other words, given the path of the response of real interest rates and the assumption that the monetary policy shock has not effect on output in the long-run, the determination of output is a "partial equilibrium" exercise relying only on the Euler equation. The rest of the model does not effect the determination of output.

[18] We will allow for long-run effects of monetary shocks on output below.

Next, consider the Phillips curve—equation (17). We can solve this equation forward and get that the response of inflation to a monetary shock is

$$\hat{\pi}_t = \kappa\zeta \sum_{j=0}^{\infty} \beta^j E_t \hat{y}_{t+j}. \tag{21}$$

This shows that the response of inflation is fully determined by $\kappa\zeta$—the slope of the Phillips curve—and the sum of the response of output at different horizons. Combining equations (20) and (21), we get a relationship between the response of inflation and the response of real interest rates:

$$\hat{\pi}_t = -\kappa\zeta\sigma \sum_{j=0}^{\infty} \beta^j E_t \hat{r}^{\ell}_{t+j}. \tag{22}$$

If monetary shocks have long-run effects on inflation, equation (22) becomes

$$\hat{\pi}_t = -\kappa\zeta\sigma \sum_{j=0}^{\infty} \beta^j E_t \hat{r}^{\ell}_{t+j} + \hat{\pi}_{\infty}, \tag{23}$$

where $\hat{\pi}_{\infty}$ denotes the long-run response of inflation to the monetary shock.[19] The monetary rule we introduce in section 4 implies that $\pi_{\infty} = 0$.

In section 3, we present empirical evidence on the response of nominal interest rates, real interest rates, and inflation to news about future monetary policy. Equation (23) shows how the relative size of the response of inflation and real interest rates pins down $\kappa\zeta\sigma$ given our assumptions about the Euler equation and the Phillips curve. In other words, the evidence we present in section 3 identifies the parameter combination $\kappa\zeta\sigma$ in the structural model we present in section 4. The evidence we present does not allow us to separately identify σ, κ, and ζ.[20] Notice furthermore, that this result holds for any monetary policy rule that can produce the response of real interest rates we observe in the data.

Equation (23) shows clearly that irrespective of the values of the parameters of the model, inflation should fall more in the short run than in the long run in response to a positive shock to real interest rates. Figure 1 shows the generic response of inflation and nominal and real interest rates to a monetary shock in our model. The model implies that inflation should jump down on

[19] The extra term arises because the long-run Phillips curve in our model is not completely vertical (because of discounting). For this reason, a monetary shock can have a (small) permanent effect on output if it has a permanent effect on inflation. Specifically, the Phillips curve implies that $E_t y_{\infty} = (1-\beta)E_t \pi_{\infty}/(\kappa\zeta)$, where $\hat{y}_{\infty}$ denotes the long-run response of output to a monetary shock. This implies that solving forward the Euler equation yields $\hat{y}_t = -\sigma \hat{r}^{\ell}_t + E_t \hat{y}_{\infty}$. Plugging this into equation (21) yields equation (23).

[20] We would need evidence on the response of output to the monetary shocks we identify to be able to identify σ. Distinguishing between κ and ζ is not possible using macro data given the setup we assumed in section 4.

impact and then converge back to the long-run response of inflation as the shock to real interest rates dies out. The figure is drawn for particular values of the structural parameters. The autoregressive parameters ρ_1 and ρ_2 are chosen to roughly match the change in real interest rates at the time of FOMC announcements in the data. The value of $\kappa\zeta\sigma$ is illustrative and we allow for a non-zero value of $\hat{\pi}_\infty$, which is also chosen in an illustrative manner.[21] However, the general shape of the inflation response—initial drop and then increase back to long-run response—is the same irrespective of the values of these parameters.

Figure 2 presents our estimated response of inflation and nominal and real interest rates in the form of a figure for ease of comparison with the results from the model. In sharp contrast with the predictions of the model, the inflation response we estimate in the data is small initially but builds over time. In fact, our point estimate suggest a small "price puzzle"—positive response of inflation to an increase in real interest rates—in the short run, although this is statistically insignificant.

In the model presented above, inflation is purely forward looking. This is evident from equation (21). The response we estimate in the data suggests, however, that inflation in the real world responds to shocks in a sluggish manner. To be able to capture the inflation inertia we estimate in the data, we augment the model discussed above by allowing inflation to be influenced by past inflation in addition to future output gaps:

$$\hat{\pi}_t = \gamma\hat{\pi}_{t-1} + \kappa\zeta\sum_{j=0}^{\infty}\beta^j E_t\hat{y}_{t+j}. \tag{24}$$

Phillips curves of this form have been widely used in the recent literature (see, e.g., Woodford, 2003; Christiano et al., 2005). We will refer to this Phillips curve as the hybrid Phillips curve.

With this additional feature, our model is able to match the responses of inflation and nominal and real interest rates that we estimate in the data. A good fit requires a value of γ close to one. We set $\gamma = 0.999$. We also set the subjective discount factor $\beta = 0.99$ and the endogenous feedback term in the monetary policy rule to $\phi_\pi = 0.5$. We then estimate the remaining parameters—the composite parameter $\kappa\zeta\sigma$ as well as ρ_1 and ρ_2—by indirect inference (our estimate approach may also be described as simulated method of moments). The moments we use in our estimation are the responses of 1, 2, 3, 5, and 10-year nominal yields, 2, 3, 5, and 10-year real yields, and the 2, 3, 5, and 10-year instantaneous nominal and real forward rates to our policy news shock. We minimize a simple sum of the squared deviations of the moments in the data and the model. So as not to

[21]To allow for a non-zero value of $\hat{\pi}_\infty$ we add a second permanent component to the monetary policy rule.

have to estimate the size of the shock, we scale the responses from the model in such a way that they perfectly match the 3Y real forward rate. We construct standard errors by bootstrapping. Our bootstrap procedure is to re-sample the data with replacement, estimate the empirical moments using the Rigobon method on the re-sampled data, and then estimate the structural parameters using a loss function based on the estimated empirical moments for the re-sampled data. We repeat this procedure 1000 times.

Figure 3 presents the response of inflation and nominal and real interest rates for our estimated model with a hybrid Phillips curve. In this case, the inflation response builds over time before starting to gradually dissipate as in the data. Table 6 presents our estimates of the structural parameters (Panel A). The autoregressive roots from equation (19) are estimated to be 0.92 and 0.44. These parameter values generate the hump-shaped response of real interest rates that we see in the data. The composite parameter $\kappa\zeta\sigma$ is estimated to be 1.2x10^{-4} with a 95% confidence interval of $[1\text{x}10^{-6}, 1.9\text{x}10^{-3}]$. Panel C of Table 6 presents the fit of the model to the moments we use in the estimation.

Larger values for $\kappa\zeta\sigma$ imply a larger response of inflation and thus a larger difference between the response of nominal interest rates and real interest rates. Figure 4 illustrates this by plotting the impulse response functions of nominal and real interest rates and inflation for a case where $\kappa\zeta\sigma = 0.01$. In this case, the inflation response so large after the monetary shock that the nominal interest rate response becomes negative only a few periods after the initial shock and largely tracks inflation. Intuitively, in a model with small amounts of nominal and real rigidities, monetary policy shocks largely result in inflation and the nominal interest rate tracks the rate of inflation since monetary policy has a small effect on real interest rates relative to inflation.

5.3 Interpreting Our Estimate of $\kappa\zeta\sigma$

Our estimates for the response of interest rates to our policy news shock in Table 1 have substantial standard errors. Nevertheless, the small value of $\kappa\zeta\sigma$ that we estimate in our structural estimation (and larger but still small upper bound on the confidence interval for $\kappa\zeta\sigma$) implies that we are able to reject a large set of models—models in which either output responds strongly to real interest rates or prices respond strongly to output. To see this, it is useful to discuss what conventional values of κ, ζ, and σ are.

First, consider κ, which governs the degree of nominal rigidity in the model. A large recent literature has used micro date on the prices of individual goods to estimate the frequency with which prices change in the economy.[22] This research suggests that the appropriate value for the quarterly frequency of price change ($(1-\alpha)$ in the model presented in section 4) lies in the range $[0.2, 0.5]$. For concreteness, let's set the quarterly frequency of price change to 0.25 implying an average duration of prices of one year. This implies that $\kappa = 0.086$.

Next, consider σ—the intertemporal elasticity of substitution. Long-run evidence on balanced growth suggests a value of $\sigma = 1$. Empirical estimates of the intertemporal elasticity of substitution for non-durable consumption range from close to zero to above one (Hall, 1988; Gruber, 2006). However, our model does not explicitly incorporate investment. This implies that σ must be interpreted as capturing not only the elasticity of consumption demand with respect to the real interest rate but also the elasticity of investment demand and the demand for consumer durables. On the other hand, it may be that the short-run intertemporal elasticity is smaller than the long-run intertemporal elasticity. We therefore consider values of σ between 0.1 and 5.

Finally, consider ζ—which governs the degree of real rigidity in the model. Woodford (2003, ch. 3) argues that for New Keynesian models to generate persistent fluctuations in output and other defining features of business cycles it is crucial to incorporate a substantial amount of real rigidities into these models. Woodford explores several sources of real rigidities and, in particular, emphasizes the importance of heterogeneous factor markets. We follow Woodford (2003, ch. 3) and introduce heterogeneous labor markets in the model derived in section 4. This is the main source of real rigidities in the model as discussed in section 4. Given this setup, the parameter ζ is a function of several "deep" parameters. Specifically, $\zeta = (\omega + \sigma^{-1})/(1 + \omega\theta)$, where $\omega = (\eta^{-1} + 1 - a)/a$, and η is the Frisch elasticity of labor supply, a is the exponent on labor in the production function, and θ is the elasticity of substitution between different goods in the economy (see appendix C for details). If we assume the following values for these parameters: $\eta = 1$, $a = 2/3$, $\theta = 7$, and assume that $\sigma = 1$, we get that $\zeta = 0.14$. There are various alternative mechanisms for generating real rigidities. However, direct empirical evidence on the extent of real rigidity is hard to come by.[23]

We can now ask what values of σ and ζ are implied by our estimate of $\kappa\zeta\sigma$ given the value for

[22] See Nakamura and Steinsson (2012) and Klenow and Malin (2011) for surveys of this literature.

[23] See Gopinath and Itskhoki (2010) and Nakamura and Steinsson (2012) for recent discussions of evidence for for real rigidity.

κ we discuss above. Panel B of Table 6 shows that if $\sigma = 5$, ζ must be 0.0003 for $\kappa\zeta\sigma$ to match our estimate. Even for a value of σ as low as 0.1, ζ must be 0.016 for $\kappa\zeta\sigma$ to match our estimate. Even taking into account sampling error—i.e., using a value for $\kappa\zeta\sigma$ equal to the upper bound of our 95% confidence interval—only raises ζ to 0.045, which is still below the value implied by our model in section 4 as calibrated above. This discussion makes clear that the combinations of values for σ and ζ that are needed to match our empirical estimate of $\kappa\zeta\sigma$ imply that the response of output to real interest rates must be quite small—i.e., σ must be quite small—or the response of prices to output must be quite small—i.e., ζ must be quite small—or both.

Given that conventional parameter values for the heterogeneous labor markets model discussed above generate a larger value of $\kappa\zeta\sigma$ than we estimate, we next consider a richer model that allows for additional sources of real rigidities. In particular, we consider the model developed in Christiano, Eichenbaum, and Evans (2005, henchforth CEE) and Altig et al. (2011 henchforth ACEL). This model incorporates investment and capital accumulation and it incorporates factor market rigidity in the form of sticky wages, investment adjustment costs and firm specific capital.

We replace the monetary policy rule in the CEE/ACEL model with our monetary policy rule and consider the response of the model to our estimated monetary shock. This model can match our empirical evidence quite well if we set the price and wage rigidity parameters to 0.9 (implying the prices and wages change once every 10 quarters on average) and the elasticity of investment with respect to a temporary increase in the price of installed capital to 1/25.[24] Figure 5 illustrates this by plotting the response of the nominal and real interest rates and inflation to our monetary policy shock. The estimates in ACEL imply prices changing every 9.4 quarters and wages every 4.5 quarters. ACEL estimate a value of 0.66 for the elasticity of investment with respect to a temporary increase in the price of installed capital.[25]

If we instead use the estimated values of all the structural parameters from CEE, the response of inflation to the monetary shock is too large. Figure 6 plots the response of the nominal and real interest rates and inflation to our monetary policy shock in the CEE/ACEL model with CEE's original parameter values. We therefore conclude that our empirical evidence points to a smaller elasticity of investment with respect to movements in the real interest rate and a somewhat larger amount of real

[24]We set all other parameters equal to the values estimated in CEE.

[25]ACEL's estimate implies that a 1% permanent increase in the price of installed capital leads to a 66% change in investment, while our calibrated value implies that such a change in the price of installed capital leads to a 4% increase in investment.

rigidities than CEE and ACEL estimate. For relatively transitory shocks to monetary policy such as those analyzed in CEE, our calibration of the CEE/ACEL model yields a somewhat smaller effect of monetary shocks on output than the parameter values estimated in CEE. The greater nominal and real rigidities amplify the effects of monetary shocks, while the lower investment elasticity reduce these effects. For our much more persistent monetary shock, our alternative parameterization yields a somewhat larger effect of monetary shocks on output.

6 Conclusion

In this paper, we follow in the tradition of work by Christiano, Eichenbaum, and Evans (2005) and others who attempt to fit structural models of monetary policy to evidence on the response of real variables to monetary shocks. We focus on the effects of a "policy news shock" that we construct as a summary measure of the Fed's impact on nominal interest rates over the year following an FOMC announcement. By construction, this variable has strong predictive power for movements in nominal interest rates. However, we document that it also has strong predictive power for movements in real interest reates. In fact, real interest rates move close to one-for-one with nominal rates in response to a policy news shock at horizons out to 3 years. Despite large movements in real interest rates, the response of inflation is small.

We show that the sluggish response of prices to movements in real interest rates associated with monetary shocks provides a great deal of information about the degree of monetary non-neutrality in business cycle models. The two key parameters in determining the response of inflation to movements in real interest rates associated with monetary shocks are: 1) the responsiveness of output to movements in the real interest rate, as determined by the intertemporal elasticity of substitution and in the elasticity of investment to real interest rate movements and 2) the responsiveness of inflation to output, as determined by the magnitude of nominal and real rigidities.

We develop a method-of-moments estimation approach to assess the implications of the empirical evidence we document for the structural parameters of a workhorse monetary model. Despite the short time-period over which real interest rate data are available, and the resulting large standard errors on the interest rate responses, our analysis yields strong conclusions about the parameters of our model. We find that matching our evidence on the response of inflation to real interest rate movements requires a small elasticity of output with respect to the real interest rate, a large amount of nominal and real rigidities, or both.

Our estimates thus provide strong support for the mechanisms generating large real rigidities that have been analyzed in the monetary economics literature. We explicitly investigate the ability of two such models of real rigidities—heterogeneous factor markets, and wage rigidities—to explain our empirical results. We find that these models can match the responses we observe in the data, albeit with a somewhat higher degree of real rigidity and a lower responsiveness of output to the real interest rate than is typically assumed in the existing literature. We also find strong support for mechanisms generating inflation inertial. In the data, we find that the inflation response to a monetary shock is initially small and grows over time. However, the bare bones New Keynesian Phillips curve predicts exactly the opposite: a large immediate inflation response to a monetary shock, which dies out over time.

Business cycle models with modest price adjustment frictions generate radically different predictions from our baseline estimates. In such models, the response of inflation to our monetary shocks is large. The response of nominal interest rates largely track the response of inflation. This implies that nominal rates fall after a deflationary monetary shock. Nominal and real interest rates, thus, move in opposite directions—in contrast to the nearly one-for-one movements that we observe in the data.

A Construction of the Policy New Shock

The policy news shock is constructed as the first principle component of the change in five interest rates. The first of these is the change in market expectations of the Federal Funds Rate over the remainder of the month in which the FOMC meeting occurs. To construct this variable from the change in the price of the current month's Federal Funds Rate futures contract, we must adjust for the fact that a part of the month has already elapsed when the FOMC meeting occurs. Suppose the month in question has m_0 days and the FOMC meeting occurs on day d_0. Let $f^1_{t-\Delta t}$ denote the price of the current month's Federal Funds Rate futures contract immediately before the FOMC announcement and f^1_t the price of this contract immediately following the FOMC announcement. Let r_0 denote the average Federal Funds Rate during the month up until the point of the FOMC announcement and r_1 the average Federal Funds Rate for the remainder of the month. Then

$$f^1_{t-\Delta t} = \frac{d_0}{m_0} r_{-1} + \frac{m_0 - d_0}{m_0} E_{t-\Delta t} r_0,$$
$$f^1_t = \frac{d_0}{m_0} r_{-1} + \frac{m_0 - d_0}{m_0} E_t r_0.$$

As a result

$$E_t r_0 - E_{t-\Delta t} r_0 = \frac{m_0}{m_0 - d_0}(f^1_t - f^1_{t-\Delta t}).$$

When the FOMC meeting occurs on a day when there are 7 days or less remaining in a month, we instead use the change in the price of next month's Fed Funds Futures contract. This avoids multiplying $f^1_t - f^1_{t-\Delta t}$ by a very large factor.

The second variable used in constructing the policy news shock is the change in the expected Federal Funds Rate at the time of the next scheduled FOMC meeting. Similar issues arise in constructing this variable as with the variable described above. Let m_1 denote the number of days in the month in which the next scheduled FOMC meeting occurs and let d_1 denote the day of the meeting. The next scheduled FOMC meeting may occur in the next month or as late as 3 months after the current meeting. Let $f^n_{t-\Delta t}$ denote the price of the Federal Funds Rate futures contract for the month of the next scheduled FOMC meeting immediately before the FOMC announcement and f^n_t the price of this contract immediately following the FOMC announcement. Let r_1 denote the Federal Funds Rate after then next scheduled FOMC meeting. Analogous calculations to what we present above yield

$$E_t r_1 - E_{t-\Delta t} r_1 = \frac{m_1}{m_1 - d_1}\left[(f^n_t - f^n_{t-\Delta t}) - \frac{d_1}{m_1}(E_t r_0 - E_{t-\Delta t} r_0)\right].$$

As with the first variable, if the next scheduled FOMC meeting occurs on a on a day when there are 7 days or less remaining in a month, we instead use the change in the price of next month's Fed Funds Futures contract.

The last three variables used are simply the change in the price of the Eurodollar futures at the time of the FOMC announcements.

B Derivation of Our Heteroskedasticity-Based Estimator

Let Ω_{Ri} denote the variance-covariance matrix of $[\Delta i_t, \Delta s_t]$ in regime Ri. Then Ω_{Ri} is given by

$$\Omega_{Ri} = \begin{bmatrix} \sigma^2_{\epsilon,Ri} + \sum_j \beta^2_{i,j}\sigma^2_{\eta,j} & \gamma\sigma^2_{\epsilon,Ri} + \sum_j \beta_{i,j}\beta_{s,j}\sigma^2_{\eta,j} \\ \gamma\sigma^2_{\epsilon,Ri} + \sum_j \beta_{i,j}\beta_{s,j}\sigma^2_{\eta,j} & \gamma^2\sigma^2_{\epsilon,Ri} + \sum_j \beta^2_{s,j}\sigma^2_{\eta,j} \end{bmatrix},$$

where j indexes the elements of η_t. Notice that

$$\Delta\Omega = \Omega_{R1} - \Omega_{R2} = (\sigma^2_{\epsilon,R1} - \sigma^2_{\epsilon,R2}) \begin{bmatrix} 1 & \gamma \\ \gamma & \gamma^2 \end{bmatrix}.$$

Thus,

$$\gamma = \frac{\Delta\Omega_{12}}{\Delta\Omega_{11}} = \frac{\mathrm{cov}_{R1}(\Delta i_t, \Delta s_t) - \mathrm{cov}_{R2}(\Delta i_t, \Delta s_t)}{\mathrm{var}_{R1}(\Delta i_t, \Delta s_t) - \mathrm{var}_{R2}(\Delta i_t, \Delta s_t)}.$$

C A Log-Linear Approximation of Private Sector Behavior

We seek a log-linear approximation of the equation describing private sector behavior around a zero-growth, zero-inflation steady state. We start by deriving a log-linear approximation for the consumption Euler equation that related consumption growth and a one-period, riskless, nominal bond. This equation takes the form $E_t[M_{t,t+1}(1+i_t)] = 1$, where i_t denotes the yield on a one-period, riskless, nominal bond. Using equation (7) to plug in for $M_{t,t+1}$ and rearranging terms yields

$$E_t\left[\beta U_c(C_{t+1}, \xi_{t+1})\frac{P_t}{P_{t+1}}\right] = \frac{U_c(C_t, \xi_t)}{1+i_t}. \tag{25}$$

The zero-growth, zero-inflation steady state of this equation is $\beta(1+\bar{\imath})$. A first order Taylor series approximation of equation (25) is

$$\hat{c}_t = E_t\hat{c}_{t+1} - \sigma(\hat{\imath}_t - E_t\hat{\pi}_{t+1}) - \sigma E_t\Delta\hat{\xi}_{ct+1}, \tag{26}$$

where $\hat{c}_t = (C_t - C)/C$, $\hat{\pi}_t = \pi_t - 1$, $\hat{\imath}_t = (1 + i_t - 1 - \bar{\imath})/(1+\bar{\imath})$, and $\hat{\xi}_{ct} = (U_{cc}/U_c)(\xi_t - 1)$. The parameter $\sigma = -U_c/(U_{cc}C)$ denotes the intertemporal elasticity of substitution of households.

We next log-linearize labor demand, labor supply, and the production function and combine these equations to get an expression for the marginal costs in period $t+j$ of a firm that last changed its price in period t. Let $\ell_{t,t+j}(x)$ denote the percent deviation from steady state in period $t+j$ of hours worked for workers in industry x that last was able to change prices in period t. Let other industry level variables be defined analogously. We assume that $f(L_t(x)) = L_t^a(x)$.

A log-linear approximation of labor demand—equation (14)—in period $t+j$ for industry x that was last able to change its prices in period t is then

$$\hat{w}_{t,t+j}(x) = \hat{a}_{t+j} - (1-a)\hat{\ell}_{t,t+j}(x) + \hat{s}_{t,t+j}(x), \tag{27}$$

where $\hat{w}_{t,t+j}(x)$ and $\hat{s}_{t,t+j}(x)$ denote the percentage deviation of real wages and real marginal costs, respectively, from their steady state values.

A log-linear approximation of labor supply—equation (8) —in period $t+j$ for industry x that was last able to change its prices in period t is

$$\hat{w}_{t,t+j}(x) = \eta^{-1}\hat{\ell}_{t,t+j}(x) + \sigma^{-1}\hat{c}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j}, \tag{28}$$

where $\hat{\xi}_{\ell,t+j} = (V_{\ell\xi}/V_\ell)(\xi_t - 1)$. The parameter $\eta = V_\ell/(V_{\ell\ell}L)$ is the Frisch elasticity of labor supply.

A log-linear approximation of the production function—equation (11)—in period $t+j$ for industry x that was last able to change its prices in period t is

$$\hat{y}_{t,t+j}(x) = \hat{a}_{t+j} + a\hat{\ell}_{t,t+j}(x). \tag{29}$$

Combining labor demand and labor supply—equations (27) and (28)—to eliminate $\hat{w}_{t,t+j}(x)$ yields

$$\hat{s}_{t,t+j}(x) = (\eta^{-1} + 1 - a)\hat{\ell}_{t,t+j}(x) + \sigma^{-1}\hat{c}_{t+j} - \hat{a}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j}.$$

Using the production function—equation (29)—to eliminate $\hat{\ell}_{t,t+j}(x)$ yields

$$\hat{s}_{t,t+j}(x) = \omega\hat{y}_{t,t+j}(x) + \sigma^{-1}\hat{c}_{t+j} - (\omega+1)\hat{a}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j}, \tag{30}$$

where $\omega = (\eta^{-1} + 1 - a)/a$.

Taking logs of consumer demand—equation (9)—in period $t+j$ for industry x what was last able to change its prices in period t yields

$$\hat{y}_{t,t+j}(z) = -\theta\hat{p}_t(x) + \theta\sum_{k=1}^{j}\hat{\pi}_{t+k} + \hat{y}_{t+j}, \tag{31}$$

where we use the fact that $Y_t = C_t$ and $y_t(x) = c_t(x)$. Plugging this equation into equation (30) and again using the fact that $Y_t = C_t$ yields

$$\hat{s}_{t,t+j}(x) = -\omega\theta\hat{p}_t(x) + \omega\theta\sum_{k=1}^{j}\hat{\pi}_{t+k} + (\omega+\sigma^{-1})\hat{y}_{t+j} - (\omega+1)\hat{a}_{t+j} + \hat{\xi}_{\ell,t+j} - \hat{\xi}_{c,t+j} \tag{32}$$

It is useful to derive the level of output that would prevail if all prices were flexible. Since our model does not have any industry specific shocks (other than the opportunity to change prices), marginal costs of all firms are the same when prices are flexible. Firm price setting in this case yields $p_t(x) = \mu S_t$, where $\mu = \theta/(\theta-1)$. This implies that all prices are equal and that $S_t/P_t = 1/\mu$. Since real marginal cost is a constant, we have $\hat{s}_t = 0$. The flexible price version of equation (**??**) is then

$$(\omega+\sigma^{-1})\hat{y}_t^n = (\omega+1)\hat{a}_t - \hat{\xi}_{\ell,t} + \hat{\xi}_{c,t}, \tag{33}$$

where we use the fact that output in all industries is the same under flexible prices and $\hat{y}_t = \hat{c}_t$ and denote the rate of output under flexible prices as y_t^n. We will refer to y_t^n as the natural rate of output.

Combining equations (32) and (33) yields

$$\hat{s}_{t,t+j}(x) = -\omega\theta\hat{p}_t(x) + \omega\theta\sum_{k=1}^{j}\hat{\pi}_{t+k} + (\omega+\sigma^{-1})(\hat{y}_{t+j} - \hat{y}_{t+j}^n) \tag{34}$$

We next log-linearize the price setting equation—equation (15). This yields:

$$\sum_{j=0}^{\infty}(\alpha\beta)^j\hat{p}_t(x) - \sum_{j=0}^{\infty}(\alpha\beta)^jE_t\hat{s}_{t,t+j}(x) - \sum_{j=1}^{\infty}(\alpha\beta)^j\sum_{k=1}^{j}E_t\hat{\pi}_{t+k} = 0.$$

Manipulation of this equation yields

$$\hat{p}_t(x) = (1-\alpha\beta)\sum_{j=0}^{\infty}(\alpha\beta)^jE_t\hat{s}_{t,t+j}(x) + \alpha\beta\sum_{j=1}^{\infty}(\alpha\beta)^jE_t\hat{\pi}_{t+j}. \tag{35}$$

Using equation (34) to eliminate $\hat{s}_{t,t+j}(x)$ in equation (35) and manipulating the resulting equation yields

$$\hat{p}_t(x) = (1-\alpha\beta)\zeta\sum_{j=0}^{\infty}(\alpha\beta)^jE_t(\hat{y}_{t+j} - \hat{y}_{t+j}^n) + \alpha\beta\sum_{j=1}^{\infty}(\alpha\beta)^jE_t\hat{\pi}_{t+j}, \tag{36}$$

where $\zeta = (\omega+\sigma^{-1})/(1+\omega\theta)$.

Log-linearization of the expression for the price index—equation (10)—yields

$$\hat{\pi}_t = \frac{1-\alpha}{\alpha}\hat{p}_t(x). \tag{37}$$

Using this last equation to replace $\hat{p}_t(x)$ in equation (36) yields

$$\hat{\pi}_t = \kappa\zeta \sum_{j=0}^{\infty} (\alpha\beta)^j E_t(\hat{y}_{t+j} - \hat{y}_{t+j}^n) + (1-\alpha)\beta \sum_{j=1}^{\infty} (\alpha\beta)^j E_t \hat{\pi}_{t+j},$$

where $\kappa = (1-\alpha)(1-\alpha\beta)/\alpha$. Quasi-differencing the resulting equation yields

$$\hat{\pi}_t - \alpha\beta E_t \hat{\pi}_{t+1} = \kappa\zeta(\hat{y}_t - \hat{y}_t^n) + (1-\alpha)\beta E_t \hat{\pi}_{t+1},$$

which implies

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \kappa\zeta(\hat{y}_t - \hat{y}_t^n). \tag{38}$$

Finally, we rewrite the household's Euler equation—equation (26) in terms of the output gap:

$$y_t - y_t^n = E_t(y_{t+1} - y_{t+1}^n) - \sigma(\hat{\imath}_t - E_t \hat{\pi}_{t+1} - r_t^n), \tag{39}$$

where r_t^n denotes the "natural rate of interest" as is given by

$$r_t^n = E_t \Delta\xi_{c,t+1} + \frac{1}{\sigma} E_t \Delta y_{t+1}^n. \tag{40}$$

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TABLE 1
Response of Interest Rates and Inflation to Monetary Shocks

	Policy News Shock			Fed Funds Shock		
	Nominal	Real	Inflation	Nominal	Real	Inflation
Current Fed Funds Rate	0.76			0.83		
	(0.16)			(0.09)		
3M Treasury Yield	0.53			0.39		
	(0.20)			(0.23)		
6M Treasury Yield	0.79			0.54		
	(0.16)			(0.16)		
1Y Treasury Yield	0.98			0.43		
	(0.24)			(0.20)		
2Y Treasury Yield	0.86	0.85	0.01	0.50	0.53	-0.03
	(0.35)	(0.26)	(0.18)	(0.52)	(0.35)	(0.24)
3Y Treasury Yield	0.78	0.77	0.00	0.40	0.44	-0.04
	(0.38)	(0.26)	(0.18)	(0.55)	(0.33)	(0.27)
5Y Treasury Yield	0.65	0.66	-0.01	0.09	0.17	-0.08
	(0.29)	(0.20)	(0.13)	(0.21)	(0.12)	(0.14)
10Y Treasury Yield	0.24	0.39	-0.15	-0.12	0.01	-0.13
	(0.23)	(0.17)	(0.10)	(0.14)	(0.10)	(0.11)
2Y Treasury Inst. Forward Rate	0.79	0.68	0.11	0.31	0.33	-0.02
	(0.45)	(0.29)	(0.23)	(0.61)	(0.38)	(0.36)
3Y Treasury Inst. Forward Rate	0.45	0.56	-0.11	0.07	0.15	-0.08
	(0.40)	(0.29)	(0.17)	(0.54)	(0.34)	(0.32)
5Y Treasury Inst. Forward Rate	0.06	0.35	-0.29	-0.24	-0.06	-0.18
	(0.24)	(0.21)	(0.10)	(0.14)	(0.12)	(0.11)
10Y Treasury Inst. Forward Rate	-0.26	0.01	-0.27	-0.36	-0.16	-0.19
	(0.21)	(0.16)	(0.12)	(0.12)	(0.10)	(0.12)

Each estimate comes from a separate "regression." The dependent variable in each regression is the one day change in the variable stated in the left-most column. The independent variable is a change in the policy new shock (first three columns) or a change in the expected federal funds rate (last three columns) over a 30 minute windor around the time of FOMC announcements. For the federal funds rate, this is the expected federal funds rate over the the remainded of the current month unless the FOMC date in question occurs when there are 7 days or less remaining in the month, in which case it is the change in the expected federal funds rate over the next month. All results are based on Rigobon's (2003) method of identification by heteroskedasticity. The sample period is Jan 1st 2000 to Jan 25th 2012, except that we drop the second half of 2008 and the first half of 2009. The "treatment" sample is all regularly scheduled FOMC meeting days. The "control" sample is all Tuesdays and Wednesdays that are not FOMC meeting days and excluding a 10 day period after 9/11/2001. For 2Y and 3Y yields and real forwards, the sample starts in 2004. The sample size of the treatment sample for the 2Y and 3Y yields and forwards is 57. The sample size of the treatment sample for all other regressions is 89. Standard errors are calculated using a non-parametric bootstrap with 5000 iterations.

TABLE 2

Comparison with Alternative Methodologies

	30-Minute Window Rigobon Policy New Shock		One-Day Window Rigobon Policy New Shock		One-Day Window OLS Policy New Shock		One-Day Window Rigobon 2Y Nominal Yield	
	Nominal	Real	Nominal	Real	Nominal	Real	Nominal	Real
2Y Treasury Yield	0.86	0.85	1.00	0.84	1.16	0.98	1.00	0.71
	(0.35)	(0.26)	(3.86)	(39.95)	(0.16)	(0.15)	--	(2.21)
3Y Treasury Yield	0.78	0.77	0.91	0.79	1.12	0.95	0.97	0.73
	(0.38)	(0.26)	(2.11)	(5.95)	(0.18)	(0.16)	(1.41)	(3.51)
5Y Treasury Yield	0.65	0.66	0.39	0.52	0.81	0.67	0.64	0.65
	(0.29)	(0.20)	(2.48)	(0.37)	(0.11)	(0.10)	(5.38)	(63.44)
10Y Treasury Yield	0.24	0.39	0.01	0.28	0.48	0.45	0.14	0.38
	(0.23)	(0.17)	(16.81)	(0.34)	(0.11)	(0.11)	(8.68)	(41.32)

Each estimate comes from a separate "regression." The dependent variable in each regression is the one day change in the variable stated in the left-most column. The independent variable is a change in the policy news shock over a 30-minute window around FOMC announcements (first two columns) or a change in the policy news shock over a one-day window around FOMC announcements (middle four columns) or a change in the 2-Year nominal yield over the one-day window around FOMC announcements (last two columns). Results in columns 1-4 and 7-8 are based on Rigobon's (2003) method of identification by heteroskedasticity, while results in columns 5-6 are based on OLS. The sample period is Jan 1st 2000 to Jan 25th 2012, except that we drop the second half of 2008 and the first half of 2009. The "treatment" sample for the Rigobon method is all regularly scheduled FOMC meeting days. The "control" sample is all Tuesdays and Wednesdays that are not FOMC meeting days and excluding a 10 day period after 9/11/2001. For 2Y and 3Y yields and real forwards, the sample starts in 2004. The sample size of the treatment sample for the 2Y and 3Y yields and forwards is 57. The sample size of the treatment sample for all other regressions is 89. Standard errors for the Rigobon method are calculated using a non-parametric bootstrap with 5000 iterations.

TABLE 3

Effects of Monetary Shocks on Survey Expectations

	Nominal	Real	Inflation
1 quarter	1.14**	1.34**	-0.20
	(0.58)	(0.60)	(0.30)
2 quarters	1.17**	1.53***	-0.36
	(0.59)	(0.58)	(0.27)
3 quarters	1.00	1.17**	-0.17
	(0.61)	(0.59)	(0.25)
4 quarters	0.84	0.98*	-0.14
	(0.59)	(0.57)	(0.24)
5 quarters	0.77	0.55	0.22
	(0.81)	(0.81)	(0.30)
6 quarters	1.86**	1.52*	0.34
	(0.78)	(0.82)	(0.34)
7 quarters	4.45***	4.04***	0.41
	(1.38)	(1.44)	(0.58)

This table presents the results of regressing changes in survey expectations from the *Blue Chip Economic Indicators* on the policy news shock. Since the *Blue Chip* survey expectations are available at a monthly frequency, we construct a corresponding monthly measure of our policy news shock. In particular, we calculate the sum of the policy news shocks that occur over the month except for those that occur in the first week (because we do not know whether these occurred before or after the survey response). The dependent variable is the change in the forecasted value of a variable N quarters ahead, between this month's survey and last month's survey. We consider the effects on expected future 3-month T-Bill rates, short-term real interest rates and inflation, where the inflation rate is the GDP deflator and the short-term real interest rate is calculated as the difference between the expected 3-month T-bill rate and the expected GDP deflator for a given quarter. The sample period is January 1995 to January 2012, except that we exclude the second half of 2008 and the first half of 2009.

TABLE 4

Breakeven Inflation versus Inflation Swaps

	Breakeven	Swaps
Inflation Over Next 2 Years	0.01	0.24
	(0.19)	(0.32)
Inflation Over Next 3 Years	0.00	0.31
	(0.18)	(0.30)
Inflation Over Next 5 Years	-0.01	-0.04
	(0.16)	(0.17)
Inflation Over Next 10 Years	-0.15	-0.18
	(0.14)	(0.16)

Each estimate comes from a separate "regression." The dependent variable in each regression is the one day change in expected inflation measured either by breakeven inflation from the difference between nominal Treasuries and TIPS (first column) or from inflation swaps (second column) for the period stated in the left-most column. The independent variable is a change in the policy new shock over a 30 minute window around the time of FOMC announcements. All results are based on Rigobon's (2003) method of identification by heteroskedasticity. The sample period is Jan 1st 2005 to Jan 25th 2012, except that we drop the second half of 2008 and the first half of 2009. The "treatment" sample is all regularly scheduled FOMC meeting days. The "control" sample is all Tuesdays and Wednesdays that are not FOMC meeting days. The sample size of the treatment sample is 49. Standard errors are calculated using a non-parametric bootstrap with 5000 iterations.

TABLE 5

Mean Reversion

Horizon	Nominal Yields			Real Yields		
(Trading Days)	2-Year	3-Year	5-Year	2-Year	3-Year	5-Year
1	1.29	1.18	0.97	1.34	1.28	0.91
	(0.17)	(0.18)	(0.17)	(0.26)	(0.24)	(0.13)
5	1.24	1.07	0.84	1.00	0.88	0.78
	(0.30)	(0.30)	(0.30)	(0.47)	(0.42)	(0.24)
10	1.15	0.99	0.81	0.90	0.79	0.63
	(0.41)	(0.42)	(0.41)	(0.67)	(0.58)	(0.32)
20	1.20	1.00	0.76	1.72	1.37	1.04
	(0.57)	(0.58)	(0.57)	(0.98)	(0.83)	(0.45)
60	1.59	1.14	0.62	1.53	1.20	0.30
	(1.02)	(1.00)	(0.94)	(1.79)	(1.46)	(0.73)
125	4.67	3.75	2.46	6.47	5.44	2.35
	(1.57)	(1.46)	(1.31)	(2.56)	(2.10)	(1.02)
250	6.07	4.92	3.35	8.64	7.11	3.02
	(2.62)	(2.27)	(1.79)	(3.33)	(2.83)	(1.36)

This table presents the results of regressing the cumulative change in yields between the day before the FOMC announcement and 1, 5, 10, 20, 60, 125 and 250 trading days after the announcement on the policy news shock in the 30 minute interval surrounding the FOMC announcement. The first three columns present results for nominal zero coupon yields, and the next three columns present results for real zero coupon yields. Standard errors are in parentheses.

TABLE 6
Estimates of Structural Parameters

Panel A: Parameter Estimates

$\kappa\zeta\sigma$	0.00014 [0.000001, 0.00192]
ρ_1	0.922 [0.837, 0.972]
ρ_2	0.440 [0.024, 0.836]

Panel B: Possible Breakdown of $\kappa\zeta\sigma$

	ζ	σ	κ
Calibration I:	0.016311	0.1	0.086
Calibration II:	0.003262	0.5	0.086
Calibration III:	0.001631	1.0	0.086
Calibration IV:	0.000326	5.0	0.086

Panel C: Model Fit

	Data			Model		
	Nominal	Real	Inflation	Nominal	Real	Inflation
3M Treasury Yield	0.66			0.92		
6M Treasury Yield	0.99			1.08		
1Y Treasury Yield	1.22			1.18		
2Y Treasury Yield	1.07	1.05	0.02	1.10	1.19	-0.09
3Y Treasury Yield	0.97	0.96	0.01	0.95	1.06	-0.11
5Y Treasury Yield	0.81	0.83	-0.02	0.70	0.82	-0.12
10Y Treasury Yield	0.30	0.49	-0.19	0.35	0.47	-0.12
2Y Treasury Inst. Forward Rate	0.98	0.85	0.13	0.87	0.99	-0.12
3Y Treasury Inst. Forward Rate	0.56	0.69	-0.13	0.55	0.69	-0.14
5Y Treasury Inst. Forward Rate	0.07	0.44	-0.37	0.18	0.32	-0.14
10Y Treasury Inst. Forward Rate	-0.32	0.02	-0.34	-0.06	0.03	-0.09

TABLE A1

Response of Interest Rates to Monetary Shocks for Different Sample Periods

	Baseline Sample		Pre-Crisis (2000-2007)		Full Sample	
	Nominal	Real	Nominal	Real	Nominal	Real
Current Fed Funds Rate	0.76		0.66		0.84	
	(0.16)		(0.18)		(0.15)	
3M Treasury Yield	0.53		0.71		0.46	
	(0.20)		(0.18)		(0.27)	
6M Treasury Yield	0.79		0.83		0.76	
	(0.16)		(0.18)		(0.24)	
1Y Treasury Yield	0.98		0.97		0.99	
	(0.24)		(0.26)		(0.29)	
2Y Treasury Yield	0.86	0.85	0.79	0.79	0.95	1.43
	(0.35)	(0.26)	(0.43)	(0.33)	(0.36)	(0.38)
3Y Treasury Yield	0.78	0.77	0.72	0.73	0.95	1.21
	(0.38)	(0.26)	(0.44)	(0.34)	(0.35)	(0.32)
5Y Treasury Yield	0.65	0.66	0.66	0.67	0.89	1.04
	(0.29)	(0.20)	(0.30)	(0.21)	(0.28)	(0.23)
10Y Treasury Yield	0.24	0.39	0.32	0.48	0.56	0.74
	(0.23)	(0.17)	(0.26)	(0.19)	(0.27)	(0.22)
2Y Treasury Inst. Forward Rate	0.79	0.68	0.74	0.66	1.01	0.74
	(0.45)	(0.29)	(0.52)	(0.36)	(0.41)	(0.32)
3Y Treasury Inst. Forward Rate	0.45	0.56	0.41	0.55	0.85	0.81
	(0.40)	(0.29)	(0.46)	(0.35)	(0.40)	(0.35)
5Y Treasury Inst. Forward Rate	0.06	0.35	0.13	0.48	0.51	0.78
	(0.24)	(0.21)	(0.26)	(0.22)	(0.35)	(0.30)
10Y Treasury Inst. Forward Rate	-0.26	0.01	-0.09	0.22	0.04	0.16
	(0.21)	(0.16)	(0.22)	(0.17)	(0.32)	(0.19)

Each estimate comes from a separate "regression." The dependent variable in each regression is the one day change in the variable stated in the left-most column. The independent variable is a change in the policy news shock over a 30 minute windor around the time of FOMC announcements. All results are based on the Rigobon's (2003) method of identification by heteroskedasticity. The "treatment" sample is all regularly scheduled FOMC meeting days. The "control" sample is all Tuesdays and Wednesdays that are not FOMC meeting days and excluding a 10 day period after 9/11/2001. The baseline sample period is Jan 1st 2000 to Jan 25th 2012, except that we drop the second half of 2008 and the first half of 2009. The "Full Sample" is Jan 1st 2000 to Jan 25th 2012. The "Pre-Crisis" sample is 2000-2007. For 2Y and 3Y yields and real forwards, the sample starts in 2004. Standard errors are calculated using a non-parametric bootstrap with 5000 iterations.

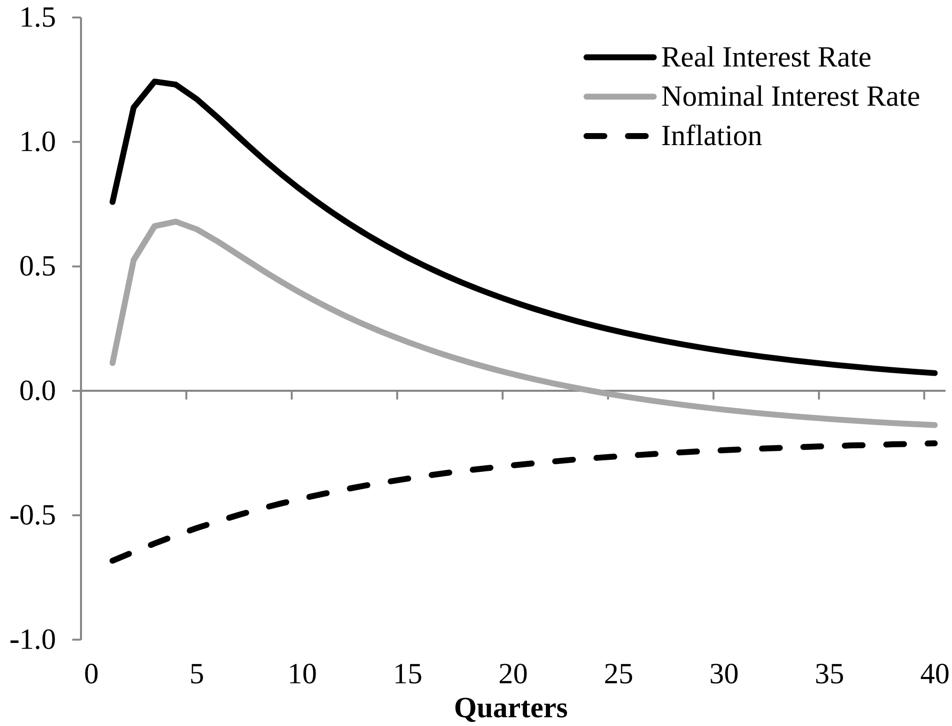

Figure 1: Interest Rate and Inflation in the Simple New Keynesian Model

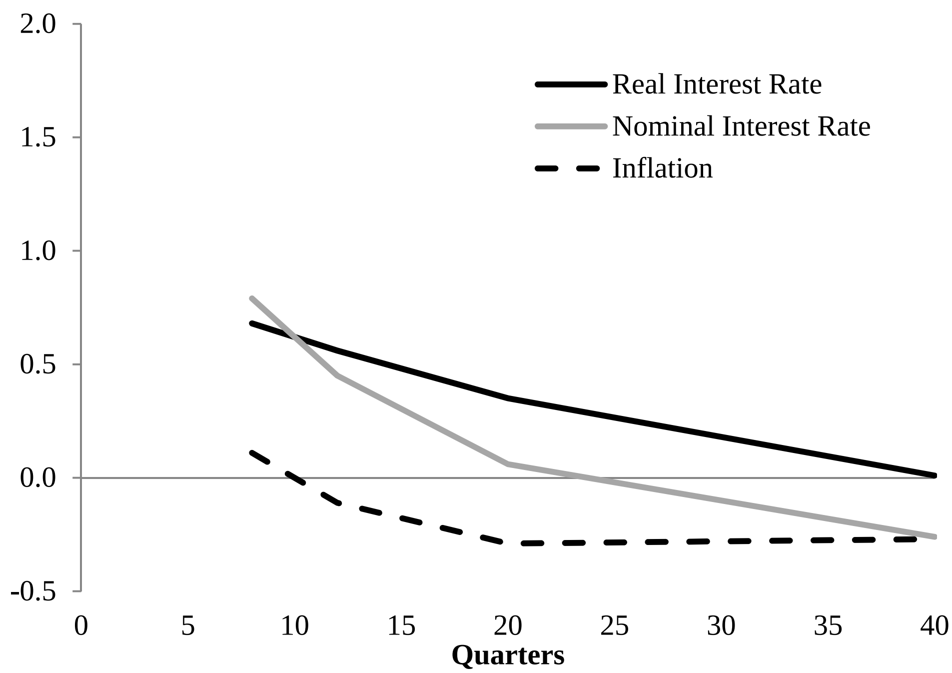

Figure 2: Interest Rates and Inflation in the Data

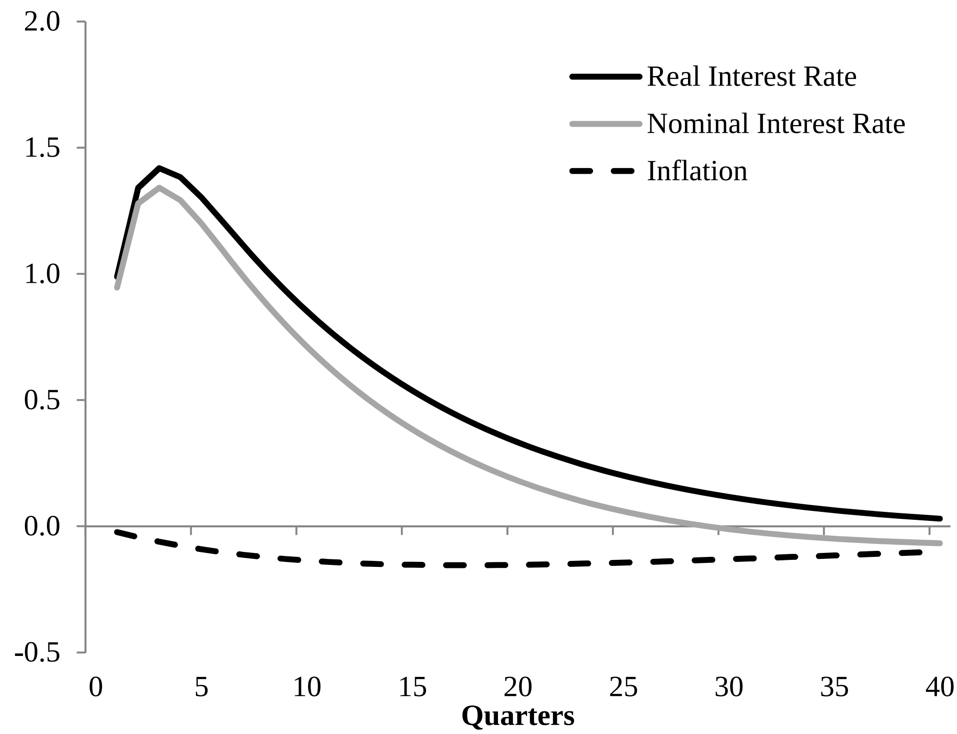

Figure 3: Response of Inflation and Interest Rates in Model with Hybrid Phillips Curve

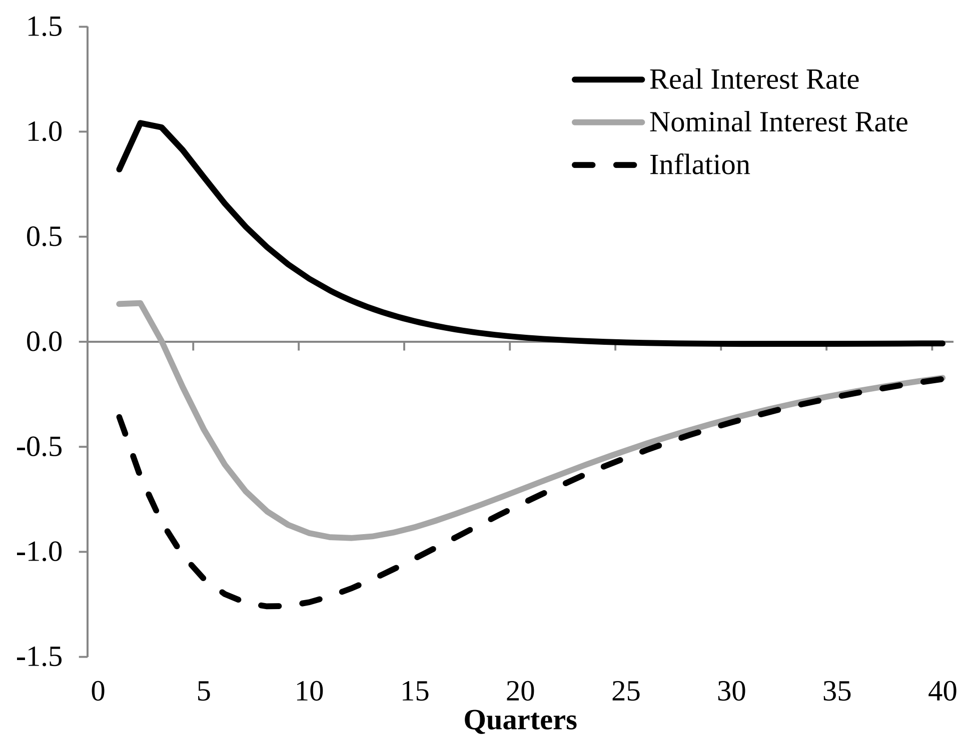

Figure 4: Response of Inflation and Interest Rates in Model with Hybrid Phillips Curve with Counter-Factually Large $\kappa\zeta\sigma$

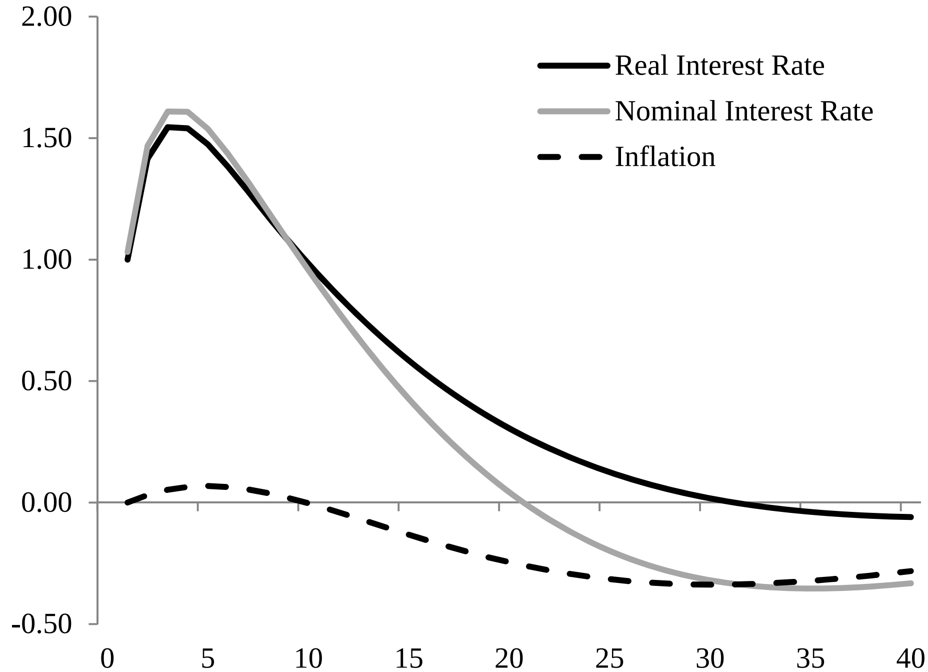

Figure 5: Response of Inflation and Interest Rates in the CEE/ACEL Model Recalibrated

Note: We replace the monetary policy rule in the CEE/ACEL model with our monetary rule and shock the model with our monetary policy shock. We also recalibrate three parameters. We set the frequency of price change and wage change such that prices and wages change on average once every 10 quarters and we set the elasticity of investment to the price of capital to 1/25.

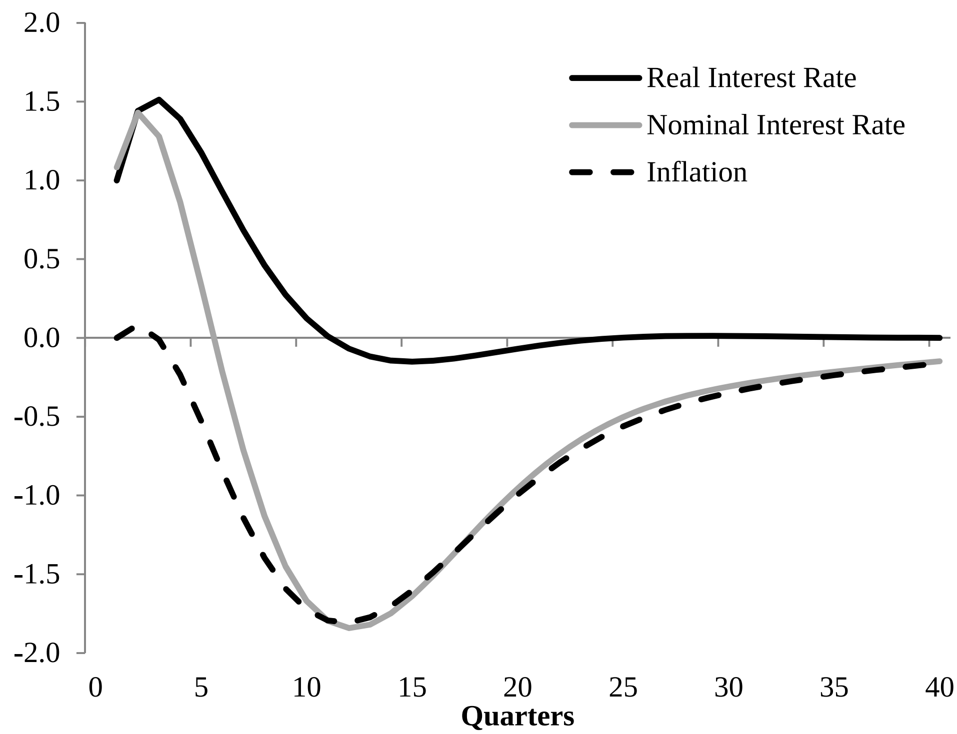

Figure 6: Response of Inflation and Interest Rates in the CEE/ACEL Model

Note: We replace the monetary policy rule in the CEE/ACEL model with our monetary rule and shock the model with our monetary policy shock. Otherwise, we use the parameters estimated by CEE.