What does Monetary Policy do to Long-Term Interest Rates at the Zero Lower Bound?

Jonathan H. Wright*

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Abstract

The federal funds rate has been stuck at the zero bound for over three years and the Fed has turned to unconventional monetary policies, such as large scale asset purchases to provide stimulus to the economy. This paper uses a structural VAR with daily data to identify the effects of monetary policy shocks on various longer-term interest rates during this period. The VAR is identified using the assumption that monetary policy shocks are heteroskedastic: monetary policy shocks have especially high variance on days of FOMC meetings and certain speeches, while there is nothing unusual about these days from the perspective of any other shocks to the economy. A complementary high-frequency event-study approach is also used. I find that stimulative monetary policy shocks lower Treasury and corporate bond yields, but the effects die off fairly fast, with an estimated half-life of about two months.
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*Department of Economics, Johns Hopkins University, Baltimore MD 21218; wrightj@jhu.edu.
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1 Introduction

During the recent financial crisis, the Federal Reserve sharply lowered the target for the federal funds rate. In December 2008, the federal funds rate was set to the zero lower bound (more precisely in a target range from zero to 25 basis points), and has remained there since then. With monetary policy stuck at the zero bound, the Federal Open Market Committee (FOMC) began using other, less conventional, ways to further stimulate aggregate demand. This included statements signaling that the funds rate would be kept at the zero bound for a long time, programs geared towards supporting certain critical credit markets that were frozen, such as the Commercial Paper Funding Facility and the Term Asset-Backed Securities Loan Facility. And it included providing additional stimulus to the economy by large-scale asset purchases (LSAPs) of Treasury securities and other high-grade bonds, a policy that is commonly referred to as quantitative easing. A key motivation for these purchases was to try to lower the interest rates being paid by households and businesses, so as to support consumption and investment spending. The rationale put forth by Federal Reserve officials mainly relies on a preferred habitat paradigm, as envisioned by Modigliani and Sutch (1966, 1967) and more recently by Vayanos and Vila (2009) in which markets are segmented, investors demand bonds of a specific type, and the interest rate is determined by the supply and demand of bonds of that particular type (Kohn (2009)). The LSAPs could also work in other ways, such as by affecting agents' expectations of the future course of monetary policy.

More than three years after the overnight rate hit the zero bound, there is a rapidly-growing literature on assessing the effects of the unconventional monetary policies that have been used over this period. Important contributions include Doh (2010), D'Amico and King (2010), Gagnon et al. (2010), Neely (2010), Hancock and

Passmore (2011), Krishnamurthy and Vissing-Jorgenson (2011) and Hamilton and Wu (2012). Also, Swanson (2011) reexamined Operation Twist from the 1960s using an event-study perspective, and compared it to the unconventional monetary policies presently being employed by the Federal Reserve.

Measuring the effects of monetary policy shocks in this environment however poses special challenges. In normal times, the federal funds rate measures the stance of monetary policy. But things are murkier at the zero bound. There isn't as clean a single measure of the overall stance of unconventional monetary policy. And while one could proxy the stance of monetary policy by the size of the Fed's balance sheet, with forward-looking financial markets, one would expect a policy of asset purchases to impact asset prices not at the time that the purchases are actually made, but rather at the time that investors learn that they will take place. LSAPs are announced ahead of time, in the statements that follow FOMC meetings. These statements are in turn anticipated to some extent by investors, whose expectations have been guided by speeches and other comments by FOMC members. Furthermore, whereas the federal funds futures market gives a fairly clear measure of investors' real-time expectations for changes in the target federal funds rate, there is no such measure of expectations of the size of LSAPs.

In this paper, I propose measuring the effects of monetary policy shocks during this period of unconventional monetary policy using a structural vector autoregression (VAR) in financial variables at the daily frequency, employing the methodology of Rigobon (2003) and Rigobon and Sack (2003, 2004, 2005). The idea is to identify days on which the variance of monetary policy shocks was especially high, during the period when the federal funds rate was stuck at the zero bound and unconventional approaches to monetary policy were being deployed. These are days of FOMC meetings and days with other announcements that apparently altered investors' views about the likely extent of monetary policy actions. Comparing the variance-covariance matrix of VAR innovations on these and other days enables identification of the effects of these monetary policy shocks. In principle, this goes back to the idea of measuring monetary policy shocks in a VAR of Sims (1980), Bernanke (1986) and Christiano, Eichenbaum and Evans (1996), but it does so without tying monetary policy decisions to the level of the target federal funds rates. But unlike the earlier VAR literature, identification does not depend on the standard short-run zero restrictions. Instead, this is an identification strategy using heteroskedasticity in daily-frequency data.

It should be emphasized that this approach addresses a somewhat different question from the analysis of the effects of LSAPs by Gagnon et al. (2010), Krishnamurthy and Vissing-Jorgenson (2011) and other authors. My approach here identifies policy shocks from the *total* effect of FOMC-related news on a set of asset prices during this period of unconventional monetary policy. FOMC statements could impact asset prices via LSAPs—LSAPs are surely the dominant tool of monetary policy when the economy is stuck at the zero bound. But FOMC statements could also work in other ways, such as by signaling that the federal funds rate will be kept low (over and above the signaling effect of LSAPs), or even by changing agents' beliefs about the underlying state of the economy (if they think that the Fed has some private information). The proposed methodology measures the total effects of FOMC news and cannot disentangle the effects of these different channels. Of course, the separate identification of the effects of different FOMC statements is an important question. Nonetheless, the structural VAR approach considered here brings some important advantages. It circumvents the difficulties in measuring market expectations for Fed statements—it isn't necessary to specify what the markets learned from Fed statements, it is only necessary to specify the times at which significant news came out, a much easier task. It allows for the possibility that other shocks occurred on the same days as the monetary policy shocks. And it provides an estimate of the persistence of the monetary policy shocks, which the standard event-study methodology cannot do.

Over the period since November 2008, I estimate that monetary policy shocks have a significant effect on ten-year yields and long-maturity corporate bond yields that wear off over the next few months. The effect on two-year Treasury yields is very small. The initial effect on corporate bond yields is a bit more than half as large as the effect on ten-year Treasury yields. This finding is important as it shows that the news about purchases of Treasury securities had effects that were not limited to the Treasury yield curve. That is, the monetary policy shocks not only impacted Treasury rates, but were also transmitted to private yields which have a more direct bearing on economic activity. There is slight evidence of a rotation in breakeven rates from Treasury Inflation Protected Securities (TIPS), with short-term breakevens rising and long-term forward breakevens falling.

The plan for the remainder of this paper is as follows. Section 2 discusses the methodology and the identifying assumptions. Section 3 describes the data and reports the results of the empirical work. Section 4 discusses a closely-related "event-study" approach that relates the VAR errors to monetary policy surprises measured using high-frequency intradaily data in small windows that bracket the announcement times. This alternative methodology ends up giving consistent results, but with estimates that are somewhat more precise. Section 5 concludes.

2 The Method

I assume that a px1 vector of yields, Y_t, has the reduced form VAR representation

$$A(L)Y_t = \mu + \varepsilon_t \tag{1}$$

where ε_t denote the reduced form forecast errors. I further assume that these reduced form errors can be related to a set of underlying structural shocks

$$\varepsilon_t = \Sigma_{i=1}^{p} R_i \eta_{i,t} \tag{2}$$

where $\eta_{i,t}$ is the ith structural shock, R_i is a px1 vector, and the structural shocks are independent of each other and over time. The parameters $A(L)$, μ and $\{R_i\}_{i=1}^{p}$ are all assumed to be constant.

The monetary policy shock is ordered first, but this is for notational convenience only. The ordering of variables is irrelevant as a Choleski decomposition will not be used for identification. The monetary policy shock has mean zero and variance σ_1^2 on announcement days, and variance σ_0^2 on all other days, while all other structural shocks are identically distributed with mean zero and variance 1 on all dates. The identifying assumption is that $\sigma_0^2 \neq \sigma_1^2$. Put another way, the identifying assumption is that news about monetary policy comes out in a lumpy manner, and the days on which it comes out are determined by accident of the calendar; and so the volatility of other structural shocks should be identical on these and other days. The conditional variance of the other structural shocks can vary from day to day, so long as their average variance is the same on monetary policy announcement and non-announcement days.[1] This strategy of identification through heteroskedasticity was first proposed by Rigobon (2003) and applied to asset price data by Rigobon and Sack (2003, 2004, 2005), becoming quite popular in the identification of structural VARs since then.

Let Σ_0 and Σ_1 denote the variance-covariance matrices of reduced form errors on

[1] This assumption seems mild, but as an illustration of how it could fail, note that nearly all FOMC meetings are scheduled on Tuesdays and Wednesdays and so are virtually guaranteed not to overlap with a release of the employment report (which comes out on Fridays). Of course other data releases are particularly likely to come out on FOMC meeting dates. My identifying assumption treats the overall impact of these calendar effects as negligible. The identifying assumption is moreover testable.

non-announcement and announcement days, respectively. Clearly,

$$\Sigma_1 - \Sigma_0 = R_1 R_1' \sigma_1^2 - R_1 R_1' \sigma_0^2 = R_1 R_1' (\sigma_1^2 - \sigma_0^2) \tag{3}$$

This allows R_1 to be identified. Without loss of generality, I adopt the normalization that $\sigma_1^2 - \sigma_0^2 = 1$, as $R_1 R_1'$ and $(\sigma_1^2 - \sigma_0^2)$ are not separately identified. I am seeking only to identify the effects of monetary policy shocks, not the other structural shocks in the VAR $(\eta_2, ... \eta_p)$, therefore imposing further structure on the system is not needed.

The econometric strategy is to estimate the VAR and construct the sample variance-covariance matrices of residuals on non-announcement and announcement days, respectively, $\hat{\Sigma}_0$ and $\hat{\Sigma}_1$. Then the parameters in the vector R_1 can be estimated by solving the minimum distance problem

$$\hat{R}_1 = \arg\min_{R_1} [vech(\hat{\Sigma}_1 - \hat{\Sigma}_0) - vech(R_1 R_1')]' [\hat{V}_0 + \hat{V}_1]^{-1} [vech(\hat{\Sigma}_1 - \hat{\Sigma}_0) - vech(R_1 R_1')] \tag{4}$$

where $\hat{V}_0$ and $\hat{V}_1$ are estimates of the variance-covariance matrices of $vech(\hat{\Sigma}_0)$ and $vech(\hat{\Sigma}_1)$, respectively. Estimates of the impulse responses can then be traced out.

This leaves the question of statistical inference. Use of the bootstrap may help to mitigate concerns about statistical inference in a small sample size. I do bootstrap inference in three parts. First, I want to test the hypothesis that announcement and non-announcement days are no different: that $\Sigma_0 = \Sigma_1$. I do this using the test statistic

$$[vech(\hat{\Sigma}_1 - \hat{\Sigma}_0)]' [\hat{V}_0 + \hat{V}_1]^{-1} [vech(\hat{\Sigma}_1 - \hat{\Sigma}_0)] \tag{5}$$

and comparing it to a distribution in which announcement and non-announcement days are randomly scrambled, so that the two variance-covariance matrices are equal by construction under the null in the bootstrap samples. Rejection of this null hypothesis means that the identification condition is satisfied.

Second, I want to conduct inference on the structural impulse responses, given that they are identified. As the data are persistent, I use the bias-adjusted bootstrap of Kilian (1998), except that instead of resampling from individual vectors of residuals, I use the stationary bootstrap (Politis and Romano (1994)) to resample blocks of residuals of expected length of 10 days. This means that the bootstrap should preserve some of the volatility clustering that is evident in the original data.[2] This allows confidence intervals for the impulse responses to be constructed. This bias adjustment is also applied to the point estimates.

Finally, this same bootstrap can be used to test the hypothesis that $\Sigma_1 - \Sigma_0 = R_1 R_1'$, in other words that there is a single monetary policy shock. This is done by comparing the test statistic

$$[vech(\hat{\Sigma}_1 - \hat{\Sigma}_0) - vech(\hat{R}_1 \hat{R}_1')]'[\hat{V}_0 + \hat{V}_1]^{-1}[vech(\hat{\Sigma}_1 - \hat{\Sigma}_0) - vech(\hat{R}_1 \hat{R}_1')] \tag{6}$$

to the distribution from the bias-adjusted bootstrap.[3]

3 Data and Results

In the baseline implementation of this method, I use daily data on six different interest rates from the period November 3 2008 to September 30 2011. These are the two- and ten-year nominal Treasury zero-coupon yields from the dataset of Gürkaynak, Sack and Wright (2007), the five-year TIPS breakeven[4] and the five-to-ten-year forward

[2] Simply resampling from the residuals in the usual way would however give very similar results.

[3] More precisely, if $\hat{\Sigma}_0^*$, $\hat{\Sigma}_1^*$, $\hat{R}_1^*$, $\hat{V}_0^*$ and $\hat{V}_1^*$ denote the bootstrap analogs of $\hat{\Sigma}_0$, $\hat{\Sigma}_1$, $\hat{R}_1$, $\hat{V}_0$ and $\hat{V}_1$, respectively, then the bootstrap simulates the distributions of $\xi'[\hat{V}_0^* + \hat{V}_1^*]^{-1}\xi$ where $\xi = vech(\hat{\Sigma}_1^* - \hat{\Sigma}_0^*) - vech(\hat{R}_1^* \hat{R}_1^{*\prime}) - (vech(\hat{\Sigma}_1 - \hat{\Sigma}_0) - vech(\hat{R}_1 \hat{R}_1'))$.

[4] This is the spread between a nominal and TIPS bond, also known as inflation compensation. It is influenced by expected inflation, the inflation risk premium, and the TIPS liquidity premium.

TIPS breakeven, from the dataset of Gürkaynak, Sack and Wright (2010) and the Moody's indices of BAA and AAA corporate bond yields (not spreads). A VAR was fitted to these data, with the lag length selected by minimizing the Bayes Information Criterion—this resulted in a lag length of 1.

Table 1 shows the list of 28 monetary policy announcement days. The criterion for inclusion in this list is that it be either the day of any FOMC meeting during the period in which monetary policy was stuck at the zero bound,[5] or the day of another announcement or speech by Chairman Bernanke that was seen as especially germane to the prospects for unconventional monetary policy. One might of course include days of other speeches, or releases of FOMC minutes. I did not do so, because it is important that the estimation of the variance-covariance matrix on announcement days is not contaminated with days on which there is only trivial or indirect news about unconventional monetary policy; that will only blunt the distinction between the two variance-covariance matrices that is crucial to identification.

The days listed in Table 1 span the first period of quantitative easing (QE1), during which time the Fed bought a range of assets including a large volume of mortgage backed securities, the second period of quantitative easing (QE2), which involved Treasury purchases alone, and what I refer to as the third period of quantitative easing (QE3) that included the extension of the maturity of the Fed's Treasury holdings as well as the reinvestment of maturing mortgage backed securities. Within the 28 days listed in Table 1, 13 of them are days that seem especially important—they are days around the start of the first, second and third phases of quantitative easing. These especially important announcement days are marked in bold.

[5]December 16, 2008 was included. This was the day of the FOMC meeting at which the funds rate was set at zero, but the statement also included discussion of LSAPs. The unscheduled FOMC meeting of May 9, 2010 (after which a statement related to foreign exchange swaps was released) is not included because it has no direct bearing on domestic monetary policy.

The variance-covariance matrix of reduced form errors was then estimated over the 28 announcement days, and over non-announcement days. The method described in the previous section was then used to estimate R_1, the contemporaneous effects of a monetary policy shock on yields.

The resulting impulse responses function estimates and 90 percent bootstrap confidence intervals in this baseline VAR are reported in Figure 1. The identified monetary policy shock is normalized to lower ten-year yields by 25 basis points instantaneously. The shock lowers AAA and BAA rates, by about half as much as the drop in ten-year Treasury yields. These effects tend to wear off over time fairly fast—the impulse responses on ten-year Treasuries and corporate yields are statistically significant, but only for a short time. The half-life of the estimated impulse responses for Treasury and corporate yields is two or three months. Two-year yields fall, but the effect is modest.[6] Short-term breakeven rates rise slightly, while longer-term forward breakeven rates fall, but these effects are not statistically significant. The estimates of the initial effects are mostly consistent with the evidence from event studies. For example, Krishnamurthy and Vissing-Jorgenson (2011) found that quantitative easing policies lower long-term Treasuries and the highest rated corporate bonds, and report some evidence that breakeven rates rise. They however found that quantitative easing has negligible effects on BAA rates.

Table 2 reports the results of forecast error variance decompositions, measuring what percentage of the variance of the h-step ahead forecast error owes to the structural monetary policy shocks. Results are shown for each variable at selected forecast horizons, along with 90 percent bootstrap confidence intervals.[7] The monetary policy

[6]Obviously over this period, monetary policy shocks could have no effect on the federal funds rate or other very short-term interest rates by construction. But the two-year yield was not at the zero bound (it averaged 81 basis points over the sample), and so monetary policy surprises could conceivably have had some effect on this. However, it turns out that the effect is small.

[7]Note again that the size of the monetary policy shocks is not idenfiied—it is necessary to impose

shocks that explain 10 percent of the short-horizon error variance of ten-year Treasury yields, are estimated to account for a smaller share of the forecast error variance of ten-year Treasury yields at longer horizons, and 1-4 percent of the forecast error variance of corporate yields.

The top panel of Table 3 reports the results of comparing the test statistics in equations (5) and (6) with their bootstrap p-values in this baseline VAR. The null hypothesis that the reduced form variance-covariance matrix is the same on announcement and non-announcement days is rejected. The null hypothesis that the difference between the two variance-covariance matrices can be factored in the form $R_1 R_1^{'}$ is not rejected. That indicates that the data can be well characterized by a single monetary policy shock.

The structural VAR approach measures the monetary policy shock directly from its effects on interest rates. As noted in the introduction, this has a number of advantages: expectations do not have to be measured, and dynamic effects can be traced out. However, it also has a number of limitations. In particular, it is silent on the relative contribution of different aspects of unconventional monetary policy (forward looking guidance about the federal funds rate, LSAPs etc.). Nevertheless, looking at the evidence here in conjunction with other studies that have considered the effects of asset purchases more directly, and also noting that the main effect of monetary policy shocks during the crisis is on long-term interest rates, while short-term interest rates are little changed, it seems reasonable to surmise that LSAPs represent an important component of these identified policy shocks.

a normalization to pin down $\sigma_1^2 - \sigma_0^2$. For the purpose of the forecast error variance decompositions, I normalize the monetary policy shock to explain 10 percent of the one-day forecast error variance of ten-year yields.

3.1 Robustness checks and extensions

This subsection reports the results of three types of extensions and robustness checks. First, the analysis is redone using the more stringent definition of the announcement dates (only the announcement days marked in bold in Table 1). This should make the difference between policy and non-policy dates starker, potentially helping identification. Impulse response estimates are shown in Figure 2. The results are quite similar to those in Figure 1, except that the impulse responses are a little more precisely estimated in this case.

The second robustness check is for the sample period chosen to estimate the VAR. The baseline VAR is estimated over a short sample period. A natural alternative is to consider estimating the reduced form parameters in $A(L)$ over the period since January 1999 (when the TIPS yields are first available), while continuing to estimate Σ_0 and Σ_1 on non-announcement and announcement days starting in November 2008. This gives the potential benefit of greater efficiency, although at the potential cost of having to impose the same coefficients of the VAR in the crisis and pre-crisis periods. The results of this exercise are shown in Figure 3. They are again qualitatively similar to those shown in Figure 1, but the impulse responses are a little more precisely estimated.

I also consider an alternative specification for the set of variables included in the VAR, replacing the corporate bond yields with the yield on current-coupon thirty-year Fannie Mae mortgage backed securities.[8] The results of this exercise are shown in Figure 4. The monetary policy shock that lowers ten-year Treasury yields by 25

[8]Current coupon securities are benchmark mortgage backed securities (MBS). Naturally one would be most interested in actual mortgage rates, rather than the yields on MBS, from the perspective of assessing the ability of monetary policy to support the housing market. However, mortgage rates are not available at the daily frequency, and so MBS rates are the best available substitute for use in this paper.

basis points is estimated to lower MBS rates by about 15 basis points. The effect is statistically significant for a couple of months, but the effect again wears off fairly quickly. This paper does not differentiate between the first, second and third phases of quantitative easing. However, QE1 involved heavy purchases of MBS, whereas QE2 entailed purchases of Treasuries only, while QE3 involved elements of both. It seems reasonable to surmise that if one were able separately to identify monetary policy shocks in these subperiods, then the sensitivity of MBS rates would be bigger in QE1 than in QE2.[9]

As two final robustness checks, I redo the baseline results except that instead of estimating the VAR by OLS, I employ two alternative methods. The first is to estimate the VAR as the posterior mean using the Minnesota prior.[10] This imposes shrinkage towards the prior that all the variables are univariate random walks, and so represents another way to address the potential concern about the downward bias in VAR estimates of persistence. The second is to simulate the mean and 5th/95th percentiles of the posterior of the impulse responses in a Bayesian VAR with the normal-inverse Wishart prior.[11] The results from these two exercises, shown in Figures 5 and 6 respectively, are again broadly similar to those in Figure 1.[12]

Table 3 includes the specification tests of the hypotheses that $\Sigma_0 = \Sigma_1$ and that

[9] In other (not reported) robustness checks, I considered trivariate VARs with two- and ten-year nominal Treasury yields plus one other interest rate (a breakeven rate, a corporate bond yield, or the MBS yield). These VARs again gave similar results, though in some cases the confidence intervals were a bit tighter.

[10] The Minnesota prior (Doan, Litterman and Sims (1984)) shrinks the VAR towards the series being independent random walks. In my implementation, the shrinkage parameter is set to 1.

[11] This was done by Gibbs sampling, as described in Koop and Korobilis (2010), using the code associated with that paper.

[12] An alternative approach is to avoid estimating a VAR altogether, and simply assume that the interest rates approximately follow random walks. This means that the one-step-ahead forecast errors, ε_t, can simply be approximated by ΔY_t. This approach gives up on trying to estimate the impulse responses at longer horizons, and was employed by Rigobon and Sack (2005). Results using this approach are in a web appendix—the instantaneous impulse responses are broadly similar to those reported in this paper.

$\Sigma_1 - \Sigma_0$ can be factored into the form $R_1 R_1'$ for the alternative definition of announcement dates, the alternative sample period for estimating $A(L)$, the alternative choices of variables in the VAR, and using the Minnesota prior to estimate the VAR. In all four cases, the hypothesis that announcement and non-announcement days are equivalent is rejected, while the hypothesis of a single monetary policy shock is accepted.

4 Event-study methodology and intradaily data

Identification through heteroskedasticity collapses to the event-study methodology in the limiting case that the announcement windows contain only the shocks that we wish to identify–that is, when the variances of all other shocks are negligible. That's a stronger assumption, and is surely not reasonable using daily data, especially over this turbulent period, but it might be an adequate approximation when high-frequency intradaily data are used. To consider an event-study methodology, I took quotes on the front contracts on two-, five-, ten- and thirty-year bond futures trading on the Chicago Mercantile Exchange (CME) from Tickdata. Table 1 shows the times of each of the announcements. The monetary policy shock is computed as the first principal component of yield changes[13] from 15 minutes before each of these announcements to 1 hour and 45 minutes afterwards, re-scaled to have a standard deviation of one, and signed so that a positive surprise represents falling yields.[14] No macroeconomic news announcements occurred in any of these windows and so it seems reasonable to assume that the monetary policy shock was the overwhelming driver of asset prices

[13] Yield changes were constructed as returns on the futures contract divided by the duration of the cheapest-to-deliver security in the deliverable basket.

[14] This is a fairly wide window, but results are similar using a tighter window from 15 minutes before the announcement to 15 minutes afterwards. However, the announcements considered represent the interpretation of statements and speeches, as opposed to giving information about the numerical value of the target funds rate. Consequently, it seems natural to allow a relatively wide window for the market to digest the news.

in these time periods. Unlike in the event studies of Gagnon et al. (2010) and Krishnamurthy and Vissing-Jorgenson (2011), the monetary policy surprises are being measured directly from intraday changes in asset prices.

The approach here is similar in spirit to that of Gürkaynak, Sack and Swanson (2005). These authors recognized that FOMC statements contained both news about the current setting of the federal funds rate and about its likely future trajectory. Following many other papers (going back to Kuttner (2001)), they proposed using current and next-month federal funds futures quotes to measure the surprise component of the setting of the target federal funds rate—their key innovation was that they proposed using the orthogonal change in four-quarter-ahead eurodollar futures rates as an asset-price-based quantification of the separate information in the statement about the outlook for monetary policy going forward. They called these the *target* and *path* surprises. However, since December 2008, there have been no surprises in the target federal funds rate, and FOMC statements have done little to alter monetary policy expectations over the next few quarters. Under these circumstances, it seems perhaps more appropriate to use changes in longer-term interest rates as an asset-price-based quantification of monetary policy surprises during this period of unconventional policy.[15] This directly resolves the problem faced by event studies such as Gagnon et al. (2010) and Krishnamurthy and Vissing-Jorgenson (2011) that they did not have data on market expectations concerning the size of LSAPs.

Table 4 reports the slope coefficients from regressions of various yield changes and asset price returns onto the monetary policy surprises, measured as described in the previous paragraph, over the 28 days listed in Table 1. The left-hand-side variables are not limited to the variables considered in the VAR. Note that in these

[15] Another option would be to use intradaily changes in longer-term eurodollar futures quotes, but these are quite illiquid at maturities beyond a year or two, and so the use of Treasury futures is preferable.

regressions, whereas the right-hand-side variable is constructed using high-frequency intradaily data, the left-hand side variables are daily changes, except for stock index futures, which are available intradaily.[16]

A one standard deviation monetary policy surprise is estimated to lower ten-year Treasury yields by 12 basis points. For comparison, Gürkaynak, Sack and Swanson (2005) estimated that over a period before monetary policy hit the zero bound, it would take a 100 basis point surprise cut in the target funds rate to lower ten-year Treasury yields by about this much. In Table 4, corporate bond yields are estimated to fall by about 7 basis points (a bit more than half as much as the decline in ten-year Treasury yields), while two-year Treasury yields again fall only a little. There is a rotation of TIPS breakevens, with five-year breakevens rising and five-to-ten-year forward breakevens falling. A possible interpretation is that the stronger outlook for demand boosts the short-to-medium-run inflation outlook, but the fact that the LSAPs are overwhelmingly concentrated in nominal (rather than TIPS) securities has an offsetting effect, pushing longer-term breakevens lower. A one standard deviation monetary policy surprise is estimated to lower Canadian, UK and German ten-year government bond yields[17] by one-third to one-half as much as the decline in ten-year US Treasury yields–this indicates that the monetary policy actions have impacted global expectations for short-term interest rates and/or global risk premia, consistent with Neely (2010). The Canadian dollar, UK pound and euro all appreciate relative to the US dollar, by between 0.5 and 1.1 percent, thereby offsetting some of the stimulative effect of Fed actions on other countries. Rates on current coupon thirty-year Fannie Mae mortgage backed securities fall about 7 basis points. Stock prices

[16] These are returns on the S&P futures contract trading on the CME from Tickdata, from 15 minutes before each announcement to 1 hour and 45 minutes afterwards.

[17] These are zero-coupon yields obtained at the daily frequency from the websites of the Bank of Canada, Bank of England and Bundesbank, respectively.

rise; a monetary policy surprise that lowers ten-year yields by 12 basis points is estimated to boost stock returns by a bit over half a percentage point[18]. All of these effects are highly statistically significant, even though the left-hand-side variable is measured at the daily frequency in most cases, and even though the sample size is just 28 observations. The SMB factor of Fama and French (returns on small stocks less returns on big stocks) is not significantly affected, consistent with the finding by some researchers that in recent decades size does not seem to be a priced risk factor in equity markets any more[19]. But the monetary policy shock does significantly increase the HML factor (returns on value stocks less returns on growth stocks). Perhaps firms with high ratios of book value to market value are most sensitive to the credit channel of the transmission mechanism of monetary policy.

I also regressed the estimated reduced form errors from the daily VAR (equation (1)) onto these monetary policy shocks. The coefficients are interpreted as estimates of R_1 in equation (2), and in conjunction with the estimates of the VAR slope coefficients in $A(L)$, this allows the effects of the monetary policy shock on the variables in the VAR to be traced out.[20] The resulting impulse responses are shown in Figure 7, along with 90 percent confidence intervals, using the bootstrap procedure defined in section 2.[21]. The results in Figure 7 are quite similar to those in Figure 1, but the confidence intervals are a lot tighter[22]. The monetary policy shock is estimated to lower long-

[18]For comparison, Bernanke and Kuttner (2005) estimated that, before the zero bound was reached, an unanticipated 25 basis point surprise reduction of the federal funds rate raised stock prices by about 1 percent.

[19]See, for example, Amihud (2002).

[20]The idea of identifying a VAR using an auxiliary dataset at higher frequency than the VAR observations was proposed in other contexts by Faust, Swanson and Wright (2004) and Bernanke and Kuttner (2005).

[21]The bootstrap also resamples the intradaily monetary policy surprises—for each bootstrap residual corresponding to an announcement day, I take the intradaily monetary policy surprise for that day. The set of bootstrap residuals are regressed on the set of bootstrap monetary policy surprises to obtain the bootstrap estimate of R_1.

[22]Note that the impulse responses at horizon 0 in Figure 7 give the estimates of R_1. These are not quite the same as the estimates reported in Table 4. The parameters in R_1 are estimated

term Treasury and corporate bond yields, with the effect wearing off over time but remaining statistically significant for a few months. The half-life of the estimated impulse responses is two or three months. The effect on two-year Treasury yields is again small. Short-term breakevens rise, and long-term forward breakevens fall, perhaps for the reasons discussed above, with these effects being on the borderline of statistically significance. The web appendix to this paper shows the analogs of Figures 2-6, but using this event-study approach; again the estimated impulse responses are similar, but the confidence intervals are tighter.

Table 5 shows the monetary policy surprises for each announcement day, estimated using high-frequency intradaily data, as proposed in this section. The statement accompanying the March 2009 FOMC meeting (indicating heavy asset purchases) corresponds to nearly a 4 standard deviation monetary policy surprise. The estimates in Figure 7 would suggest that this lowered ten-year Treasury yields by roughly 50 basis points on impact. Krishnamurthy and Vissing-Jorgenson (2011) consider that the statements accompanying the August, September and November 2010 FOMC meetings collectively revealed the essence of the information about QE2. Much information about QE2 came out at times other than these FOMC meetings[23] and so I would be skeptical of simply adding up the responses to these particular three events to attempt to measure the total effect of this particular monetary program. If one does so anyway, the three FOMC announcements sum up to a 1.3 standard deviation surprise. The estimates in Figure 7 indicate that a 1.3 standard deviation monetary policy surprise should lower ten-year Treasury yields by about 15 basis points on

by regressing the reduced form errors in the VAR on the monetary policy shocks; Table 4 instead regresses daily (or intradaily) returns or yield changes on those monetary policy shocks. However, the estimates of R_1 and the estimates reported in Table 4 are fairly close.

[23]For example, the Fed was reported to have sent a survey to primary dealers asking them to estimate the size of QE2 in late October 2010. The survey form supplied three options: $250 billion, $500 billion and $1 trillion. The very fact of setting up the survey question in this way was a signal that dealers surely did not miss.

impact.

Of course, judging by the impulse responses in this paper, all these effects wore off over the subsequent months.

5 Conclusions

In response to the financial crisis and the ensuing deep recession, the Federal Reserve pushed the federal funds rate to the zero lower bound and began engaging in unorthodox monetary policies, notably large-scale asset purchases. This paper has proposed using the tools of identification through heteroskedasticity and high-frequency event-study analysis to measure the effects of monetary policy shocks on the configuration of interest rates when the conventional tool of monetary policy is stuck at the zero bound. Monetary policy shocks are estimated to have effects on both long-term Treasury and corporate bond yields that are generally statistically significant, though the effects fade fairly fast over the subsequent months. Consistent with this result, QE1, QE2 and QE3 (the maturity extension program) were all characterized by declines in interest rates that were reversed over the subsequent months. A possible—although optimistic—interpretation is that the economic stimulus provided by these Federal Reserve actions caused the economy to pick up. Another interpretation is that markets initially overreacted to the news of these quantitative easing actions.

The VAR considered in this paper does not measure effects of shocks on low-frequency macroeconomic aggregates. But having estimates of the effects of monetary policy shocks on asset prices may be helpful for addressing this question. It could be used to motivate sign restrictions in a lower-frequency structural VAR, or to calibrate the shock in a macroeconomic model. For example, Chung et al. (2011) simulated the effect of QE2 in the Federal Reserve's FRB/US model. Their simulation assumed that QE2 lowered Treasury term premia by 25 basis points, but had no direct effect on spreads of corporate and mortgage rates over their Treasury counterparts. Meanwhile, in FRB/US, the stronger economic outlook induced by lower term premia endogenously causes corporate and mortgage rates to fall by more than the drop in Treasury yields. The evidence in the present paper would suggest that Chung et al. overstates the support to aggregate demand because I find that monetary policy surprises had *smaller* effects on private sector rates than on Treasury yields. Also, I find that the effects of the policy shocks wear off faster than Chung et al. assumed. To the extent that longer term interest rates are important for aggregate demand, unconventional monetary policy at the zero bound has had a stimulative effect on the economy, but it might have been quite modest.

Table 1: Dates of Monetary Policy Announcements at the Zero Bound

Date	Event	Time
11/25/2008	**Fed Announces Purchases of MBS and Agency Bonds**	**08:15**
12/1/2008	**Bernanke states Treasuries may be purchased**	**13:45**
12/16/2008	**FOMC Meeting**	**14:15**
1/28/2009	**FOMC Meeting**	**14:15**
3/18/2009	**FOMC Meeting**	**14:15**
4/29/2009	FOMC Meeting	14:15
6/24/2009	FOMC Meeting	14:15
8/12/2009	FOMC Meeting	14:15
9/23/2009	FOMC Meeting	14:15
11/4/2009	FOMC Meeting	14:15
12/16/2009	FOMC Meeting	14:15
1/27/2010	FOMC Meeting	14:15
3/16/2010	FOMC Meeting	14:15
4/28/2010	FOMC Meeting	14:15
6/23/2010	FOMC Meeting	14:15
8/10/2010	**FOMC Meeting**	**14:15**
8/27/2010	**Bernanke Speech at Jackson Hole**	**10:00**
9/21/2010	**FOMC Meeting**	**14:15**
10/15/2010	**Bernanke Speech at Boston Fed**	**08:15**
11/3/2010	**FOMC Meeting**	**14:15**
12/14/2010	FOMC Meeting	14:15
1/26/2011	FOMC Meeting	14:15
3/15/2011	FOMC Meeting	14:15
4/27/2011	FOMC Meeting	12:30
6/2/2011	FOMC Meeting	12:30
8/9/2011	**FOMC Meeting**	**14:15**
8/26/2011	**Bernanke Speech at Jackson Hole**	**10:00**
9/21/2011	**FOMC Meeting**	**14:15**

Notes: This table lists the days that are treated as "announcement days" for the identification strategy considered in this paper. It consists of all FOMC meetings during the period when the federal funds rate is stuck at the zero bound, and the days of certain important speeches and announcements concerning large-scale asset purchases. Announcement days that are treated as especially important are marked in bold. Times are in all cases Eastern time.

Table 2: Forecast Error Variance Decompositions

Horizon (in days)	1	50	100	150	200	250
10 Year Treasury	10.0	10.0	8.2	7.5	7.5	7.5
		(2.6,15.3)	(2.2,15.6)	(2.2,15.3)	(2.1,15.1)	(2.1,15.1)
2 Year Treasury	5.8	7.8	7.0	6.7	6.7	6.7
	(0.2,9.3)	(0.4,12.7)	(0.5,12.8)	(0.6,13.0)	(0.6,12.9)	(0.7,13.1)
5 Year Bkeven	0.2	0.5	1.0	1.4	1.7	1.9
	(0.0,2.8)	(0.1,7.0)	(0.1,9.1)	(0.1,9.6)	(0.2,10.2)	(0.2,10.1)
5-10 Year Bkeven	1.0	2.7	2.7	2.5	2.5	2.6
	(0.2,6.3)	(0.8,10.7)	(1.0,11.1)	(1.2,11.1)	(1.3,11.3)	(1.3,11.3)
BAA Yields	2.3	4.7	4.2	4.1	4.2	4.2
	(0.7,16.1)	(2.0,14.1)	(2.2,14.8)	(2.4,14.8)	(2.5,14.9)	(2.4,15.0)
AAA Yields	3.0	2.6	1.9	1.6	1.3	1.2
	(0.7,23.1)	(1.0,19.0)	(1.4,14.9)	(1.3,14.1)	(1.3,13.7)	(1.3,13.9)

Notes: This table reports the estimates of the share of the forecast error variance of the 6 variables in the system at selected horizons that is due to the monetary policy shock. 90 percent confidence intervals are in parentheses, constructed as described in the text. The size of the monetary policy shock is normalized to account for 10 percent of the variance of the one-day ahead forecast of ten-year Treasury yields

Table 3: Specification tests

Hypothesis	Wald Statistic	Bootstrap p-value
Baseline VAR: All Announcement Days		
$\Sigma_0 = \Sigma_1$	67.9	0.005
$\Sigma_1 - \Sigma_0 = R_1 R_1'$	32.7	0.852
Baseline VAR: 13 Most Important Announcement Days		
$\Sigma_0 = \Sigma_1$	146.8	0.000
$\Sigma_1 - \Sigma_0 = R_1 R_1'$	112.6	0.519
Baseline VAR: Longer Estimation Period		
$\Sigma_0 = \Sigma_1$	72.7	0.001
$\Sigma_1 - \Sigma_0 = R_1 R_1'$	40.7	0.583
Alternative VAR with MBS rates		
$\Sigma_0 = \Sigma_1$	57.7	0.005
$\Sigma_1 - \Sigma_0 = R_1 R_1'$	30.8	0.383
Baseline VAR Estimated with Minnesota Prior		
$\Sigma_0 = \Sigma_1$	67.8	0.005
$\Sigma_1 - \Sigma_0 = R_1 R_1'$	33.2	0.568

Notes: This table reports the results of specification tests of the hypotheses that the variance-covariance matrix of reduced form errors is the same on announcement and non-announcement days, and that there is a one-dimensional structural shock that characterizes the difference between these two sets of days. Bootstrap p-values, constructed as described in the text, are included in both cases. Results are shown both for the baseline case (top panel) and for four robustness checks.

Table 4: Coefficients in regressions of yield changes and returns on intradaily monetary policy surprises

	Slope Coefficient	Standard Error	R-squared
AAA Yields	-0.073***	0.011	44.6
BAA Yields	-0.073***	0.009	48.2
Two-year Treasuries	-0.062***	0.006	77.3
Ten-year Treasuries	-0.123***	0.016	71.6
Five-year Breakevens	0.013**	0.006	9.1
Five-to-ten year forward breakevens	-0.028***	0.010	18.8
Ten-year Canadian Yields	-0.056***	0.006	49.8
Ten-Year UK Yields	-0.043***	0.016	35.9
Ten-Year German Yields	-0.036***	0.008	30.1
Fannie Mae MBS Yield	-0.071***	0.022	32.0
Canadian Dollar	0.556***	0.182	26.6
UK Pound	0.730***	0.238	39.7
Euro	1.092***	0.176	52.4
SMB returns	-0.050	0.099	0.7
HML returns	0.434**	0.205	15.7
S&P returns	0.549***	0.190	21.9

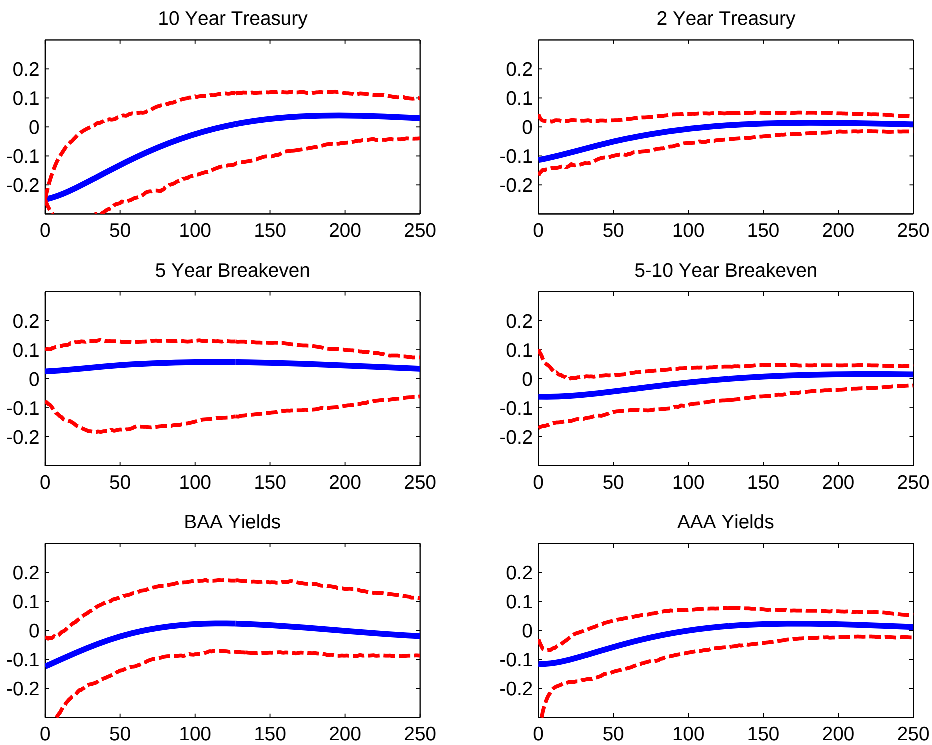
Notes: This table reports the results of daily yield changes or returns (intradaily for the case of the S&P futures returns) onto the monetary policy surprise, measured from high-frequency changes in Treasury futures, as described in the text. Yields are in percentage points; returns are 100 times log gross returns. Exchange rate returns are returns of the currency shown relative to the US dollar. The regression is run over the 28 announcement days listed in Table 1. The standard errors are heteroskedasticity-robust. One, two and three asterisks denote significance at the 10, 5 and 1 percent levels, respectively.

Table 5: Monetary Policy Surprises at the Zero Bound

Date	Policy Surprise
11/25/2008	0.85
12/1/2008	0.96
12/16/2008	2.54
1/28/2009	-0.26
3/18/2009	3.89
4/29/2009	-0.60
6/24/2009	-1.07
8/12/2009	0.18
9/23/2009	0.98
11/4/2009	0.14
12/16/2009	-0.27
1/27/2010	-0.60
3/16/2010	0.43
4/28/2010	0.06
6/23/2010	0.24
8/10/2010	0.66
8/27/2010	-0.95
9/21/2010	0.70
10/15/2010	-0.24
11/3/2010	-0.05
12/14/2010	-0.39
1/26/2011	0.05
3/15/2011	-0.48
4/27/2011	0.24
6/2/2011	-0.35
8/9/2011	1.07
8/26/2011	-0.12
9/21/2011	0.17

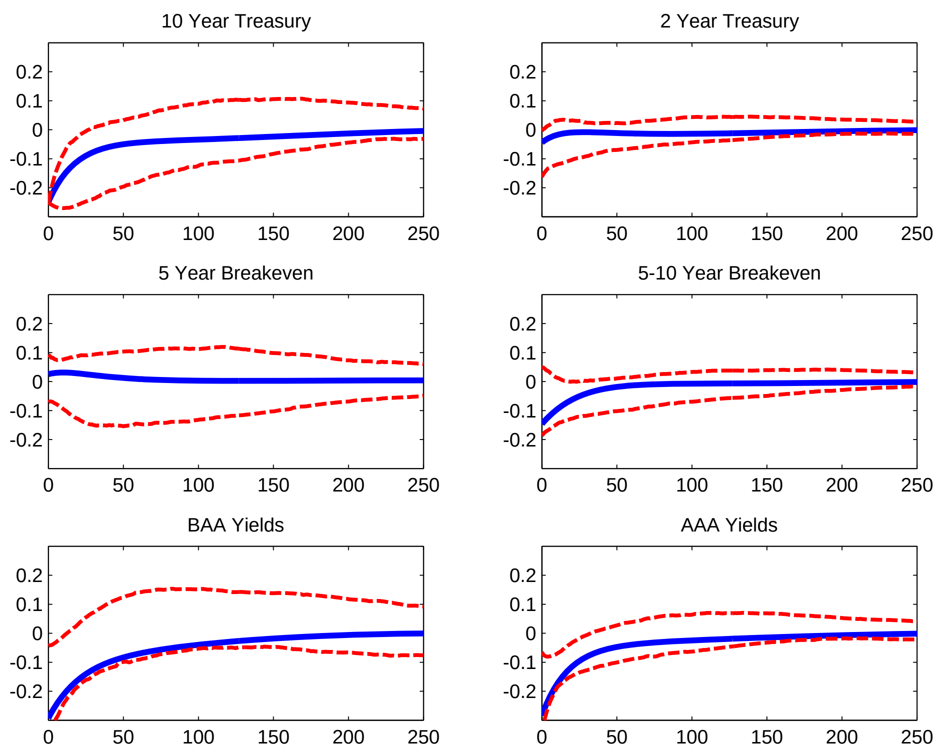
Notes: This table shows the monetary policy surprises, estimated as the first principal component of intradaily changes in yields on Treasury futures contracts on all announcement days, as described in section 4. The surprises are normalized to have a unit standard deviation and are signed so that a positive number represents falling yields.

Figure 1: Estimated Impulse Responses in Baseline VAR



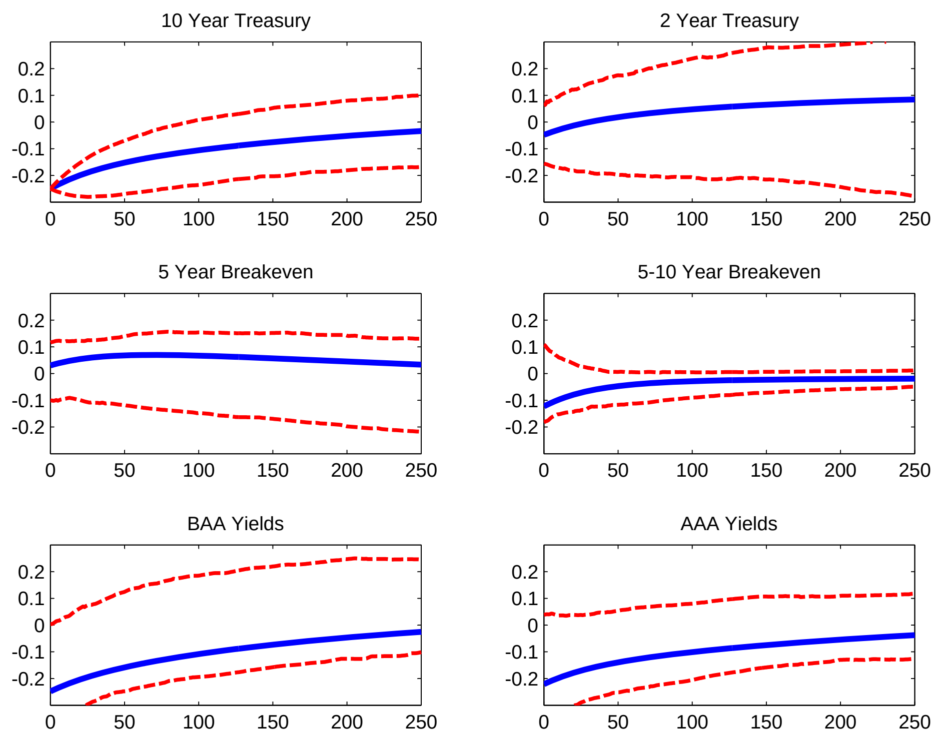
Note: Estimates of the impulse responses from monetary policy shocks onto the 6 variables in the system, from 0 to 250 days. 90 percent bootstrap confidence intervals are also shown, constructed as described in the text. The monetary policy shock is normalized to lower ten-year yields by 25 basis points.

Figure 2: Estimated Impulse Responses Using only 13 Announcement Days



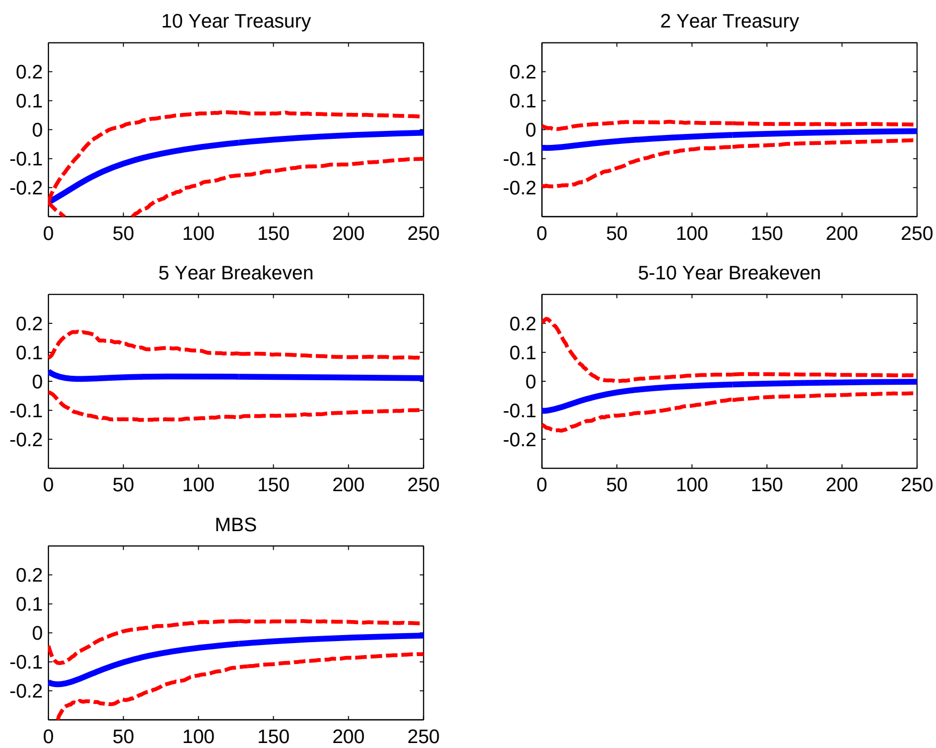
Note: As for Figure 1, except that only the 13 days highlighted in bold in Table 1 are treated as announcement days.

Figure 3: Estimated Impulse Responses Using Longer Sample to Estimate VAR



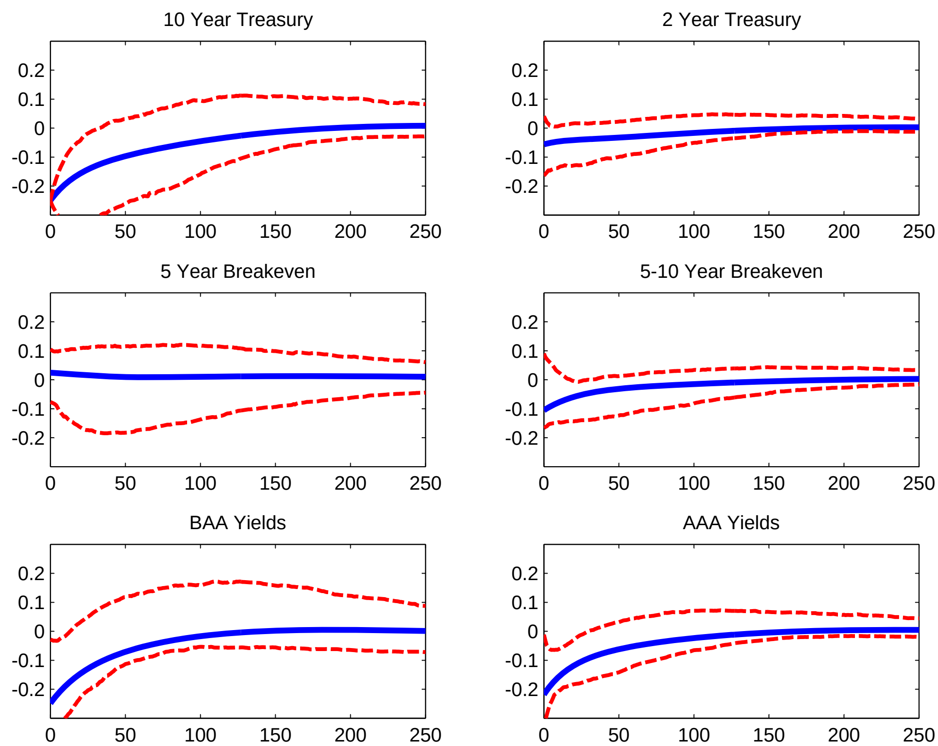
Note: As for Figure 1, except that the reduced form VAR was estimated over the period since Janaury 1999, as described in the text.

Figure 4: Estimated Impulse Responses Using Alternative VAR with MBS Rates



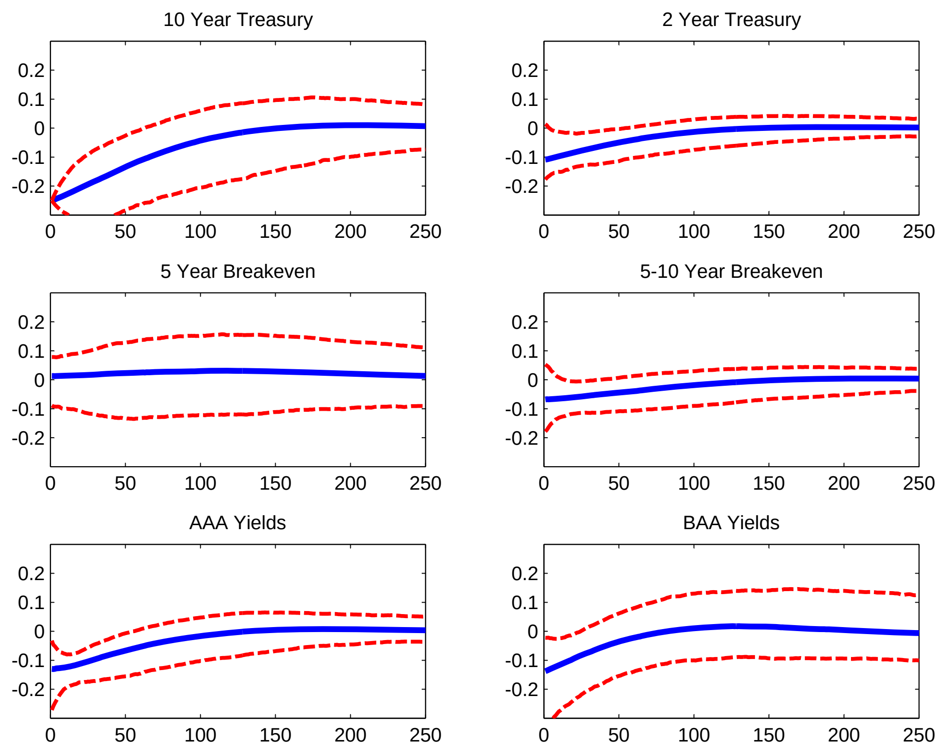
Note: As for Figure 1, except that the reduced form VAR included Fannie Mae current coupon MBS yields instead of corporate bond rates.

Figure 5: Estimated Impulse Responses Using Minnesota Prior



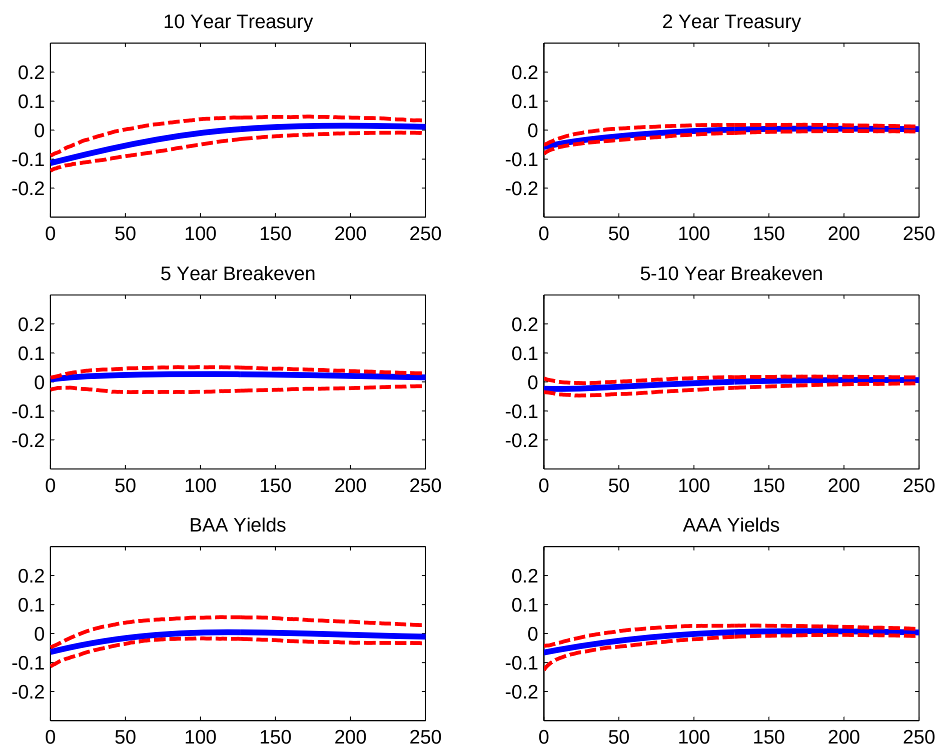
Note: As for Figure 1, except that the reduced form VAR is estimated as the posterior mean corresponding to the Minnesota prior of Doan, Litterman and Sims (1984) with a shrinkage parameter of 1.

Figure 6: Posterior for Impulse Responses Using Normal-Inverse Wishart Prior



Note: As for Figure 1, except that the figure shows the mean and 5th/95th percentiles of the posterior distribution of the impulse responses with the normal-inverse Wishart prior, approximated using Gibbs sampling.

Figure 7: Estimated Impulse Responses in Baseline VAR using Event-Study Identification



Note: Estimates of the impulse responses from regressing monetary policy shocks onto the 6 variables in the system, from 0 to 250 days. The monetary policy shocks were identified as the first principal component of changes in bond futures quotes in intraday windows around the events listed in Table 1. The reduced form VAR errors were then regressed onto these monetary policy shocks and the impulse responses were computed as described in the text. 90 percent bootstrap confidence intervals are also shown.

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