Conventional Monetary Policy and the Term Structure of Interest Rates during the Financial Crisis*

Tolga Cenesizoglu — HEC Montréal
Denis Larocque — HEC Montréal
Michel Normandin — HEC Montréal

August 21, 2013

Abstract

There is a growing literature on whether the unconventional policies of the Fed during the financial crisis have been effective. However, the literature is relatively silent on the effectiveness of conventional monetary policies during the financial crisis, a rather surprising fact given that conventional policies were the Fed's initial response to the financial crisis. This is a nontrivial question due to problems associated with the existing methods of identifying conventional monetary policy shocks in the context of the financial crisis. In this perspective, our paper analyzes the effectiveness of conventional monetary policy in changing the term structure of interest rates during the financial crisis. Our identification strategy based on the conditional heteroskedasticity of the structural innovations allows us to specify flexible structural vector autoregressive (SVAR) processes that do not suffer from the problems associated with existing methods. Comparing results based on sample periods excluding and including the financial crisis, we find that conventional monetary policy as measured in our SVAR has lost its effectiveness in changing the term structure of interest rates during the financial crisis. This result suggests that the Fed's use of unconventional policies, at least, with the objective of changing the term structure of interest rates was appropriate.

Key words: Conventional Monetary Policy, Term Structure of Interest Rates, Structural Vector AutoRegression, Conditional Heteroskedasticity, Financial Crisis.

JEL Codes: C32, E43, G12

*Corresponding Author: Michel Normandin, phone: +1 514 3406841, email: michel.normandin@hec.ca

1 Introduction

There has been a growing debate on whether monetary policy had any significant effect on the economy and the financial markets during the recent financial crisis. On the one hand, Mishkin (2009) and Bernanke (2009) argue that monetary policy during the financial crisis has indeed been effective. For example, in his Stamp lecture at the London School of Economics, Bernanke argues: "The Fed's monetary easing has been reflected in significant declines in a number of lending rates, especially shorter-term rates, thus offsetting to some degree the effects of the financial turmoil on financial conditions." On the other hand, Krugman (2008) and some members of the Fed (Board of Governors of the Federal Reserve System (2008)) were concerned that monetary policy lost its effectiveness during the financial crisis. For example, Krugman writes in his column in the New York Times: " ... the usual tools of monetary policy - above all the Federal Reserve's ability to pump up the economy by cutting interest rates - have lost all traction."

To understand this debate, one has to distinguish between conventional and unconventional monetary policy. As a response to the financial crisis, the Fed first implemented the conventional monetary policy action of short-term government debt purchases via open market operations with the short-term objective of a desired quantity of reserves and/or a desired fed funds rate. However, due to the unprecedented nature of events, the Fed decided to take further policy actions during the financial crisis. In contrast to the conventional policy, when implementing these so-called unconventional policies, the Fed actively used its balance sheet to directly affect market prices and conditions (see Borio and Disyatat (2009)). There is a growing literature analyzing whether these unconventional policies have been effective (see Christensen, Lopez, and Rudebusch (2009), Stroebel and Taylor (2009), Taylor and Williams (2009), Cecioni, Ferrero, and Secchi (2011), Thornton (2011), Wu (2011) and Duygan-Bump, Parkinson, Rosengren, Suarez, and Willen (2013)). On the other hand, the literature is relatively silent on the effectiveness of conventional monetary policy during the financial crisis. This is an important question considering that it is appropriate for the Fed to implement unconventional policies only to the extent that conventional policies were ineffective in the first place. In this paper, we contribute to the literature by analyzing the effectiveness of the conventional monetary policy, which we simply refer as the monetary policy for the rest of the paper unless stated otherwise, in changing the term structure of interest rates during the financial crisis. This is not a trivial question given problems associated with existing methods of identifying monetary policy shocks in the context of the financial crisis.

These existing methods can be broadly grouped into two major categories. Among others, Cook and Hahn (1989), Roley and Sellon (1995) and Kuttner (2001) use an event-study approach with high frequency data on the days when the Fed changed the funds rate target. On the other hand, the structural vector autoregressive (SVAR) approach with low frequency data seeks to identify monetary policy shocks by imposing certain restrictions on the contemporaneous interactions among variables. These restrictions can take the form of short run exclusions (Evans and Marshall (1998)); long run restrictions (Evans and Marshall (1998)); sign restrictions (Roush (2007)); or nonlinear restrictions reflecting no arbitrage conditions (Smith and Taylor (2010), Ang, Boivin, Dong, and Loo-Kung (2011), Ang and Piazzesi (2003)).[1] Both of these approaches face significant problems in identifying

[1]Recently, Cochrane and Piazzesi (2002) and Farka and DaSilva (2011) combine the high-frequency event-study approach with the low-frequency SVAR approach to identify monetary policy shocks.

monetary policy shocks in the context of the financial crisis.

In particular, the event study approach implicitly assumes that the various shocks, other than monetary policy shocks, affecting the economy and the financial markets do not occur systematically on the policy announcement dates, so that the effect of monetary policy shocks can be identified by aggregating over a sufficiently large number of event days, even though each event day may be individually contaminated by other shocks. This assumption might have been violated during the financial crisis given that the Fed systematically decreased the fed funds rate in response to market-wide shocks. Furthermore, there is only a very limited number of policy announcement days during the financial crisis, making it rather difficult to identify monetary policy shocks based on the event-study approach.

Similarly, the standard SVAR approaches need to impose certain restrictions. In almost all the studies mentioned above, the set of restrictions imposed define the fed funds rate as the unique relevant indicator of monetary policy. As we show, these restrictions do not hold in the data independent of whether we include or exclude the financial crisis. Hence, it is relatively difficult to justify the assumption that the fed funds rate is the unique relevant indicator of monetary policy especially during the financial crisis. One should consider the possibility that the Fed may also have implicit targets for borrowed and nonborrowed reserves, especially during the financial crisis, such that the relevant indicator is a combination of all the policy variables.

To illustrate how potential problems associated with common restrictions alter the conclusions on the effectiveness of monetary policy in changing the term structure of interest rates, we start with a preliminary analysis where monetary policy shocks are identified based on two different sets of restrictions. Specifically, we consider a SVAR framework for output, prices, reserve market variables and three term structure factors extracted from a set of monthly yields on zero-coupon US government bonds with different maturities. In the first approach, we impose restrictions consistent with the assumption that the fed funds rate is the monetary policy indicator, as is common practice. In the second approach, we use an alternative set of restrictions where the monetary policy indicator is assumed to be nonborrowed reserves. We consider two sample periods. The first one corresponds to the period before the financial crisis, between November 1982 and March 2007. The second one also includes the first part of the financial crisis before September 2008, which we refer as the financial crisis period for the purposes of our paper. We argue that it becomes relatively difficult to identify conventional monetary policy shocks based on reserve market variables after August 2008 due to two main reasons: (1) The reserve market variables no longer behave normally after August 2008; (2) the Fed started implementing the most important ones of several unconventional policies in September 2008 in response to unprecedented events at the peak of the financial crisis.

We estimate the SVAR based on these two sample periods. The impulse response functions of the term structure factors to an expansionary monetary policy shock reveal substantial discrepancies between these two approaches. For example, before the financial crisis, the slope of the yield curve increases significantly in the short run when the fed funds rate is the monetary policy indicator, whereas it does not respond significantly when the monetary policy indicator is nonborrowed reserves.[2] More importantly, these differences become even more striking when we consider the whole sample period including the financial crisis. Specifically, the impulse response functions

[2] Our results based on the fed funds rate as the monetary policy indicator before the financial crisis are broadly consistent with the studies mentioned above.

of the term structure factors do not seem to change significantly following the financial crisis when the fed funds rate is assumed to be the indicator of monetary policy. In contrast, the impulse response functions of the term structure factors change dramatically following the financial crisis when we consider nonborrowed reserves as the monetary policy indicator. Compared to the sample period before the financial crisis, their reactions become much smaller in magnitude and statistically insignificant. Overall, these results reveal the discrepancies associated with identification strategies that limit the policy indicator to a unique variable. This in turn does not help to settle the debate on the effectiveness of monetary policy and calls for a more robust approach.

In this perspective, our paper analyzes the effectiveness of monetary policy in changing the term structure of interest rates based on a flexible approach. Specifically, we consider once again a SVAR framework for output, prices, reserve market variables and the term structure factors. However, our approach differs from previous studies due to our identification strategy based on the conditional heteroskedasticity of the structural innovations. The identification of a SVAR under this environment follows from Sentana and Fiorentini (2001) and is applied in Normandin and Phaneuf (2004). The idea behind this identification strategy is based on the fact that time variation in the conditional volatilities of the structural innovations provides additional information for identifying more parameters (relative to the usual conditionally homoskedastic case). As a result, unlike a recursive identification strategy, no arbitrary restrictions need to be imposed and the Fed is allowed to adopt a mixed strategy where it targets neither the interest rate nor the monetary aggregate exclusively. This is in line with the definition of conventional monetary policy with the short-term objective of a desired quantity of reserves and/or a desired fed funds rate. Although our identification strategy allows us to leave the SVAR unrestricted, we still choose to impose a minimal set of restrictions based on a simple formulation of the reserve market. This ensures that the estimated system is a coherent framework for the analysis of monetary policy. Furthermore, we specify the conditional variances of the structural innovations as univariate generalized autoregressive conditional heteroskedasticity of order one (GARCH (1,1)) processes. Again, we estimate the SVAR for sample periods excluding and including the financial crisis. The parameter estimates reveal several important results. First, regardless of the sample period considered, all structural innovations in the SVAR are conditionally heteroskedastic, a condition for our identification strategy to work. Second, the parameter estimates suggest that the Fed does indeed adopt a mixed strategy where it targets both the fed funds rate and the other reserve variables.

Also, the impulse response functions of the term structure factors to an expansionary monetary policy shock in our framework reveal the ineffectiveness of monetary policy following the financial crisis. Specifically, before the financial crisis, the level of the yield curve decreases significantly in the short and medium runs, the slope decreases significantly in the medium run and the curvature decreases significantly only in the very short run. Furthermore, the reactions based on our approach are stronger compared to those based on the identification strategy restricting the monetary policy indicator to be either the fed funds rate or nonborrowed reserves. However, when we consider the whole sample period including the financial crisis, these reactions become much smaller in magnitude and, more importantly, mostly insignificant. The magnitude of the change in these reactions following the financial crisis is remarkable considering that the financial crisis period represents only a small part of the whole sample period.

A similar result emerges when one constructs the implied impulse responses of yields based on the impulse responses of the term structure factors. Specifically, all yields decrease significantly following an expansionary monetary policy shock before the financial crisis, whereas they do not respond significantly when we include the financial crisis in our sample. These results suggest that the monetary policy might not have been as effective in changing the yield curve during the financial crisis as before.[3]

We also analyze the economic factors behind the muted reactions of the term structure factors to monetary policy shocks when we include the financial crisis in our sample. To this end, we extend the decomposition approach of Campbell and Ammer (1993) to disentangle the initial responses of yields with different maturities into the initial responses of three economic fundamentals: inflation, real rate of return and risk premium. We find that the negative response of yields to an expansionary monetary policy shock before the financial crisis can be mainly explained by the negative response of real rate of return at the short end of the yield curve and the negative response of excess returns at the long end. The dramatic change in the responses of yields to monetary policy shocks following the financial crisis can be explained by the substantial changes in the responses of both future real rate of return and excess returns. In particular, following the financial crisis, monetary policy no longer affects investors' expectations about future real rate of return or excess returns. These results suggest that the financial crisis might have affected how investors update their expectations about future values of economic fundamentals, especially about future values of real rate of return and excess returns.

Finally, we analyze the robustness of our results to using alternative measures of key variables and sample periods. First, we use total balances instead of total reserves following Carpenter and Demiralp (2008), who argue that total balances at the Fed are a better measure to describe the dynamics of the fed funds market. Second, following the argument in Vilasuso (1999) that the effects of monetary policy shocks depend on the Fed's operating procedures, we use February 1994 as an alternative starting point for both of our samples. This is when the Fed adopted the current practice of announcing its target for the fed funds rate. The empirical results suggest that our conclusion on the ineffectiveness of monetary policy in changing the term structure of interest rates is robust to using alternative measures of total reserves and potential changes in Fed's operating procedures.

The rest of the paper is organized as follows. In Section 2, we motivate our choices for pre-crisis and crisis periods by discussing conventional and unconventional policies in the historical context of the financial crisis. Section 3 discusses the data and the construction of the term structure factors. Section 4 presents the results from our preliminary analysis. Section 5 outlines our estimation methodology and identification strategy. Section 6 reports the parameter estimates, impulse response functions, variance decompositions, and initial response decompositions. Section 7 presents a robustness analysis and Section 8 concludes.

2 Conventional and Unconventional Policies during the Financial Crisis

This section discusses the various conventional and unconventional monetary policies. In light of this discussion, we select for our empirical analysis the sample covering the period between November 1982 and March 2007 that

[3]This is consistent with a handful of papers analyzing the impact of such policies during the financial crisis. For example, Medeiros and Rodriguez (2011) find that neither the level nor the slope of the yield curve responds significantly to a conventional monetary policy shock, while the slope responds only slightly in the short run. Similarly, Abbassi and Linzert (2011) find that the conventional monetary policies of the European Central Bank have been ineffective during the financial crisis.

excludes the financial crisis, and the sample between November 1982 and August 2008 that also includes the part of crisis for which conventional monetary policies can be accurately identified.[4]

In this context, comparing the empirical results obtained from the two samples provides information about changes (if any) in the effectiveness of conventional monetary policies in affecting the term structure of interest rates.[5] Note that this represents a conservative analysis since any significant difference is a strong indication of the structural break in the effectiveness of the monetary policy during the financial crisis, given the limited number of additional observations included in the sample covering both the pre-crisis and the crisis periods.[6]

2.1 Historical Context

As housing prices across the US began to fall in the late spring and early summer of 2006, the delinquency rates of subprime mortgages also began to increase. However, the impact of these events on the financial system was not clear until the early spring of 2007, when the first signs of the financial crisis started showing up. By June 2007, the Fed was still cautiously optimistic as most economic indicators such as employment, inflation, and consumer spending were pointing in the right direction for the US economy and, thus, the Federal Open Market Committe (FOMC) voted to keep the Fed funds target rate at 5.25 percent.

However, by the late summer and early fall of 2007, many financial institutions were suffering from huge losses on subprime mortgages. For example, banks such as Bear Stearns and BNP Paribas liquidated or halted redemptions from several investment funds while, other financial institutions such as Countrywide Financial warned of difficult conditions ahead. Rating agencies such as Standard and Poor's, Moody's Investor Services and Fitch Ratings downgraded several securities and companies which had significant exposure to subprime mortages. Although the FOMC voted to keep the Fed funds target at its previous level of 5.25 percent on August 7, 2007, it was becoming evident that the financial markets needed help. Thus, the Fed was forced to first emphasize its role of lender of last resort by announcing on August 10, 2007 that it "is providing liquidity to facilitate the orderly functioning of financial markets",[7] and then reduced the target rate by 50 basis points from, 5.25 to 4.75 percent, on September 18, 2007 in an unscheduled FOMC meeting.

At this point, it was clear that the financial markets were in a crisis, although it did not reach its peak until one year later, in September 2008, when the US government took Fannie Mae and Freddie Mac into conservatorship, Lehman Brothers declared bankruptcy, and the Fed rescued The American International Group. In response to these extraordinary events, policy makers began to take unprecedented actions in September 2008. For example,

[4] As is common practice, we choose November 1982 as the starting date of both sample periods so as to avoid the atypical Fed operating procedures pursued under the Volcker's episode between October 1979 and October 1982, where little effort, if any, went into stabilizing either the fed funds rate or the borrowed reserves (see Strongin (1995)). As a robustness test, we also consider February 1994 as the starting data of both sample periods. This is when the Fed adopted the current practice of announcing its target for the fed funds rate. As we discuss in Section 7, our results are robust to using February 1994 as an alternative starting date.

[5] This empirical approach is similar to a Chow test for structural breaks at known dates. In our application, however, we do not split the full sample in two distinct subsamples, given that the second subsample capturing exclusively the financial crisis would contain too few observations to perform estimation.

[6] Given the conservative nature of our empirical approach, a lack of any significant difference between the empirical results based on these two subsamples cannot, however, be interpreted as the absence of a structural break.

[7] http://www.federalreserve.gov/newsevents/press/monetary/20070810a.htm

the House voted for the first time on the Emergency Economic Stabilization Act of 2008, which was eventually signed into law by President Bush on October 3, 2008, creating the Troubled Asset Relief Program (TARP) and committing $700 billion that provided most of the necessary funds for the implementation of unconventional policies. Similarly, the Fed began creating several programs, named facilities, to ease tensions in different parts of the financial system.[8]

2.2 The Financial Crisis

Although it is hard to determine the exact date when the financial crisis started, one can try to identify certain key events as its first signs based on several time lines of the financial crisis available from different sources. For example, as the first event in their time line of the financial crisis,[9] the Federal Reserve Bank of St. Louis marks the announcement on February 27, 2007 by The Federal Home Loan Mortgage Corporation (Freddie Mac) that it will no longer buy the most risky subprime mortgages and mortgage-related securities. On the other hand, the BBC marks the revelation of huge subprime losses on February 8, 2007 by HSBC as the first event in their time line of the financial crisis.[10]

The bankruptcy of New Century Financial, a leading subprime lender, on April 2, 2007 is marked as the second event in the time line of the financial crisis from both of these sources. Mankiw and Ball (2010) also mention the bankruptcy of New Century Financial in April 2007 as the first significant event of the financial crisis. Calomiris (2009) and Claessens, Dell'Ariccia, Igan, and Laeven (2010) argue that the beginning of the financial crisis was marked by the increase in subprime delinquency rates in the spring of 2007.

Although they might not agree on the exact date when the financial crisis started, most sources agree that the first signs of the financial crisis showed up in the early spring of 2007 by the bankruptcy of New Century Financial. Hence, we assume that the financial crisis started in April 2007 and our pre-crisis sample period ends in March 2007.

2.3 Conventional and Unconventional Policies

In our empirical analysis, we identify conventional monetary policy based on the reserve market variables, i.e. the fed funds rate, nonborrowed reserves and total reserves. Hence, a natural way to start our discussion on conventional and unconventional policies is to present the evolution of these variables before, during and after the financial crisis.

[8] For example, Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility (AMLF) was created on September 19, 2008, Commercial Paper Funding Facility (CPFF) was created on October 7, 2008, Money Market Investor Funding Facility (MMIFF) was created on October 21, 2008, and Term Asset-Backed Securities Lending Facility (TALF) was created on November 25, 2008. In late 2008, the Fed started buying $600 billion worth of mortgage backed securities from financial institutions, an operation which was later termed as the first round of quantitative easing, or QE1. In October 2010, when the Fed implemented a second round of quantitative easing, or QE2, and promised to buy $600 billion worth of Treasury securities by the end of the third quarter of 2011. The Fed announced a third round of quantitative easing, or QE3, in September 2012, by promising to purchase $40 billion of mortgage debt per month and increased this amount to $85 billion in December 2012 in a fourth and the most recent round of quantitative easing, QE4.

[9] http://timeline.stlouisfed.org/pdf/CrisisTimeline.pdf

[10] http://news.bbc.co.uk/2/hi/8242825.stm

Panel (a) of Figure 1 presents the monthly averages of daily fed funds effective rate (ff_t) and fed funds target rate. As discussed above in the historical context of the financial crisis, the Fed kept the target rate at its pre-crisis level of 5.25 percent until September 18, 2007, when it was reduced by 50 basis points to 4.75 percent. The target rate was then cut by 25 or 50 basis points in each of the scheduled FOMC meetings between September 2007 and April 2008, eventually reaching 2 percent on April 30, 2008. During the summer and early fall of 2008, the FOMC voted several times to keep the target rate at 2 percent. However, as it can be seen from Panel (a) of Figure 1, in September 2008, the effective rate began to deviate significantly from the target rate as a result of unprecedented events during the midst of the financial crisis. The Fed then cut the target rate by 50 basis points on October 8, 2008 and by another 50 basis points on October 29, 2008. Finally, on December 16, 2008, the Fed decided to establish a target range for the effective Fed funds rate of 0 to 0.25 percent.[11]

Panel (b) of Figure 1 presents borrowed reserves (br_t) and the total reserves adjusted for changes in reserve requirements (tr_t). Borrowed reserves are defined as the total borrowings of depository institutions through not only the Fed's regular discount window programs, but also other Fed liquidity facilities. Most of these liquidity facilities were created to ease tensions in different parts of the financial markets and considered as unconventional policies. Term Auction Facility (TAF) created on December 12, 2007, in response to "elevated pressures in short-term funding markets" is generally considered as the first one of these unconventional policies.[12] As a result of TAF, borrowed reserves began to increase significantly in December 2007. However, to be consistent with the FOMC's objective for the Fed funds rate, total reserves were maintained around their levels prior to December 2007. As a result of this policy, nonborrowed reserves, which are defined as the difference between total and borrowed reserves, began to decrease in December 2007 and became negative for the first time in history in January 2008. Thus, one needs to control for the borrowings of the depository institutions through TAF when calculating a measure of funds available to depository institutions from the regular discount window programs since the creation of TAF in December 2007. This is done by simply considering the sum of the borrowings under TAF and the usual definition of nonborrowed reserves, which is available from the Federal Reserve Bank of St. Louis. Panel (b) of Figure 1 presents both the uncorrected and corrected measures of nonborrowed reserves. However, even the corrected measure of nonborrowed reserves became negative in September 2008 when it was evident that the borrowing needs of depository institutions far exceeded the funds available through the regular discount window programs as well as TAF, and the Fed started implementing other unconventional policies. This is also when total reserves began to increase to unprecedented levels as the Fed abandoned its policy of maintaining total reserves at their pre-crisis levels.

In choosing the end date for our second sample period, there is a trade off between minimizing any potential problems in the identification of conventional policies due to the implementation of unconventional policies and maximizing the number of observations during the financial crisis. On the one extreme, we can be very conser-

[11] The Fed funds target rate series from the Federal Reserve Bank of St. Louis is discontinued and, hence, is not presented after December 2008.

[12] There was also another program termed "Term Discount Window Program" announced on August 17, 2007, under which the Fed allowed the provision of term financing for as long as 30 days and eventually to 90 days on March 16, 2008. Although the Fed deviated from its usual practice of overnight loans under this program, this program is not generally considered as an unconventional policy since it is a relatively small change in the Fed's usual operations compared to unconventional policies.

vative and choose November 2007 as the last observation in our second sample period. This choice minimizes any potential problems in the identification of conventional policies due to the implementation of unconventional policies, since it excludes any unconventional policies. However, during this period between April and November 2007, the Fed's response to the financial crisis through conventional policies was relatively muted compared to its response after November 2007. Specifically, the Fed decreased the target rate only twice: first by 50 basis points from 5.25 to 4.75 percent on September 18, 2007 and then by 25 basis points to 4.50 percent on October 31, 2007. Furthermore, total reserves were mostly maintained at their pre-crisis levels. In contrast, between November 2007 and December 2008, the Fed decreased the target rate eight times from 4.50 percent to a range between 0 and 0.25 percent. Hence, we might not observe any significant effect of conventional policies on the term structure of interest rates. More importantly, this choice also limits the number of monthly observations during the financial crisis period to a mere eight observations between April and November 2007. On the other extreme, we can choose December 2012 when the last round of quantitative easing was announced. Although this choice maximizes the number of observations during the financial crisis period, it also opens the door to a plethora of potential problems, such as zero fed funds target rate, negative nonborrowed reserves, and any potential problem due to the implementation of unconventional policies in the identification of conventional policies.

In between these two extremes, we choose August 2008 as the last date in our second sample period. First of all, we believe that the period between April 2007 and August 2008 provides us with enough observations to identify the impact of the financial crisis on the effectiveness of conventional monetary policies in changing the term structure of interest rates. Secondly, we believe that any potential problems due to the implementation of unconventional policies on the identification of conventional policies during this period are minimal. In particular, we control for the effect of TAF on the identification of conventional policies by considering a measure of nonborrowed reserves corrected for borrowings under TAF as discussed above. [13] There are also several other reasons why we choose August 2008 as the last date in our sample period. It is the last month before the corrected measure of nonborrowed reserves became negative. Furthermore, the fed funds target is still well above its lower bound of zero as of August 2008. Finally, it is the last month before September 2008, which is generally considered as the peak of the financial crisis when the Fed started implementing unconventional policies in full force as discussed in the historical context.

3 Data

In this section, we briefly describe the monthly US data used in our empirical analysis. The base set of variables is relatively standard and includes the industrial production index (ip_t), the (all-item, all-urban-consumer) price index (p_t), the world-export commodity-price index (cp_t), the non-borrowed reserves with TAF (nbr_t), the total reserves adjusted for changes in reserve requirements (tr_t) and the nominal fed funds rate (ff_t). As will be discussed in Section 7, we also considered using total balances (tb_t), i.e. the sum of total reserves and contractual clearing

[13] There were also two other unconventional policies created during this period, Term Securities Lending Facility (TSLF, created on March 11, 2008) and Primary Dealer Credit Facility (PDCF, created on March 16, 2008). However, these unconventional policies were intended for primary dealers and not for depository institutions. Hence, they should not have any significant effect on the identification of conventional policy based on fed funds rate and reserve market variables.

balances (ccb_t), instead of total reserves following the suggestion of Carpenter and Demiralp (2008).

The series ip_t, nbr_t, tr_t, tb_t, ccb_t and ff_t are released by the Board of Governors, while p_t and cp_t are obtained from the US Bureau of Labor Statistics and the International Financial Statistics, respectively. Following the literature, we use seasonally adjusted monthly data expressed in logarithms, except the fed funds rate which is in level.

To extract the term structure factors, we follow Diebold and Li (2006) and consider a three-factor Nelson-Siegel yield curve. Specifically, define the factor loadings $\alpha_{\tau,1} = 1$, $\alpha_{\tau,2} = \left(\frac{1-e^{-\lambda_t \tau}}{\lambda_t \tau}\right)$, and $\alpha_{\tau,3} = \left(\frac{1-e^{-\lambda_t \tau}}{\lambda_t \tau} - e^{-\lambda_t \tau}\right)$ where λ_t governs the exponential decay rate and is set to 0.0609 for all t. We obtain the factors ($f_{1,t}$, $f_{2,t}$ and $f_{3,t}$) by estimating the following three-factor model for each month in our sample via OLS:

$$y_t(\tau) = f_{1,t}\alpha_{\tau,1} + f_{2,t}\alpha_{\tau,2} + f_{3,t}\alpha_{\tau,3}, \tag{1}$$

where $y_t(\tau)$ is the yield in month t on the zero-coupon US government bonds with a maturity of τ months. We estimate this model using Fama-Bliss discount bond yields with maturities of 1, 3, 12, 24, 36, 48 and 60 months from the Center for Research in Security Prices (CRSP).[14]

The interpretations of the factors are relatively standard: The first factor $f_{1,t}$ is a long-term factor which governs the level of the yield curve. An increase in $f_{1,t}$ increases all yields equally and, thus, the level of the yield curve. The second factor $f_{2,t}$ is a short-term factor which can be interpreted as the negative of the yield curve slope. An increase in $f_{2,t}$ increases short yields more than long yields and, thus, decreases the slope of the yield curve. Finally, the third factor $f_{3,t}$ is a medium-term factor which is closely related to the curvature of the yield curve. An increase in $f_{3,t}$ has little effects on very short or very long yields but increases medium-term yields, thus increasing the curvature of the yield curve.

4 Preliminary Analysis

In order to distinguish between exogenous and endogenous monetary policy components in a SVAR with conditionally homoskedastic shocks, one needs to impose certain restrictions on the contemporaneous relations between the variables. One such so-called identification strategy is the recursive approach where only one of any two variables can have a contemporaneous effect on the other. Although simple and commonly used, the recursive approach forces a choice between a pure interest rate or a pure reserve targeting, when analyzing the effects of monetary policy on other variables. The common approach in the literature is to use the fed funds rate as the monetary policy indicator. In this section, we provide some preliminary empirical evidence that the choice of monetary policy indicator in standard approaches is important when analyzing the effects of monetary policy shocks on the

[14] Diebold and Li (2006) pool individual bonds into fixed maturities and obtain a larger set of maturities by interpolation. The difference in the set of yields used does not significantly affect the extracted term structure factors. One can obtain monthly data on the yields used in Diebold and Li (2006) between 1970 and 2001 from http://www.ssc.upenn.edu/ fdiebold/papers/paper49/. This allows us to compare the term structure factors extracted from the set of yields used in Diebold and Li (2006) and those extracted from the set of yields used in our paper. For the period between 1970 and 2001, the correlations between the factors extracted from the two sets of yields are, respectively, 0.97, 0.98 and 0.90 for the first, second and third factors. Time-series graphs of these two sets of factors (not displayed) also reveal that the differences between them are only minor.

term structure of interest rates, especially in the context of the financial crisis. That is, we show that one can reach completely different conclusions depending on the choice of the monetary policy indicator even before, but more so, when we include the financial crisis.

To this end, we follow the procedure proposed by Evans and Marshall (1998). In addition, we consider two different recursive identification strategies for each SVAR. Specifically, for a given term structure factor $f_{i,t}$ ($i = 1, 2, 3$), we start with the following κ-order SVAR[15]

$$A_i \begin{pmatrix} z_t \\ f_{i,t} \end{pmatrix} = \sum_{j=1}^{\kappa} B_{i,j} \begin{pmatrix} z_{t-j} \\ f_{i,t-j} \end{pmatrix} + \begin{pmatrix} \varepsilon_{z,t} \\ \varepsilon_{f_i,t} \end{pmatrix}, \tag{2}$$

where A_i and $B_{i,j}$ can be partitioned as follows:

$$A_i = \begin{pmatrix} A_{zz} & A_{zi} \\ A_{iz} & A_{ii} \end{pmatrix} \quad \text{and} \quad B_{i,j} = \begin{pmatrix} B_{zz,j} & B_{zi,j} \\ B_{iz,j} & B_{ii,j} \end{pmatrix}, \tag{3}$$

and κ is set to 6. The state vector z_t includes the following base set of variables: output (ip_t), price level (p_t), commodity price index, (cp_t) and the reserve variables (nbr_t, tr_t, ff_t). The matrix A_i contains the parameters capturing the contemporaneous interactions among variables. In this framework, extracting the structural innovations, $\varepsilon_t = [\varepsilon'_{z,t}, \varepsilon_{f_i,t}]'$, requires statistical innovations, ν_t, obtained from the estimation of a VAR process for $[z'_t, f_{i,t}]'$ and the knowledge of the matrix A_i. The two recursive identification strategies that we consider in this section imply that the matrix A_i is lower triangular, where the contemporaneous effect of one variable on another is determined by the order of variables in $[z'_t, f_{i,t}]'$. In both recursive identification strategies, we follow Evans and Marshall (1998) and assume that the monetary authority observes output and prices before setting the monetary policy, but these variables react to monetary policy with a lag. In the first approach, we assume that the fed funds rate is the monetary policy indicator, where it has a contemporaneous effect on nonborrowed reserves and total reserves. This in turn implies that the variables of z_t in the first approach are ordered as $z_t = [ip_t, p_t, cp_t, ff_t, nbr_t, tr_t]'$. In the second approach, we assume that the portion of nonborrowed reserves orthogonal to total reserves is the monetary policy indicator by imposing the restriction that nonborrowed reserves have no contemporaneous effect on total reserves, while they have a current effect on the fed funds rate. This in turn implies that the variables of z_t in the second approach are ordered as $z_t = [ip_t, p_t, cp_t, tr_t, nbr_t, ff_t]'$. The matrix $B_{i,j}$ captures the dynamic feedbacks across variables. To ensure that the parameter estimates and the dynamics of the base set of variables are the same regardless of the term structure factor considered, the restrictions $B_{zi,j} = 0$ for $i = 1, 2, 3$ and $j = 1, \ldots, 6$ are imposed.

We estimate the SVAR via seemingly unrelated regression equations (SURE) for each term structure factor separately. Figure 2 presents the impulse response functions of selected variables to a one standard deviation expansionary monetary policy shock. We first briefly discuss the results for selected base variables before focusing on the three factors underlying the term structure of interest rates. Before the financial crisis, the impulse response functions of selected variables such as output, price and the fed funds rate are fairly similar regardless of the

[15]The SVAR specification in Equation (2) also includes a constant term as well as dummy variables for the periods September 2001, April 2008 and March 2008-August 2008. These dummy variables are included to control for possible anomalies in the data. For the sake of exposition, we do not present these terms explicitly in Equation (2).

monetary policy indicator considered. More precisely, the reaction of output is muted in the short run but positive in the long run, price does not respond over most horizons, while the reaction of the fed funds rate remains significantly negative between 6 and 16 months.[16] *The reactions of these variables continue to be similar when we consider the fed funds rate as the monetary policy indicator over the whole sample period including the financial crisis. However, the reactions change dramatically following the financial crisis when we consider nonborrowed reserves as the monetary policy indicator. The reactions of output, price, and the fed funds rate become much smaller in magnitude and statistically insignificant, suggesting the major role played by the financial crisis on the reaction of these variables to monetary policy shocks.*

We now consider the impulse response functions of the term structure factors to an expansionary monetary policy shock. Our results suggest that the response of the yield curve to a monetary policy shock does not seem to change significantly following the financial crisis when the fed funds rate is assumed to be the indicator of monetary policy. Specifically, an expansionary monetary policy shock results in a decrease in the level, an increase in the slope and a decrease in the curvature of the yield curve in the short-run. In the long run, an expansionary monetary policy shock decreases the level and the slope but increases the curvature of the yield curve.

On the other hand, our result based on nonborrowed reserves as the monetary policy indicator suggest that there are certain differences even before the financial crisis. First, the level does not decrease significantly in the long run. Secondly, the slope of the yield curve decreases in the short run. Thirdly, the curvature no longer reacts significantly negatively. More importantly, when we consider the whole sample period including the financial crisis, the reactions of the term structure factors to monetary policy shocks change dramatically. Although during the financial crisis an expansionary monetary policy shock decreases the level and slope of the yield curve, these effects are much smaller in magnitude and dissipate over time more rapidly compared to those obtained when the policy indicator is the fed funds rate.

One can also construct the impulse response functions of yields to a monetary policy shock from the impulse response functions of the term structure factors. To see this, recall that the yield on a zero-coupon Treasury bonds with τ months to maturity is expressed as a linear function of the term structure factors and factor loadings as in Equation (1). Thus, the impulse response functions of yields are computed as follows

$$\frac{\partial y_{t+j}(\tau)}{\partial \varepsilon_{s,t}} = \alpha_{\tau,1}\frac{\partial f_{1,t+j}}{\partial \varepsilon_{s,t}} + \alpha_{\tau,2}\frac{\partial f_{2,t+j}}{\partial \varepsilon_{s,t}} + \alpha_{\tau,3}\frac{\partial f_{3,t+j}}{\partial \varepsilon_{s,t}}, \tag{4}$$

where $\frac{\partial f_{i,t+j}}{\partial \varepsilon_{s,t}}$ for $i = 1, 2, 3$ are the impulse response functions of the term structure factors following a monetary policy shock $\varepsilon_{s,t}$, which is an element of $\varepsilon_{z,t}$. Figure 3 presents these impulse response functions. Even before the financial crisis, one can easily see that the impulse response functions of yields are different depending on the choice of the monetary policy indicator. When the fed funds rate is assumed to be the monetary policy indicator, the response of yields with different maturities is significant and negative both in the short and medium run. This negative response is stronger and longer lived in the short-end of the yield curve than in the long-end. On the other hand, when the monetary policy indicator is assumed to be nonborrowed reserves, the response of yields with

[16] However, the negative reaction of the fed funds rate is stronger and longer-lived when the fed funds rate is the monetary policy indicator instead of nonborrowed reserves. Also, price reacts negatively in the short and medium runs when the fed funds rate is assumed to be the monetary policy indicator, while it does not react significantly when the monetary policy indicator is nonborrowed reserves.

different maturities is significant and negative in the short run and becomes insignificant only after three months. Once again, these differences become even more striking following the financial crisis. On the one hand, when the fed funds rate is the monetary policy indicator, the impulse response functions of yields do not change significantly following the financial crisis. On the other hand, when the monetary policy indicator is nonborrowed reserves, the responses of yields become not only mostly insignificant but also much smaller in magnitude.

To summarize, these preliminary results expose the potential problems and discrepancies associated with the choice for the monetary policy indicator imposed by the commonly used identification strategies. In other words, the effect of monetary policy shocks on the yield curve changes significantly depending on the choice of the indicator. On the one hand, the conclusions based on the fed funds rate as the indicator are similar before and during the financial crisis, suggesting that conventional monetary policies were efficient in affecting the term structure of interest rates. On the other hand, when we consider nonborrowed reserves as the indicator, the responses of the term structure factors become insignificant during the financial crisis, suggesting that conventional monetary policies were mostly ineffective in changing the term structure of interest rates. This in turn does not help to settle the debate on the effectiveness of monetary policy and calls for a more robust approach.

5 Methodology

In this section, we analyze the response of the term structure factors to monetary policy shocks from a SVAR involving the same variables as in Equation (2). However, we now identify monetary policy shocks based on a flexible approach, rather than the recursive identification strategy. In this section, we first discuss a minimal set of restrictions that we impose on some contemporaneous interactions of variables, so that the estimated system is a coherent framework for the analysis of monetary policy. We then discuss our identification strategy based on the conditional heteroskedasticity of the structural innovations and the estimation approach.

5.1 The Structural Vector Autoregressive Framework

Our identification strategy allows us to identify monetary policy shocks without having to impose any restrictions on the elements of the matrix A_i, unlike the traditional identification strategies. Nonetheless, our empirical approach places a minimal set of cross-equation restrictions on the elements of A_i to ensure that the estimated systems are a coherent framework for the analysis of monetary policy. Specifically, we consider the simple formulation of the reserve market:

$$\nu_{tr,t} = -\alpha \nu_{ff,t} + \sigma_d \varepsilon_{d,t}, \tag{5a}$$

$$(\nu_{tr,t} - \nu_{nbr,t}) = \beta \nu_{ff,t} - \sigma_b \varepsilon_{b,t}, \tag{5b}$$

$$\nu_{nbr,t} = \phi_d \sigma_d \varepsilon_{d,t} - \phi_b \sigma_b \varepsilon_{b,t} + \sigma_s \varepsilon_{s,t}, \tag{5c}$$

where $\nu_{\cdot,t}$ and $\varepsilon_{\cdot,t}$ denote statistical and structural innovations as before. The structural innovation $\varepsilon_{s,t}$ is the monetary policy shock representing an unexpected exogenous policy action taken by the Fed, while $\varepsilon_{d,t}$ and $\varepsilon_{b,t}$ denote, respectively, shocks to the demand for total reserves and the supply of borrowed reserves by commercial banks. The parameters σ_s, σ_d, and σ_b scale the structural innovations. ϕ_d and ϕ_b are parameters measuring the strength of the Fed's responses to shocks to the total demand for reserves and the supply of borrowed reserves, respectively. α and β are slope parameters that are expected to be positive.

The formulation in Equations 5 is a simple model of demand and supply of reserves. Specifically, Equation (5a) represents the banks' demand for total reserves in innovation form. Equations (5b) and (5c) represent the kinked supply of reserves. In particular, Equation (5b) is the banks' supply of borrowed reserves in innovation form, under the assumption of a zero discount-rate innovation. Equation (5c) describes the procedure that may be used by the Fed to inject reserves in the financial system. This model is often used in the empirical literature and has proven useful to analyze monetary policy (e.g. Brunner (1994), Strongin (1995), Bernanke and Mihov (1998), Normandin and Phaneuf (2004), Lanne and Lutkepohl (2008), Bouakez and Normandin (2010), and Lutkepohl (2012))

In addition to imposing the equilibrium solution of the reserve market formulation in Equations (5) in the SVAR, we also restrict the first 6 elements in the last columns (corresponding to the term structure factor) of the matrices A_i and $B_{i,j}$ to be zero as in Section 4, which ensures that the estimates and dynamics of the base set of variables are the same across various SVARs associated with the different term structure factors. These two sets of restrictions yield the following relation between the statistical and structural innovations:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & 0 \\ a_{41} & a_{42} & a_{43} & \frac{1+\phi_b}{\sigma_s} & -\frac{\phi_d+\phi_b}{\sigma_s} & \frac{\beta\phi_b-\alpha\phi_d}{\sigma_s} & 0 \\ a_{51} & a_{52} & a_{53} & 0 & \frac{1}{\sigma_d} & \frac{\alpha}{\sigma_d} & 0 \\ a_{61} & a_{62} & a_{63} & \frac{1}{\sigma_b} & -\frac{1}{\sigma_b} & \frac{\beta}{\sigma_b} & 0 \\ a_{i,71} & a_{i,72} & a_{i,73} & a_{i,74} & a_{i,75} & a_{i,76} & a_{i,77} \end{pmatrix} \begin{pmatrix} \nu_{ip,t} \\ \nu_{p,t} \\ \nu_{cp,t} \\ \nu_{nbr,t} \\ \nu_{tr,t} \\ \nu_{ff,t} \\ \nu_{f_i,t} \end{pmatrix} = \begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \\ \varepsilon_{s,t} \\ \varepsilon_{d,t} \\ \varepsilon_{b,t} \\ \varepsilon_{f_i,t} \end{pmatrix}, \tag{6}$$

where $\varepsilon_{f_i,t}$ for $i = 1, 2, 3$ are the structural innovations related to the last equations of each SVAR.

Our identification strategy discussed below allows us to leave all other elements of the matrix A_i unrestricted, in contrast to the recursive identification where A_i is lower triangular. Undoubtedly, this has several advantages. First, the statistical innovation of the monetary policy indicator, $\nu_{s,t}$, can be written as a linear combination of the reserve variables as follows:

$$\nu_{s,t} = (1 + \phi_b)\nu_{nbr,t} - (\phi_d + \phi_b)\nu_{tr,t} + (\beta\phi_b - \alpha\phi_d)\nu_{ff,t}. \tag{7}$$

Equation (7) nests common alternative descriptions of Fed operating procedures as special cases. For example, imposing the restrictions $\phi_d = 1$ and $\phi_b = -1$ implies that the Fed fully offsets shocks to total reserves demand and borrowing supply, so that it targets solely the fed funds rate which becomes the policy indicator, i.e. $\nu_{s,t} = -(\alpha + \beta)\nu_{ff,t}$. In contrast, the restrictions $\phi_d = \phi_b = 0$ imply that the Fed targets nonborrowed reserves, so that $\nu_{s,t} = \nu_{nbr,t}$. Importantly, our identification strategy allows the possibility that the Fed adopts a mixed strategy where it targets neither the interest rate nor nonborrowed reserves exclusively.

Secondly, rewriting the fourth equation of the SVAR system in Equation (6) yields

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

where $\rho_{4j} = -a_{4j}\sigma_s$, for $j = 1, 2, 3$, capture the systematic responses of the Fed in setting the monetary policy to changes in the non-reserve variables. Equation (8) implies that the statistical innovation of the monetary policy indicator, $\nu_{s,t}$, can be decomposed into systematic responses of the Fed and the structural innovation in monetary policy.

Finally, the SVAR in Equation (6) implies that the monetary policy shock affects contemporaneously all variables. Hence, these contemporaneous interactions allow one to capture potential salient interdependences between the various variables and the policy variables.

5.2 Identification

Our identification strategy is based on the assumption that the structural innovations of the SVAR in Equation (6) are conditionally heteroskedastic. The identification of the SVAR where the conditional variances of the structural innovations are modeled as GARCH processes follows from Sentana and Fiorentini (2001) and is applied in Normandin and Phaneuf (2004).[17] Here, we employ this approach and briefly discuss the intuition behind it. In this and next sections, we omit the subscript i from the notation for simplicity.

To see how the assumption of conditional heteroskedasticity allows us to identify the structural innovations of the SVAR, let $\Sigma = E(\nu_t\nu_t')$ and $\Sigma_t = E_{t-1}(\nu_t\nu_t')$ denote, respectively, the unconditional and conditional non-diagonal covariance matrices of the non-orthogonal statistical innovations. Similarly, let $\Gamma = E(\varepsilon_t\varepsilon_t')$ and $\Gamma_t = E_{t-1}(\varepsilon_t\varepsilon_t')$ denote, respectively, the unconditional and conditional diagonal covariance matrices of the orthogonal structural innovations. In this framework, without loss of generality, we normalize the unconditional covariance matrix of the structural innovations to the identity matrix, i.e. $\Gamma = I$. Under the assumption of conditional homoskedasicity of the structural innovations, the SVAR implies

$$\Sigma = A^{-1}A^{-1\prime}. \tag{9}$$

In the context of an n-variable system, the distinct elements of Σ allows us to identify $\frac{n(n+1)}{2}$ of the n^2 elements of A, leaving $\frac{n(n-1)}{2}$ elements to be identified. Under the common assumption that the structural innovations are homoskedastic, one needs to impose at least $\frac{n(n-1)}{2}$ restrictions on the elements of A to be able to identify the structural innovations. For example, the recursive identification strategy discussed in Section 4 imposes a lower triangular structure on the matrix A, which corresponds to the $\frac{n(n-1)}{2}$ restrictions necessary to achieve identification.

On the other hand, when the structural innovations are conditionally heteroskedastic, in addition to the relation between their unconditional covariance matrices in Equation (9), we have the following relation between the conditional covariance matrices of the structural and statistical innovations:

$$\Sigma_t = A^{-1}\Gamma_t A^{-1\prime}, \tag{10}$$

which in turn implies

$$\Sigma_t - \Sigma_{t-1} = A^{-1}(\Gamma_t - \Gamma_{t-1})A^{-1\prime}. \tag{11}$$

[17] Alternatively, one can model the conditional variances of the structural innovations as Markov regime switching processes. Lanne, Lutkepohl, and Maciejowska (2010) derive the conditions under which identification can be achieved in this context and Lanne and Lutkepohl (2008) apply this approach to analyze the effects of monetary policy shocks on macroeconomic aggregates before the financial crisis.

These relations allow us to identify $\frac{k(k+1)}{2}$ additional parameters of A with k being the rank of the matrix $(\Gamma_t - \Gamma_{t-1})$. Hence, if $(\Gamma_t - \Gamma_{t-1})$ has a rank of at least $(n-1)$, Equation (9) along with Equation (11) allow us to identify all n^2 elements of A without having to impose any restrictions. In our context, a necessary order condition for this is that the conditional variances of at least $(n-1)$ structural innovations are time-varying.

5.3 Estimation

The SVAR in Equation (6) can be estimated via a two-step procedure. In the first step, we obtain the statistical innovations by estimating κ-order VAR processes via SURE, where we set κ to 6. To be consistent with the restriction that $A_{zi} = B_{zi,j} = 0$ for $i = 1, 2, 3$ and $j = 1, 2, \ldots, \kappa$, we set to zero all coefficients that capture the effect of lag values of the term structure factors on the base set of variables in each VAR process. Similar to our empirical approach in Section 4, we estimate three separate SVARs, one for each of the three term structure factors.

In the second step, we estimate the SVAR parameters as well as those of the conditional covariance matrix of the structural innovations. To do so, we assume that the conditional covariance matrix of the structural innovations can be described by:

$$\Gamma_t = (I - \Theta_1 - \Theta_2) + \Theta_1 \odot \varepsilon_{t-1}\varepsilon'_{t-1} + \Theta_2 \odot \Gamma_{t-1}, \tag{12}$$

where $\odot$ denotes element-by-element multiplications and Θ_1 and Θ_2 are diagonal matrices. We normalize the intercept of the process in Equation (12), so that the unconditional covariance matrix of the structural innovations is the identity, in line with our normalization $\Gamma = I$. The conditional variance specification in Equation (12) implies a GARCH(1,1) specification for some (all) structural innovations if Θ_1 and Θ_2 are positive semi-definite (positive definite) and $I - \Theta_1 - \Theta_2$ is positive definite. We estimate the elements of the matrices A, Θ_1 and Θ_2 by maximum likelihood, assuming that the statistical innovations are conditionally normally distributed. In this context, the empirical likelihood function is constructed from the estimated statistical innovations, obtained in the first step, and the estimated conditional covariance matrix Σ_t. To compute the conditional covariance matrix Σ_t, we first initialize Γ_t and $\varepsilon_t\varepsilon'_t$ to the identity matrix in period κ, i.e. $\Gamma_\kappa = \varepsilon_\kappa\varepsilon'_\kappa = I$. Then, the conditional covariance matrix Σ_t is computed recursively based on Equations (10) and (12) for given values of A, Θ_1, and Θ_2 and the initial values for Γ_t and $\varepsilon_t\varepsilon'_t$ in period κ.

6 Empirical Results

6.1 Parameter Estimates

In this section, we present the estimates of certain parameters of the SVAR and the conditional variance specification of the structural innovations. We start with the conditional variance specification, which is crucial for our identification strategy. Table 1 reports the parameter estimates of the GARCH(1,1) processes for the sample period before the financial crisis and the whole sample period. First, all the structural innovations, except those related to the first equation of the SVAR in (6), i.e. $\varepsilon_{1,t}$, have significant ARCH and GARCH coefficients. The structural innovations related to the reserve market, i.e. $\varepsilon_{s,t}$, $\varepsilon_{d,t}$ and $\varepsilon_{b,t}$, as well as those related to the second equation, i.e.

$\varepsilon_{2,t}$, have highly persistent conditional variances - as measured by the sum of the ARCH and GARCH coefficients. Similarly, the structural innovations related to the last equation of the SVAR that includes the term structure factors, i.e. $\varepsilon_{f_i,t}$ for $i = 1, 2, 3$, have fairly persistent conditional variances. However, the structural innovations related to the first and third equations, i.e. $\varepsilon_{1,t}$ and $\varepsilon_{3,t}$, exhibit only moderately persistent conditional variances. Secondly, the parameter estimates are quite similar whether we estimate the SVAR for the sample period that includes or excludes the financial crisis. It is worth stressing that, regardless of the sample period considered, the order condition for identification is satisfied, since at least six of the structural innovations in the SVAR are conditionally heteroskedastic. In other words, these results confirm the validity of our identification strategy and suggest that we can identify monetary policy shocks through the conditional heteroskedasticity of the structural innovations.

Table 2 presents the estimates of the reserve-market parameters for the whole sample period as well as the sample period before the financial crisis. This allows us to analyze whether our identification strategy implies an empirically plausible description of the reserve market. The high and significant coefficient estimates of ϕ_d suggest that the the Fed offsets almost entirely shocks to total demand for reserves both before and during the financial crisis. On the other hand, the estimates of ϕ_b suggest that the Fed does not respond significantly to shocks to the supply of borrowed reserves regardless of whether we include or exclude the financial crisis. The estimate of the slope of the demand for total reserves, -α, has the predicted sign but is significantly different than zero only for the whole sample including the financial crisis. The slope of the supply of borrowed reserves, β, also displays the predicted sign, but is not significantly different than zero in both samples. Also, the slope of the demand for total reserves and that of the supply for borrowed reserves increase when we include the financial crisis in our sample period. This suggests that there might have been a structural break as a result of the unprecedented events during the financial crisis. Finally, there are also few changes in the parameters scaling the structural innovations of the reserve market variables, especially for the supply of borrowed reserves, when we consider the whole sample including the financial crisis. Once again, this is not surprising given the dramatic changes that took place in, not only financial markets, but also the market for bank reserves.

An advantage of our identification strategy is that we can test whether the restrictions imposed on the SVAR by the recursive identification strategy are empirically plausible. These are zero restrictions on the elements of the matrices A_i such that these matrices are lower triangular. The p-values of the χ^2 statistics for the joint test of these zero restrictions when the fed funds rate is assumed to be the indicator of monetary policy are both zero, irrespective of whether we include or exclude the financial crisis. Similarly, the p-values of the χ^2 statistics when the indicator of monetary policy is nonborrowed reserves are zero and 0.055, respectively, for sample periods excluding and including the financial crisis. The rejection of these restrictions may reflect the notion that the Fed does not pursue a pure interest rate or nonborrowed reserves targeting.

This finding confirms the limitations in analyzing the effect of monetary policy shocks on the term structure factors and yields based on the recursive identification strategy reported in Section 4. The recursive identification strategy assumes that either the fed funds or nonborrowed reserves is the exclusive indicator of monetary policy. On the other hand, our approach does not suffer from this problem as it allows the Fed to adopt a mixed strategy in line with the empirical evidence. This flexibility is especially relevant during the financial crisis.

6.2 Impulse Response Functions

Figure 4 presents the impulse response functions of the base set of variables and the term structure factors to a one standard deviation expansionary monetary policy shock. Although there are certain differences, the impulse response functions of the base set of variables before the financial crisis resemble those from the recursive identification strategy based on either the fed funds rate or nonborrowed reserves as the monetary policy indicator. More precisely, output responds positively in the medium to long run, price does not respond significantly and the fed funds rate responds negatively in the short run. The reactions of output and the fed funds rate are generally stronger than those obtained from the recursive identification strategy, regardless of the monetary policy indicator used. On the other hand, the reactions of the term structure factors based on our approach before the financial crisis resembles more those based on the recursive identification scheme when the monetary policy indicator is the nonborrowed reserves. Specifically, the level of the yield curve decreases significantly in the short and medium runs following an expansionary monetary policy. The slope does not react significantly in the short run but decreases significantly in the medium run. The curvature, on the other hand, decreases significantly only in the very short run but this reaction becomes insignificant after one month. The reactions of the term structure factors computed from our approach are much stronger compared to those based on the recursive identification strategy with either the fed funds rate or nonborrowed reserves as the monetary policy indicator.

The impulse response functions based on the whole sample period including the financial crisis reveals the impact of the financial crisis. Compared to the sample period that excludes the financial crisis, the reactions of the base set of variables are much weaker and mostly insignificant when we include the data during the recent financial crisis. Similarly, the reactions of the term structure factors are much weaker and mostly insignificant when we include the financial crisis. More precisely, the level decreases only slightly but significantly in the short run and does not react significantly in the medium or long run; the slope does not react significantly at all in any horizon; and the reaction of the curvature is mostly insignificant with the exception that it decreases slightly in the very short run and increases slightly in the very long run. In other words, the reactions of the term structure factors are, in most part, no longer statistically or economically significant when we include the financial crisis. These results can also be observed from the reaction of yields (see Figure 5). Before the financial crisis, all yields decrease following an expansionary monetary policy shock, a fact reflected by the negative reaction of the level of the yield curve. However, yields react very slightly and only in the very short run when we include the financial crisis in our sample. The reactions of the term structure factors (as well as yields) are similar to but relatively weaker than those based on the recursive identification strategy when we include the financial crisis and the monetary policy indicator is nonborrowed reserves.

To summarize, these results suggest that the monetary policy might not have been as effective in changing the yield curve during the financial crisis as before. Specifically, our results suggest that most variables, including the term structure factors, have reacted significantly to an expansionary monetary policy shock before the financial crisis. However, these reactions are neither statistically nor economically significant when we include the financial crisis. What is quite remarkable is the magnitude of these changes following the financial crisis considering that it is only a very small part of the whole sample period. These results are similar to those based on the recursive identification strategy when the monetary policy indicator is nonborrowed reserves. However, they are in contrast to what is observed when we assume that the fed funds rate is the monetary policy indicator. Given that the fed funds rate might not be the only tool that the Fed uses, especially during the financial crisis, one may reach misleading conclusions on the effectiveness of monetary policy by assuming that the fed funds rate is the indicator. On the other hand, the results based on our approach are robust to this problem, given that, in our framework, the Fed is allowed to adopt a mixed strategy.

6.3 Variance Decompositions

Figure 4 also presents the variance decomposition for selected variables in the SVAR. These results suggest that monetary policy shocks explain a non-negligible percentage of variation in the variables prior to the recent financial crisis. For output and price, it varies between 5% and 10% in the short run and increases to approximately 30% and 15%, respectively, in the long run. For the fed funds rate, this percentage varies between 15% and 40% in the short run and decreases to approximately 30% in the long run. Monetary policy shocks explain between 10% and 40% of the variation in the level of the yield curve and between 35% and 50% in the medium and long run. The percentage of variation in the slope and curvature of the yield curve that is due to monetary policy shocks is less than 10% in the short run and increases to approximately 45% and 30%, respectively, in the long run. The variance decompositions of the term structure factors prior to the financial crisis imply a similar pattern for the variance decompositions of yields presented in Figure 5. That is, prior to the financial crisis, monetary policy shocks explain nearly 15% of the variation of variance in yields in the short run and this percentage increases to around 40% in the long run.

Turning to the results based on the whole sample period including the financial crisis reveals a stark contrast. Monetary policy shocks explain only a negligible percentage of the variations in output, price and the fed funds rate, as well as the term structure factors. This implies that monetary policy shocks do not explain any variation in the yields. The variance decomposition results suggest a similar conclusion to that based on the impulse response functions. In particular, the findings indicate that the monetary policy might not have been as effective in changing the yield curve during the financial crisis as before.

6.4 Initial Response Decomposition

A monetary policy shock affects investors' expectations about future values of certain economic fundamentals, which in turn determine the yields on US treasuries. In Section 6.2, we provided empirical evidence that there has been a significant change in the effect of monetary policy shocks on the yield curve following the financial crisis. However, so far, we have been silent on how the financial crisis might have affected investors' expectations about future values of economic fundamentals underlying the yield curve. In this section, we take a closer look at the effect of monetary policy shocks on investors' expectations about economic fundamentals including and excluding the financial crisis.

Given that the change in investors' expectations about economic fundamentals due to monetary policy shocks cannot be directly observed, a structural approach is required. In this section, we follow, among others, Campbell and Ammer (1993) and decompose the unexpected changes in the yields into unexpected changes in the future values of three economic fundamentals: inflation, real rate of return, and risk premium. We then decompose the initial responses of the yields to monetary policy shocks reported in Section 6.2 into the initial responses of expectations about the future value of these three economic fundamentals. This approach allows us to understand the fundamental economic reasons underlying the significant change in the effect of monetary policy shocks on the yield curve following the financial crisis.

Based on Campbell and Ammer (1993), we show in the appendix that the unexpected change in the yield of zero coupon bond with a maturity of τ in period $t+1$, $\tilde{y}_{t+1}(\tau) = E_{t+1}[y_{t+1}(\tau)] - E_t[y_{t+1}(\tau)]$, can be decomposed into unexpected changes in future inflation ($\tilde{y}_{\pi,t+1}(\tau)$), real rate of return ($\tilde{y}_{r,t+1}(\tau)$), and risk premium (excess returns) ($\tilde{y}_{x,t+1}(\tau)$) as follows:

$$\tilde{y}_{t+1}(\tau) = \tilde{y}_{\pi,t+1}(\tau) + \tilde{y}_{r,t+1}(\tau) + \tilde{y}_{x,t+1}(\tau), \tag{13}$$

where

$$\tilde{y}_{\pi,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[\pi_{t+1+j}], \tag{14a}$$

$$\tilde{y}_{r,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[r_{t+1+j}], \tag{14b}$$

$$\tilde{y}_{x,t+1}(\tau) = \frac{1}{\tau}(E_{t+1} - E_t)\sum_{j=1}^{\tau}[x_{t+1+j}(\tau + 1 - j)], \tag{14c}$$

and π_t, r_t and $x_t(\tau)$ are inflation, real rate of return and risk premium (excess return) on a zero coupon bond with a maturity of τ in period t, respectively.

The implementation of this decomposition approach requires empirical measures for $\tilde{y}_{\pi,t+1}(\tau)$, $\tilde{y}_{r,t+1}(\tau)$ and $\tilde{y}_{x,t+1}(\tau)$. Campbell and Ammer (1993) suggest using a first-order reduced form VAR as a forecasting model to construct expectations. Specifically, they model the dynamics of the real interest rate, the change in the nominal interest rate, and the spread between the yields on bonds with long and short maturities. Based on estimated parameters and statistical innovations, they decompose the yields into their components. Our empirical approach differs from that of Campbell and Ammer (1993) in certain dimensions. First, to be consistent, we use a six-order SVAR (written as a first-order SVAR in companion form) with the same set of variables as in Sections 4 and 6.2. More importantly, the decomposition of the yields is just an intermediate step, as we are ultimately interested in decomposing the initial responses of the yields to monetary policy shocks into the initial responses of their components.

To analyze how the components of the yields are related to the underlying structural innovations, especially that of monetary policy, we start with the same SVAR as in Equation (2). For ease of analytical tractability, we rewrite the SVAR in Equation (2) as a first-order SVAR that is consistent with Equation (6) and includes all three term structure factors in the state vector simultaneously:

$$\tilde{A}\tilde{z}_t = \tilde{B}\tilde{z}_{t-1} + \tilde{\varepsilon}_t, \tag{15}$$

where

$$\begin{aligned} \tilde{z}_t &= [z_t, f_{1,t}, f_{2,t}, f_{3,t}, \ldots, z_{t-\kappa}, f_{1,t-\kappa}, f_{2,t-\kappa}, f_{3,t-\kappa}]', \\ \tilde{\varepsilon}_t &= [\varepsilon_{z,t}, \varepsilon_{f_1,t}, \varepsilon_{f_2,t}, \varepsilon_{f_3,t}, 0, \ldots, 0]', \end{aligned}$$

and $\tilde{A}$ and $\tilde{B}$ are conforming matrices defined in the appendix. The corresponding first-order reduced form VAR can be written as

$$\tilde{z}_t = \Phi \tilde{z}_{t-1} + \tilde{\nu}_t, \tag{16}$$

where $\Phi = \tilde{A}^{-1}\tilde{B}$, $\tilde{\nu}_t = \tilde{A}^{-1}\tilde{\varepsilon}_t$, $E[\tilde{\nu}_t\tilde{\nu}_t'] = \tilde{A}^{-1}\tilde{A}^{-1\prime}$. In the appendix, we show that $\tilde{y}_{\pi,t+1}(\tau)$, $\tilde{y}_{r,t+1}(\tau)$ and $\tilde{y}_{x,t+1}(\tau)$ can be written as linear functions of the structural innovations. Specifically, let e_i denote the i^{th} column of the $N \times N$ identity matrix where N is the number of rows in $\tilde{z}_t$. Then,

$$\tilde{y}_{t+1}(\tau) = k_y(\tau)\tilde{\varepsilon}_{t+1}, \tag{17a}$$

$$\tilde{y}_{\pi,t+1}(\tau) = k_\pi(\tau)\tilde{\varepsilon}_{t+1}, \tag{17b}$$

$$\tilde{y}_{r,t+1}(\tau) = k_r(\tau)\tilde{\varepsilon}_{t+1}, \tag{17c}$$

$$\tilde{y}_{x,t+1}(\tau) = k_x(\tau)\tilde{\varepsilon}_{t+1}, \tag{17d}$$

where

$$k_y(\tau) = (\alpha_{\tau,1}e_7' + \alpha_{\tau,2}e_8' + \alpha_{\tau,3}e_9')\tilde{A}^{-1}, \tag{18a}$$

$$k_\pi(\tau) = \frac{1}{\tau}e_2'(\Phi - I)\sum_{j=1}^{\tau}\Phi^{j-1}\tilde{A}^{-1}, \tag{18b}$$

$$k_r(\tau) = \frac{1}{\tau}(\alpha_{1,1}e_7' + \alpha_{1,2}e_8' + \alpha_{1,3}e_9')\sum_{j=1}^{\tau}\Phi^{j-1}\tilde{A}^{-1} - k_\pi(\tau), \tag{18c}$$

$$k_x(\tau) = (k_y(\tau) - k_\pi(\tau) - k_r(\tau)), \tag{18d}$$

and $\alpha_{\tau,i}$ for $i = 1, 2, 3$ are defined in Section 3.

Before decomposing the initial response of the yields to monetary policy shocks to initial responses of their components, we first analyze the relative importance of each component in determining the fluctuations of the yields. This can be done by decomposing the total variance of unexpected changes in the yields into variances of their components and the covariances between them as follows:

$$\begin{aligned} var(\tilde{y}_{t+1}(\tau)) &= var(\tilde{y}_{\pi,t+1}(\tau)) + var(\tilde{y}_{r,t+1}(\tau)) + var(\tilde{y}_{x,t+1}(\tau)) \\ &+ 2cov(\tilde{y}_{\pi,t+1}(\tau), \tilde{y}_{r,t+1}(\tau)) + 2cov(\tilde{y}_{\pi,t+1}(\tau), \tilde{y}_{x,t+1}(\tau)) + 2cov(\tilde{y}_{r,t+1}(\tau), \tilde{y}_{x,t+1}(\tau)), \end{aligned} \tag{19}$$

where $var(\tilde{y}_{t+1}(\tau)) = k_y(\tau)k_y(\tau)'$, $var(\tilde{y}_{\pi,t+1}(\tau)) = k_\pi(\tau)k_\pi(\tau)'$, $var(\tilde{y}_{r,t+1}(\tau)) = k_r(\tau)k_r(\tau)'$, $var(\tilde{y}_{x,t+1}(\tau)) = k_x(\tau)k_x(\tau)'$, $cov(\tilde{y}_{\pi,t+1}(\tau), \tilde{y}_{r,t+1}(\tau)) = k_\pi(\tau)k_r(\tau)'$, $cov(\tilde{y}_{\pi,t+1}(\tau), \tilde{y}_{x,t+1}(\tau)) = k_\pi(\tau)k_x(\tau)'$, and $cov(\tilde{y}_{r,t+1}(\tau), \tilde{y}_{x,t+1}(\tau)) = k_r(\tau)k_x(\tau)'$. The relative importance of each component can then be analyzed as the portion of total variance due to that component. Table 3 presents the relative importance of each component before and including the financial crisis. Our results suggest that most of the variation in the yields can be attributed to news about future real rate of return or future excess returns, with the covariance between the two also contributing slightly. None of the variation in the yields can be attributed to news about inflation or its covariance with the other two terms. Furthermore, the percentage of variation that can be attributed to news about future real rate of return decreases from approximately 100% to 0% monotonically with maturity. On the other hand, the percentage of variation that can be attributed to news about future excess returns increases from approximately 0% to 100% monotonically with maturity. These results suggest that news about future real rate of return and future excess returns explain most of the variation in the short and long ends of the yield curve, respectively. More importantly, these results hold for the sample periods including and excluding the financial crisis.

Based on the decomposition in Equation (13), one can also decompose the initial response of the yields to monetary policy shocks ($\partial\tilde{y}_{t+1}(\tau)/\partial\varepsilon_{s,t+1}$) into initial responses of their components as follows:

$$\begin{aligned}\frac{\partial\tilde{y}_{t+1}(\tau)}{\partial\varepsilon_{s,t+1}} = k_y(\tau)e_4 &= \frac{\partial\tilde{y}_{\pi,t+1}(\tau)}{\partial\varepsilon_{s,t+1}} + \frac{\partial\tilde{y}_{r,t+1}(\tau)}{\partial\varepsilon_{s,t+1}} + \frac{\partial\tilde{y}_{x,t+1}(\tau)}{\partial\varepsilon_{s,t+1}}, \\ &= k_\pi(\tau)e_4 + k_r(\tau)e_4 + k_x(\tau)e_4. \end{aligned} \tag{20}$$

Table 4 presents this decomposition based on sample periods including and excluding the financial crisis. The last column of Table 4 presents the initial responses of the yields to an expansionary monetary policy shock, which correspond to the initial responses presented in Figure 5. As discussed above, the yields respond negatively to a monetary policy shock before the financial crisis. This negative response is mainly due to the negative response of real rate of return at the short end of the yield curve, while it is mainly due to the negative response of excess returns at the long end. In other words, an expansionary monetary policy shock leads to downward revisions in investors' expectations about future real rate of return in the short run, while it decreases investors' expectations about future excess returns in the long run. On the other hand, monetary policy shocks do not affect investors' expectations about future values of inflation. Thus, revisions in investors' expectations about future values of inflation do not play any role in explaining the initial response of the yields to monetary policy shocks. This result is consistent with the insignificant impulse response function of price to an expansionary monetary policy shock presented in Figure 4.

When we consider the whole sample period including the financial crisis, as discussed above, the initial responses of the yields are much smaller in magnitude and become mostly insignificant. This dramatic change in the responses of the yields to monetary policy shocks following the financial crisis can be explained by the substantial changes in the responses of both future real rate of return and excess returns. More precisely, a monetary policy shock does not significantly impact investors' expectations about future real rate of return or excess returns when we include the financial crisis in our analysis. These results suggest that the financial crisis might have affected how investors update their expectations about future values of economic fundamentals, especially for real rate of return and excess returns. This in turn results in the muted responses of the yields to monetary policy shocks.

7 Robustness Checks

In this section, we analyze the robustness of our results to using alternative measures of key variables and sample periods. In the first check, we replace total reserves by total balances at the Fed in our model (6). Carpenter and Demiralp (2008) suggest using total balances rather than total reserves in analyzing the effects of monetary policy shocks. The reasoning behind their suggestion is that the fed funds rate is the one that clears the market for balances, which is composed of total reserves (the sum of borrowed and nonborrowed reserves) and contractual clearing balances. The latter component is the balances contracted (between an institution and its respective Reserve Bank) in order to maintain a level of balances in excess of the amount necessary to satisfy the institution's reserve balance requirements. This program was established in 1980 to provide access to Federal Reserve services for banks with low or zero reserve requirements. Until the 1990s, the contractual clearing balance program was not used by many institutions. However, there was a regime shift in the early 1990s when the institutions began to use this program actively. The proportion of contractual clearing balances in total balances increased steadily from the early 1990s to the end of 2003 when it reached its maximum accounting for slightly more than 27% of total reserves. Since then, it has steadily decreased to almost 0% in July 2012 when the program was eliminated by the Fed in order to reduce reserves administration burden on institutions and the Fed.

The first two columns of Figure 6 present the impulse response functions of yields to a one standard deviation expansionary monetary policy shock measured using total balances for the sample excluding and including the financial crisis, respectively. These impulse response functions are quite similar to those presented in Figure 5 based on total reserves. Specifically, following an expansionary monetary policy shock before the financial crisis, all yields react negatively and decrease in the short run, while they do not react significantly in the medium and long run. Importantly, the reactions of all yields at all horizons become both statistically and economically insignificant when we consider the whole sample including the financial crisis. These results suggest that our conclusion on the ineffectiveness of monetary policy in changing the term structure of interest rates is robust when we use total balances instead of total reserves.

In the second check, we consider February 1994 as the starting point of both of our samples. Among others, Vilasuso (1999) argues that the effects of monetary policy depend on the Fed's operating procedures. Specifically, he shows that these effects depend on whether the Fed uses a fed funds rate, nonborrowed reserves or borrowed reserves operating procedure. In the fall of 1982, the Fed abandoned the nonborrowed reserves operating procedure and adopted borrowed reserves operating procedure and followed it throughout the 80s and early 90s. In February 1994, the Fed adopted the current practice of announcing its target for the fed funds rate. However, as Thornton (2001) notes, this practice does not necessarily imply that the Fed implements a pure fed funds rate targeting strategy and does not consider a mixed strategy depending on the macroeconomic and financial market conditions. In fact, optimal operating procedures were still somewhat nonspecific and depended on macroeconomic and financial market conditions. (Board of Governors of the Federal Reserve System (1994))

The last two columns of Figure 6 present the impulse response functions of yields to a one standard deviation expansionary monetary policy shock for the sample periods excluding and including the financial crisis, respectively, and starting both in February 1994. These impulse response functions are quite similar to those presented in Figure 5 based on November 1982 as the starting date for our sample periods. Specifically, following an expansionary monetary policy shock before the financial crisis, all yields react negatively and decrease in the short run while they do not react significantly in the medium and long run. Importantly, the reaction of all yields at all horizons become both statistically and economically insignificant when we consider the whole sample including the financial crisis. These results suggest that our conclusion on the ineffectiveness of monetary policy in changing the term structure of interest rates is robust when we focus on the period during which the Fed was using a fed funds rate operating procedure.

8 Conclusion

There has been a growing debate on whether monetary policy has been effective during the recent financial crisis. Although the effectiveness of unconventional monetary policies has been analyzed in detail, the literature is relatively silent on whether conventional monetary policies have been effective. This is rather surprising given that it is appropriate for the Fed to implement unconventional policies only to the extent that conventional policies were ineffective in the first place. However, this is not a trivial question due to the problems associated with existing methods of identifying conventional monetary policy shocks, especially in the context of the financial crisis.

In this paper, we contribute to the debate on the effectiveness of monetary policy in the context of the financial crisis by analyzing how the factors underlying the term structure of interest rates react to conventional monetary policy shocks before and during the financial crisis. Specifically, we identify conventional monetary policy shocks in a SVAR framework from a flexible approach. This identification strategy is based on the conditional heteroskedasticity of the structural innovations and allows us not only to leave the SVAR unrestricted, but also to avoid potential inconsistencies induced by the choices of monetary policy indicators associated with the standard identification strategies.

In this framework, comparing results based on sample periods excluding and including the financial crisis reveals that conventional monetary policy might have lost its effectiveness in changing the term structure of interest rates after the financial crisis. That is, before the financial crisis, the level of the yield curve decreases significantly in the short and medium runs in response to an expansionary monetary policy, the slope decreases significantly in the medium run and the curvature decreases significantly in the very short run. However, when we consider the whole sample period including the financial crisis, these reactions become mostly insignificant and, more importantly, much smaller in magnitude. The dramatic change in the responses of yields to conventional monetary policy shocks following the financial crisis can be explained by the substantial changes in the responses of both future real rate of return and excess returns.

References

Abbassi, P., and T. Linzert, 2011, The effectiveness of monetary policy in steering money market rates during the recent financial crisis, *European Central Bank Working Paper No. 1328*.

Ang, A., J. Boivin, S. Dong, and R. Loo-Kung, 2011, Monetary policy shifts and the term structure, *Review of Economic Studies* 78, 429–457.

Ang, A., and M. Piazzesi, 2003, A no-arbitrage vector autoregression of term structure dynamics with macroeconomic and latent variables, *Journal of Monetary Economics* 50, 745–787.

Bernanke, B., 2009, The crisis and the policy response, *Stamp Lecture, London School of Economics, London, England, January*.

Board of Governors of the Federal Reserve System, 1994, The Federal reserve system: Purposes and functions, .

——— , 2008, Minutes of the Federal Open Market Committee, October 28-29.

Borio, C., and P. Disyatat, 2009, Unconventional monetary policies: An appraisal, *BIS Working Papers No 292*.

Bouakez, H., and M. Normandin, 2010, Fluctuations in the foreign exchange market: How important are monetary policy shocks?, *Journal of International Economics* 81, 139–153.

Brunner, A., 1994, The federal funds rate and the implementation of monetary policy: Estimating the federal reserve's reaction function, International Finance Discussion Paper No. 466, Board of Governors of the Federal Reserve System.

Calomiris, C. W., 2009, The subprime turmoil: What's old, what's new, and what's next, *Journal of Structured Finance* 15, 652.

Campbell, J.Y., and J. Ammer, 1993, What moves the stock and bond markets? A variance decomposition for long-term asset returns, *Journal of Finance* 48, 3–37.

Carpenter, S., and S. Demiralp, 2008, The liquidity effect in the federal funds market: Evidence at the monthly frequency, *Journal of Money, Credit and Banking* 40, 1–24.

Cecioni, M., G. Ferrero, and A. Secchi, 2011, Unconventional monetary policy in theory and in practice, *Bank of Italy Working Paper Number 102*.

Christensen, J. H. E., J. A. Lopez, and G. D. Rudebusch, 2009, Do central bank liquidity facilities affect interbank lending rates?, Federal Reserve Bank of San Francisco Working Paper 2009-13.

Claessens, S., G. Dell'Ariccia, D. Igan, and L. Laeven, 2010, Cross-country experiences and policy implications from the global financial crisis, *Economic Policy* 25, 267293.

Cochrane, J., and M. Piazzesi, 2002, The Fed and interest rates: A high-frequency identification, *American Economic Review Papers and Proceedings* 92, 90–101.

Cook, T., and T. Hahn, 1989, The effect of changes in the Federal funds rate target on market interest rates in the 1970s, *Journal of Monetary Economics* 24, 331–351.

Diebold, F.X., and C. Li, 2006, Forecasting the term structure of government bond yields, *Journal of Econometrics* 130, 337–364.

Duygan-Bump, B., P. Parkinson, E. Rosengren, G. A. Suarez, and P. Willen, 2013, How effective were the Federal Reserve emergency liquidity facilities? Evidence from the asset-backed commercial paper money market mutual fund liquidity facility, *Journal of Finance* 68, 715–737.

Evans, C., and D. Marshall, 1998, Monetary policy and the term structure of nominal interest rates: Evidence and theory, *Carnegie-Rochester Conference Volume on Public Policy* 49, 53–111.

Farka, M., and A. DaSilva, 2011, The Fed and the term structure: Addressing simultaneity within a structural VAR model, *Journal of Empirical Finance* 18, 935–952.

Krugman, P., 2008, Depression economics returns, *New York Times, November 14, 2008*.

Kuttner, K. N., 2001, Monetary policy surprises and interest rates: Evidence from the fed funds futures market, *Journal of Monetary Economics* 47, 523–544.

Lanne, M., and H. Lutkepohl, 2008, Identifying monetary policy shocks via changes in volatility, *Journal of Money, Credit and Banking* 40, 11311149.

——— , and K. Maciejowska, 2010, Structural vector autoregressions with Markov switching, *Journal of Economic Dynamics and Control* 34, 121–131.

Lutkepohl, H., 2012, Identifying structural vector autoregressions via changes in volatility, DIW Discussion Paper 1259.

Mankiw, N. G., and L. Ball, 2010, *Macroeconomics and the Financial System* (Worth Publishers).

Medeiros, C., and M. Rodriguez, 2011, The dynamics of the term structure of interest rates in the United States in light of the financial crisis of 2007-10, *International Monetary Fund Working Paper WP/11/84*.

Mishkin, F.S., 2009, Is monetary policy effective during financial crises?, *American Economic Review* 99, 573–577.

Normandin, M., and L. Phaneuf, 2004, Monetary policy shocks: Testing identification conditions under time-varying conditional volatility, *Journal of Monetary Economics* 51, 1217–1243.

Roley, V.V., and G.H. Sellon, 1995, Monetary policy actions and long term interest rates, *Federal Reserve Bank of Kansas City Economic Quarterly* 80, 77–89.

Roush, J.E., 2007, The expectations theory works for monetary policy shocks, *Journal of Monetary Economics* 54, 1631–1643.

Sentana, E., and G. Fiorentini, 2001, Identification, estimation and testing of conditionally heteroskedastic factor models, *Journal of Econometrics* 102, 143–164.

Smith, J.M., and J.B. Taylor, 2010, The term structure of policy rules, *Journal of Monetary Economics* 56, 907917.

Stroebel, J. C., and J. B. Taylor, 2009, Estimated impact of the feds mortgage-backed securities purchase program, NBER Working paper 15626.

Strongin, S., 1995, The identification of monetary policy disturbances: Explaining the liquidity puzzle, *Journal of Monetary Economics* 35, 463–498.

Taylor, J. B., and J. C. Williams, 2009, A black swan in the money market, *American Economic Journal: Macroeconomics* 1, 58–83.

Thornton, D. L., 2001, The Federal Reserve's operating procedure, nonborrowed reserves, borrowed reserves and the liquidity effect, *Journal of Banking and Finance* 25, 1717–1739.

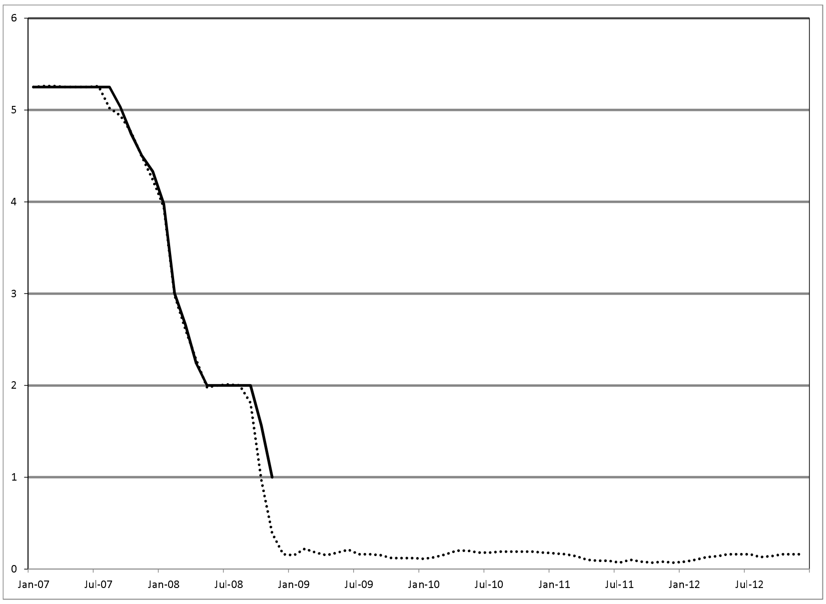
——— , 2011, The effectiveness of unconventional monetary policy: The term auction facility, *Federal Reserve Bank of St. Louis Review* 93, 439–453.

Vilasuso, J., 1999, The liquidity effect and the operating procedure of the Federal Reserve, *Journal of Macroeconomics* 21, 443–461.

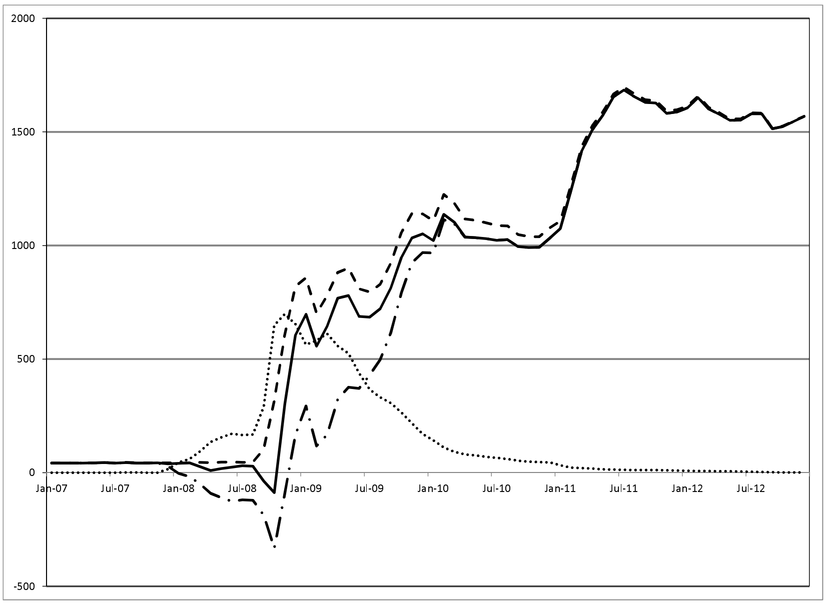
Wu, T., 2011, The U.S. money market and the term auction facility in the financial crisis of 2007-2009, *Review of Economics and Statistics* 93, 617631.

Figure 1: Evolution of Conventional Policy Variables through the Financial Crisis

(a) Effective and Target Fed Funds Rates

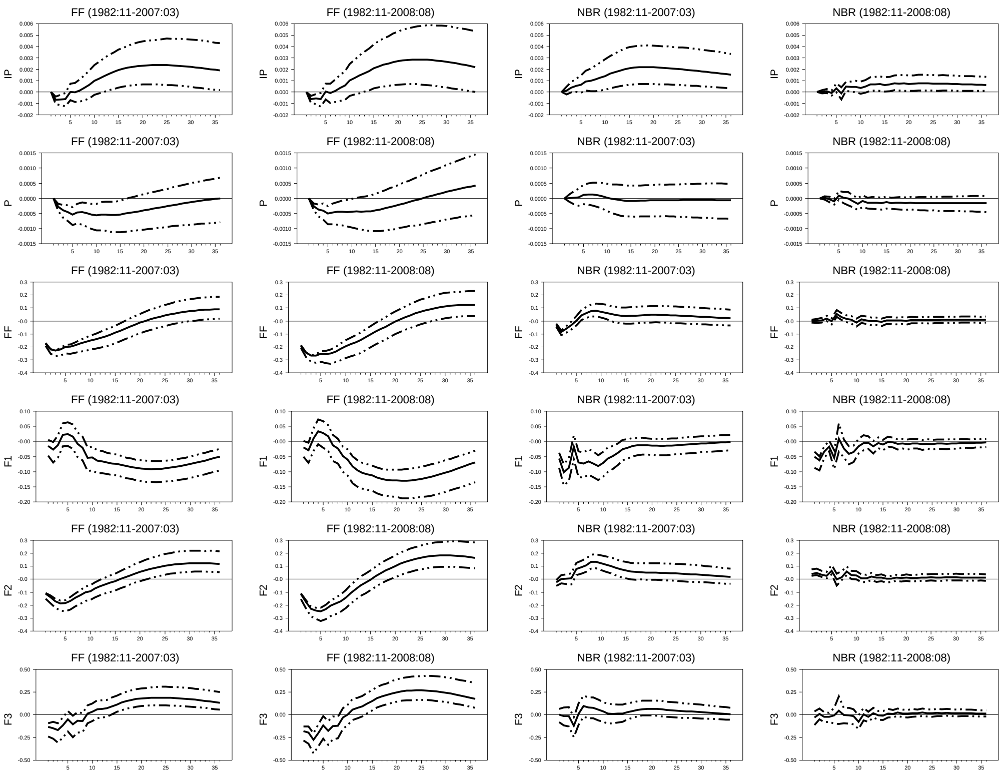


(b) Reserve Variables



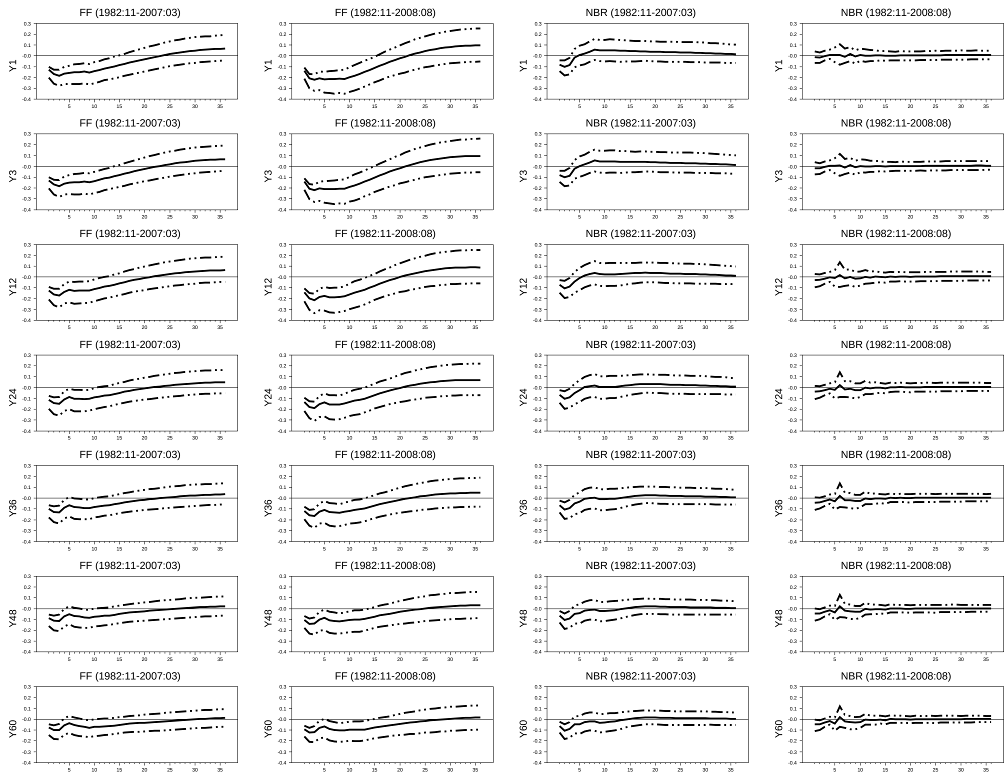
Note: The figure presents the evolution of conventional policy variables between January 2007 and December 2012. Panel (a) presents the target (solid line) and effective (dotted line) fed funds rates. Panel (b) presents borrowings of depository institutions (dotted line), total reserves (dashed line), nonborrowed reserves with TAF (solid line) and without TAF (dashed-dotted line). The target rate is discontinued in December 2008 when the Fed stopped announcing it after establishing a target range for the effective Fed funds rate of 0 to 0.25 percent on December 16, 2008.

Figure 2: Impulse Response Functions Based on Recursive Identification for Selected Variables



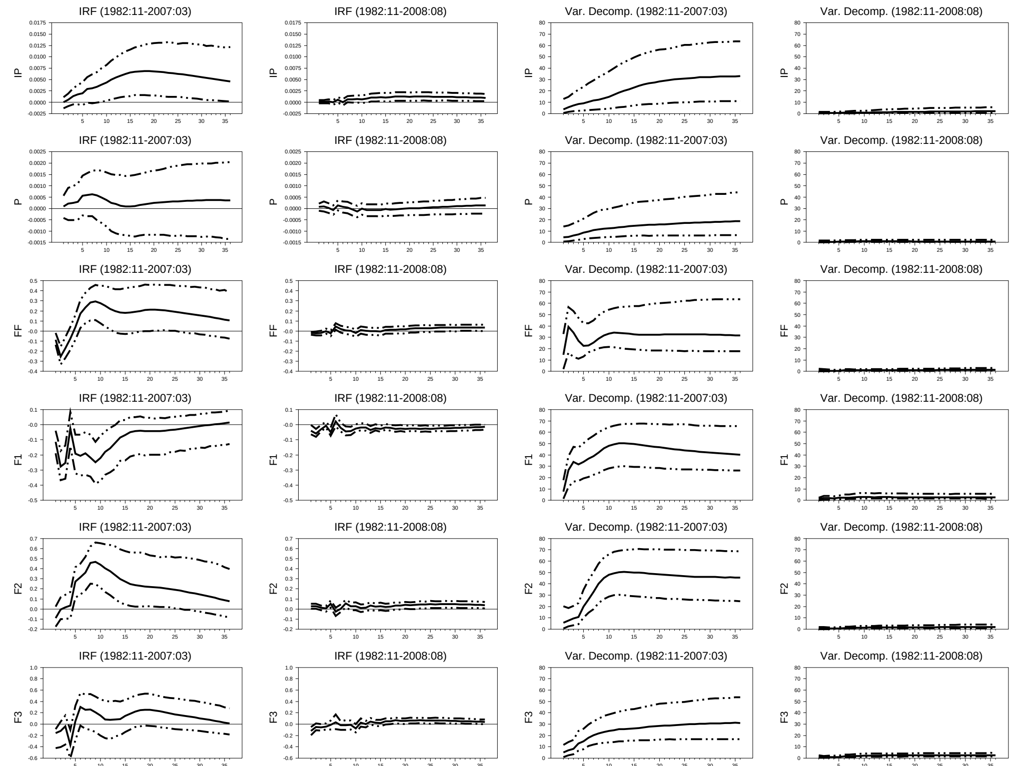
Note: The figure presents the impulse response functions (solid lines) and their corresponding 68% confidence bands (dashed lines) for selected variables in the SVAR. IP, P and FF are output, price and the fed funds rate, respectively. F1, F2 and F3 are the level, slope and curvature of the yield curve. FF corresponds to the fed funds rate as the monetary policy indicator, while NBR corresponds to nonborrowed reserves as the monetary policy indicator.

Figure 3: Impulse Response Functions Based on Recursive Identification for Zero-Coupon Treasury Yields



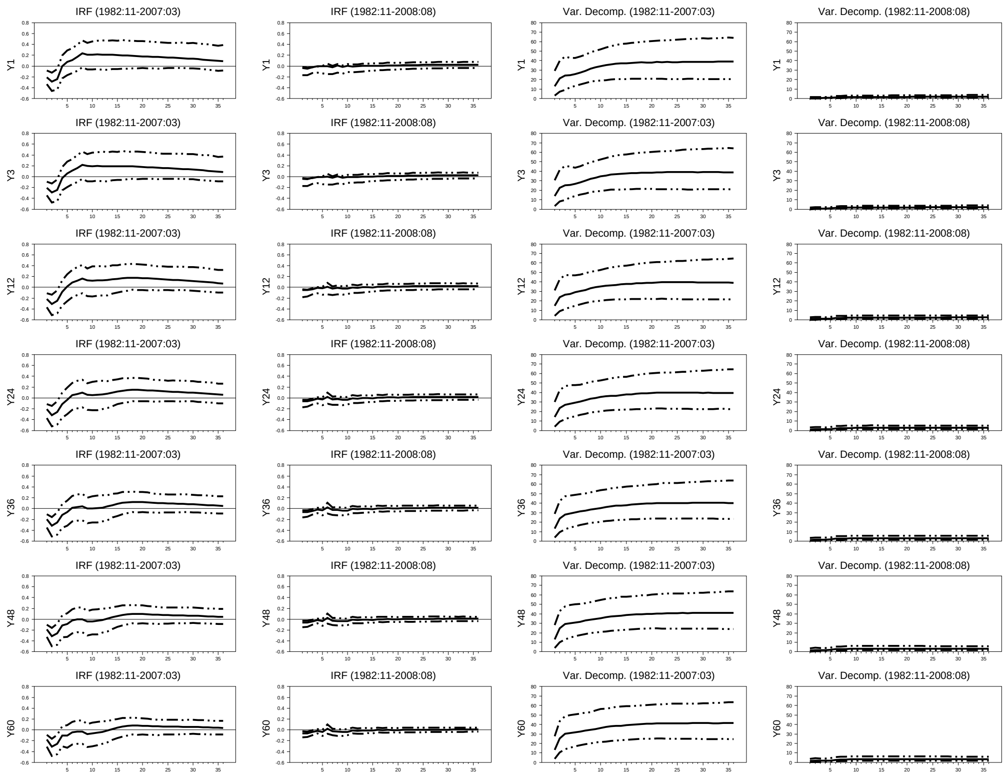
Note: The figure presents the implied impulse response functions (solid lines) and their corresponding 68% confidence bands (dashed lines) for zero-coupon Treasury yields with different maturities. Yτ denotes the yield on zero coupon Treasury bonds with τ months to maturity. FF corresponds to the fed funds rate as the monetary policy indicator, while NBR corresponds to nonborrowed reserves as the monetary policy indicator.

Figure 4: Impulse Response Functions and Variance Decompositions Based on the Flexible Identification for Selected Variables



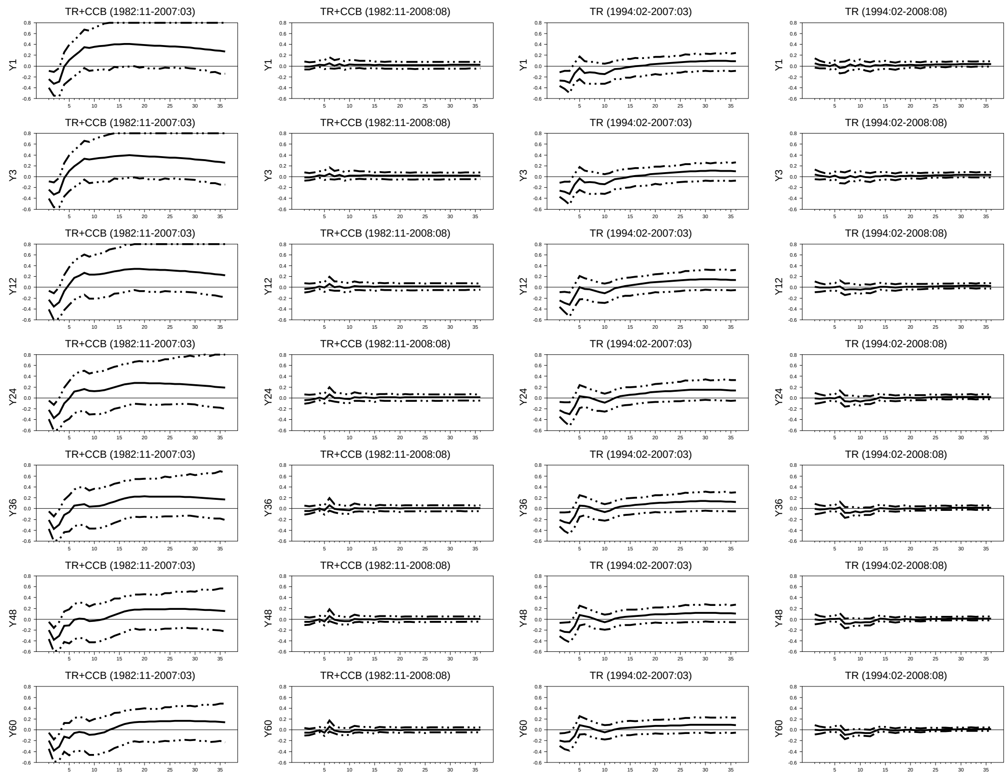
Note: The figure presents the impulse response functions (IRF) and variance decompositions (Var. Decomp.) with their corresponding 68% confidence bands (dashed lines) for selected variables in the VAR. IP, P and FF are output, price and the fed funds rate, respectively. $F1$, $F2$ and $F3$ are the level, slope and curvature of the yield curve.

Figure 5: Impulse Response Functions and Variance Decompositions Based on the Flexible Identification for Zero Coupon Treasury Yields



Note: The figure presents the impulse response functions (IRF) and variance decompositions (Var. Decomp.) with their corresponding 68% confidence bands (dashed lines) for zero coupon Treasury yields with different maturities. Yτ denotes the yield on zero coupon Treasury bonds with τ months to maturity.

Figure 6: Impulse Response Functions Based on the Flexible Identification for Zero Coupon Treasury Yields using Alternative Measures and Sample Periods



Note: The figure presents the impulse response functions (IRF) with their corresponding 68% confidence bands (dashed lines) for zero coupon Treasury yields with different maturities. Yτ denotes the yield on zero coupon Treasury bonds with τ months to maturity. The first two columns present results where we replace total reserves with total balances, i.e. the sum of total reserves (TR) and contractual clearing balances (CCB). The last two columns present results where we change the starting point of our samples to February 1994, when the Fed adopted its current practice of announcing its policy decisions.

Table 1: Parameter Estimates of the Conditional Variance Specification for the Structural Innovations

	Sample: 1982:11-2007:03		Sample: 1982:11-2008:08	
	ARCH	GARCH	ARCH	GARCH
ε_1	0.107	0.628	0.167	0.205
	(0.061)	(0.271)	(0.078)	(0.462)
ε_2	0.168	0.763	0.157	0.753
	(0.026)	(0.044)	(0.028)	(0.047)
ε_3	0.218	0.413	0.211	0.316
	(0.073)	(0.222)	(0.064)	(0.243)
ε_s	0.190	0.810	0.402	0.579
	(0.020)	(0.020)	(0.056)	(0.060)
ε_d	0.451	0.505	0.474	0.487
	(0.045)	(0.058)	(0.050)	(0.061)
ε_b	0.052	0.945	0.080	0.908
	(0.013)	(0.016)	(0.018)	(0.022)
ε_{f_1}	0.192	0.517	0.190	0.532
	(0.069)	(0.174)	(0.066)	(0.164)
ε_{f_2}	0.114	0.680	0.133	0.665
	(0.041)	(0.118)	(0.046)	(0.135)
ε_{f_3}	0.136	0.783	0.173	0.724
	(0.040)	(0.069)	(0.051)	(0.088)

Note: This table presents the estimates of ARCH and GARCH coefficients of the conditional variance specification for the structural innovations in Equation (12). ε_1, ε_2 and ε_3 are the structural innovations associated with the first, second and third equations of the SVAR in Equation (6). ε_s, ε_d and ε_b are the structural innovations associated with the reserve market. ε_{f_1}, ε_{f_2} and ε_{f_3} are the structural innovations associated with the last equation of the SVAR that includes the term structure factors one at a time. The standard errors are presented in the parentheses.

Table 2: Parameter Estimates of the Specification for the Reserve Market

	Sample: 1982:11-2007:03	Sample: 1982:11-2008:08
α	0.003	0.006
	(0.004)	(0.003)
β	0.389	1.270
	(0.297)	(0.965)
ϕ_d	0.924	1.034
	(0.018)	(0.038)
ϕ_b	0.009	0.001
	(0.011)	(0.006)
σ_s	0.037	0.026
	(0.006)	(0.002)
σ_d	0.024	0.026
	(0.002)	(0.002)
σ_b	0.081	0.307
	(0.063)	(0.245)

Note: This table presents the parameter estimates of the specification for the reserve market in Equations (5). α is the negative of the slope of the demand for total reserves, while β is the slope of the supply of borrowed reserves. ϕ_d and ϕ_b capture the Fed's responses to shocks to the total demand for reserves and to shocks to the supply of borrowed reserves, respectively. σ_d, σ_b and σ_s are the parameters scaling the structural innovations. The standard errors are presented in the parenthesis.

Table 3: Campbell and Ammer Decomposition of Yields

(a) Sample: 1982:11-2007:03

τ	$\frac{var(\tilde{y}_{\pi,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{var(\tilde{y}_{r,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{var(\tilde{y}_{x,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{2cov(\tilde{y}_{\pi,t}(\tau),\tilde{y}_{r,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{2cov(\tilde{y}_{\pi,t}(\tau),\tilde{y}_{x,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{2cov(\tilde{y}_{r,t}(\tau),\tilde{y}_{x,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$var(\tilde{y}_t(\tau))$
1	0.0000	0.9997	0.0000	0.0003	0.0000	0.0000	0.2991
	(0.0000)	(0.0004)	(0.0000)	(0.0004)	(0.0000)	(0.0000)	(0.0608)
3	0.0000	0.8264	0.0588	0.0002	0.0000	0.1147	0.2987
	(0.0000)	(0.0813)	(0.0155)	(0.0001)	(0.0000)	(0.0779)	(0.0599)
12	0.0000	0.3135	0.6279	0.0001	0.0000	0.0585	0.3309
	(0.0000)	(0.0883)	(0.1037)	(0.0000)	(0.0000)	(0.1505)	(0.0577)
24	0.0000	0.2378	0.9388	0.0000	-0.0001	-0.1765	0.3507
	(0.0000)	(0.0739)	(0.1305)	(0.0000)	(0.0000)	(0.1720)	(0.0545)
36	0.0000	0.1937	1.0231	0.0000	0.0000	-0.2168	0.3329
	(0.0000)	(0.0566)	(0.1248)	(0.0000)	(0.0000)	(0.1558)	(0.0497)
48	0.0000	0.1453	1.0228	0.0000	0.0000	-0.1681	0.3030
	(0.0000)	(0.0392)	(0.1079)	(0.0000)	(0.0000)	(0.1273)	(0.0448)
60	0.0000	0.1015	0.9908	0.0000	0.0000	-0.0922	0.2746
	(0.0000)	(0.0252)	(0.0878)	(0.0000)	(0.0000)	(0.0979)	(0.0408)

(b) Sample: 1982:11-2008:08

τ	$\frac{var(\tilde{y}_{\pi,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{var(\tilde{y}_{r,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{var(\tilde{y}_{x,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{2cov(\tilde{y}_{\pi,t}(\tau),\tilde{y}_{r,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{2cov(\tilde{y}_{\pi,t}(\tau),\tilde{y}_{x,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$\frac{2cov(\tilde{y}_{r,t}(\tau),\tilde{y}_{x,t}(\tau))}{var(\tilde{y}_t(\tau))}$	$var(\tilde{y}_t(\tau))$
1	0.0000	0.9996	0.0000	0.0004	0.0000	0.0000	0.2784
	(0.0000)	(0.0002)	(0.0000)	(0.0002)	(0.0000)	(0.0000)	(0.0251)
3	0.0000	0.8101	0.0714	0.0004	-0.0001	0.1182	0.2774
	(0.0000)	(0.0382)	(0.0089)	(0.0001)	(0.0000)	(0.0370)	(0.0249)
12	0.0000	0.4572	0.4375	0.0001	0.0000	0.1052	0.3118
	(0.0000)	(0.0563)	(0.0419)	(0.0000)	(0.0000)	(0.0595)	(0.0277)
24	0.0000	0.2097	0.6557	0.0001	0.0000	0.1345	0.3351
	(0.0000)	(0.0299)	(0.0425)	(0.0000)	(0.0000)	(0.0397)	(0.0316)
36	0.0000	0.1098	0.7644	0.0000	0.0000	0.1258	0.3186
	(0.0000)	(0.0146)	(0.0345)	(0.0000)	(0.0000)	(0.0304)	(0.0305)
48	0.0000	0.0703	0.8252	0.0000	0.0000	0.1046	0.2890
	(0.0000)	(0.0092)	(0.0290)	(0.0000)	(0.0000)	(0.0268)	(0.0276)
60	0.0000	0.0513	0.8531	0.0000	0.0000	0.0956	0.2606
	(0.0000)	(0.0069)	(0.0255)	(0.0000)	(0.0000)	(0.0240)	(0.0248)

Note: This table presents the decomposition of the total variance of unexpected changes in the yields into the variances of their components and the covariances between them. The total variances of unexpected changes in yields are presented in the left-most column. The variances of the components and the covariances between them are presented as ratios of the total variance. The standard errors, computed by the delta method, are presented in parentheses under the parameter estimates.

Table 4: Campbell and Ammer Decomposition of Initial Responses of Yields

(a) Sample: 1982:11-2007:03

τ	$\frac{\partial \tilde{y}_{\pi,t}(\tau)}{\varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{r,t}(\tau)}{\varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{x,t}(\tau)}{\varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{t}(\tau)}{\varepsilon_{s,t}}$
1	0.0001	-0.2047	0.0000	-0.2046
	(0.0002)	(0.1430)	(0.0000)	(0.1430)
3	0.0001	-0.2437	0.0360	-0.2078
	(0.0001)	(0.1364)	(0.0314)	(0.1378)
12	0.0000	0.0589	-0.2715	-0.2127
	(0.0000)	(0.0884)	(0.0814)	(0.1248)
24	0.0000	0.1223	-0.3290	-0.2067
	(0.0000)	(0.0675)	(0.1050)	(0.1160)
36	0.0000	0.1240	-0.3200	-0.1961
	(0.0000)	(0.0536)	(0.1100)	(0.1087)
48	0.0000	0.1023	-0.2874	-0.1852
	(0.0000)	(0.0421)	(0.1079)	(0.1024)
60	0.0000	0.0750	-0.2506	-0.1756
	(0.0000)	(0.0327)	(0.1034)	(0.0971)

(b) Sample: 1982:11-2008:08

τ	$\frac{\partial \tilde{y}_{\pi,t}(\tau)}{\varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{r,t}(\tau)}{\varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{x,t}(\tau)}{\varepsilon_{s,t}}$	$\frac{\partial \tilde{y}_{t}(\tau)}{\varepsilon_{s,t}}$
1	0.0000	-0.0171	0.0000	-0.0171
	(0.0001)	(0.0411)	(0.0000)	(0.0411)
3	0.0000	-0.0226	-0.0023	-0.0245
	(0.0000)	(0.0354)	(0.0103)	(0.0411)
12	0.0000	-0.0092	-0.0392	-0.0485
	(0.0000)	(0.0274)	(0.0274)	(0.0431)
24	0.0000	0.0002	-0.0617	-0.0614
	(0.0000)	(0.0211)	(0.0360)	(0.0440)
36	0.0000	0.0086	-0.0732	-0.0646
	(0.0000)	(0.0169)	(0.0388)	(0.0429)
48	0.0000	0.0116	-0.0754	-0.0638
	(0.0000)	(0.0136)	(0.0389)	(0.0411)
60	0.0000	0.0109	-0.0725	-0.0616
	(0.0000)	(0.0110)	(0.0380)	(0.0394)

Note: This table presents the decomposition of the initial response of the yields to an expansionary monetary policy shock into the initial responses of their components. The initial response of yields is presented in the left-most column and corresponds to the initial responses presented in Figure 5. The standard errors, computed by the delta method, are presented in parentheses under the parameter estimates.

Appendix

Derivation of the Decomposition in Equation (13)

The derivation follows from Campbell and Ammer (1993). Let $\rho_t(\tau)$ denote the log nominal price of a zero coupon bond with τ periods to maturity in period t. Then, the log nominal one period return on this bond held from t to $t+1$, is given by

$$b_{t+1}(\tau) = \rho_{t+1}(\tau - 1) - \rho_t(\tau). \quad \text{(A.1)}$$

Given that $\rho_{t+\tau}(0) = 0$, iterating forward the above equation and taking expectations conditional on the information set in period $t+1$ yield

$$\rho_{t+1}(\tau) = -E_{t+1} \sum_{j=1}^{\tau-1} b_{t+1+j}(\tau - j). \quad \text{(A.2)}$$

Define the log excess one period return on this bond as

$$x_{t+1}(\tau) = b_{t+1}(\tau) - \pi_{t+1} - r_{t+1}, \quad \text{(A.3)}$$

where π_{t+1} and r_{t+1} are the inflation and the real rate of return in period $t+1$, respectively. Given that $y_t(\tau) = -\rho_t(\tau)/\tau$, substituting Equation (A.3) into Equation (A.2) yields

$$y_{t+1}(\tau) = \frac{1}{\tau} E_{t+1} \sum_{j=1}^{\tau} [x_{t+1+j}(\tau + 1 - j) + \pi_{t+1+j} + r_{t+1+j}]. \quad \text{(A.4)}$$

Subtracting the expectation of Equation (A.4) conditional on information in period t from that conditional on the information in period $t+1$ yields Equation (13).

Derivation of the SVAR in Equation (15)

Define matrices $\tilde{A}$ and $\tilde{B}$ as follows:

$$\begin{aligned} \tilde{A} &= diag\{\mathbb{A}, \underbrace{I, \ldots, I}_{\kappa-1}\}, \\ \tilde{B} &= \begin{pmatrix} \mathbb{B}_1 & \mathbb{B}_2 & \mathbb{B}_3 & \ldots & \mathbb{B}_{\kappa-1} & \mathbb{B}_\kappa \\ I & 0 & 0 & \ldots & 0 & 0 \\ 0 & I & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \ldots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & I & 0 \end{pmatrix}, \end{aligned}$$

where

$$\mathbb{A} = \begin{pmatrix} A_{zz} & 0 & 0 & 0 \\ A_{1z} & A_{11} & 0 & 0 \\ A_{2z} & 0 & A_{22} & 0 \\ A_{3z} & 0 & 0 & A_{33} \end{pmatrix} \quad \text{and} \quad \mathbb{B}_j = \begin{pmatrix} B_{zz,j} & 0 & 0 & 0 \\ B_{1z,j} & B_{11,j} & 0 & 0 \\ B_{2z,j} & 0 & B_{22,j} & 0 \\ B_{3z,j} & 0 & 0 & B_{33,j} \end{pmatrix},$$

for $j = 1, \ldots, \kappa$. Then, the SVAR in Equation (2) can be rewritten as a first order SVAR that includes all three term structure factors in the state vector simultaneously and is consistent with Equation (6) and Equation (15).

The Derivation of Equations (17) and (18)

To derive the first expression in Equations (17) and (18), first note that

$$y_{t+1}(\tau) = \alpha_{\tau,1} f_{1,t+1} + \alpha_{\tau,2} f_{2,t+1} + \alpha_{\tau,3} f_{3,t+1}.$$

Then, the first expression can be derived as follows:

$$\begin{aligned}
\tilde{y}_{t+1}(\tau) = (E_{t+1} - E_t) y_{t+1}(\tau) &= (\alpha_{\tau,1} e_7' + \alpha_{\tau,2} e_8' + \alpha_{\tau,3} e_9') \tilde{A}^{-1} \tilde{\varepsilon}_{t+1}, \\
&= k_y(\tau) \tilde{\varepsilon}_{t+1}.
\end{aligned}$$

To derive the second expression, first note that the inflation in period $t+1$, π_{t+1}, is defined as the difference in the price between t and $t+1$, i.e. $\pi_{t+1} = p_{t+1} - p_t$. Note also that the price in period t, p_t, is the second element of the state vector z_t. Then, the second expression can be derived as follows:

$$\begin{aligned}
\tilde{y}_{\pi,t+1}(\tau) &= \frac{1}{\tau} (E_{t+1} - E_t) \sum_{j=1}^{\tau} [\pi_{t+1+j}], \\
&= \frac{1}{\tau} (E_{t+1} - E_t) \sum_{j=1}^{\tau} [p_{t+1+j} - p_{t+j}], \\
&= \frac{1}{\tau} e_2' (\Phi - I) \sum_{j=1}^{\tau} \Phi^{j-1} \tilde{A}^{-1} \tilde{\varepsilon}_{t+1}, \\
&= k_\pi(\tau) \tilde{\varepsilon}_{t+1}.
\end{aligned}$$

To derive the third expression, note that the real rate of return in period $t+1$, r_{t+1}, can be written as the difference between the one-period holding period return on a bond with one period to maturity, $b_{t+1}(1)$, and the inflation in period $t+1$, π_{t+1}, i.e. $r_{t+1} = b_{t+1}(1) - \pi_{t+1}$. Note also that $y_t(1) = b_{t+1}(1)$ and $\pi_{t+1} = p_{t+1} - p_t$. Then, the third expression can be derived as follows:

$$\begin{aligned}
\tilde{y}_{r,t+1}(\tau) &= \frac{1}{\tau} (E_{t+1} - E_t) \sum_{j=1}^{\tau} [r_{t+1+j}], \\
&= \frac{1}{\tau} (E_{t+1} - E_t) \sum_{j=1}^{\tau} [b_{t+1+j}(1) - \pi_{t+1+j}], \\
&= \frac{1}{\tau} (E_{t+1} - E_t) \sum_{j=1}^{\tau} [y_{t+1+j}(1) - (p_{t+1+j} - p_{t+j})], \\
&= \left(\frac{1}{\tau} (E_{t+1} - E_t) \sum_{j=1}^{\tau} [\alpha_{1,1} f_{1,t+j} + \alpha_{1,2} f_{2,t+j} + \alpha_{1,3} f_{3,t+j}] \right) - k_\pi(\tau) \tilde{\varepsilon}_{t+1}, \\
&= \frac{1}{\tau} (\alpha_{1,1} e_7' + \alpha_{1,2} e_8' + \alpha_{1,3} e_9') (\sum_{j=1}^{\tau} \Phi^{j-1}) \tilde{A}^{-1} \tilde{\varepsilon}_{t+1} - k_\pi(\tau) \tilde{\varepsilon}_{t+1}.
\end{aligned}$$

Finally, the last expression follows from the definition of $\tilde{y}_{x,t+1}(\tau)$ as the residual component in the decomposition.