Measuring the Effects of Federal Reserve Forward Guidance and Asset Purchases on Financial Markets

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Abstract

I extend the methods of Gürkaynak, Sack, and Swanson (2005) to separately identify the effects of Federal Reserve forward guidance and large-scale asset purchases (LSAPs) during the 2009–15 U.S. zero lower bound (ZLB) period. I find that both forward guidance and LSAPs had substantial and highly statistically significant effects on medium-term Treasury yields, stock prices, and exchange rates, comparable in magnitude to the effects of the federal funds rate before the ZLB. Forward guidance was more effective than LSAPs at moving short-term Treasury yields, while LSAPs were more effective than forward guidance and the federal funds rate at moving longer-term Treasury yields, corporate bond yields, and interest rate uncertainty. However, the effects of forward guidance were not very persistent, with a half-life of 1–4 months. The effects of LSAPs seem to be more persistent. I conclude that, overall in terms of these criteria, LSAPs were a more effective policy tool than forward guidance during the ZLB period.

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1. Introduction

Physical currency carries a nominal return of zero, so it is essentially impossible for a central bank to set the short-term nominal interest rate—its conventional monetary policy instrument—substantially below zero.[1] This zero lower bound (ZLB) constraint has required many central banks to pursue unconventional monetary policies to stimulate their economies after the 2007–09 global financial crisis. In this paper, I propose a new method to identify and estimate the effects of these unconventional monetary policies on financial markets and, ultimately, the economy. In particular, I estimate the effects of the U.S. Federal Reserve's "forward guidance" and "large-scale asset purchases" (or LSAPs), which were the two main types of unconventional monetary policies pursued by the Fed between January 2009 and October 2015, when its traditional monetary policy instrument, the federal funds rate, was essentially zero.

Understanding the effects of unconventional monetary policy is important for both policymakers and researchers. Many central banks have found themselves increasingly constrained by the zero lower bound in recent years and have turned to a variety of unconventional policies to stimulate their economies, despite the fact that these policies' effects are not well understood. In the present paper, I provide new and improved estimates of these effects and their persistence. The efficacy of unconventional monetary policy is also an important determinant of the cost of the ZLB and the optimal inflation target for an economy. If unconventional monetary policy is relatively ineffective, then the ZLB constraint is more costly, and policymakers should go to greater lengths to avoid hitting it in the first place, such as by choosing a higher inflation target, as advocated by Summers (1991), Blanchard, Dell'Ariccia, and Mauro (2010), Blanchard in *The Wall Street Journal* (2010), and Ball (2014). On the other hand, if unconventional monetary policy is very effective, then the ZLB constraint is not very costly and there is little reason for policymakers to raise their inflation target on that ground.

The zero lower bound period in the U.S. began on December 16, 2008, when the Federal Reserve's Federal Open Market Committee (FOMC) lowered the federal funds rate—its conventional monetary policy instrument—to essentially zero. The U.S. economy was still in a severe recession, so the FOMC began to pursue unconventional monetary policies to try to stimulate the

[1] A few central banks have recently set short-term nominal interest rates slightly below zero by charging banks a fee to hold electronic cash reserves at the central bank. This implies that the "zero lower bound" is not a hard constraint that lies exactly at zero. Nevertheless, nominal interest rates cannot fall too far below zero without leading to widespread conversion of electronic reserves into physical currency. Traditionally, this constraint is still referred to as the "zero lower bound".

Table 1: Major Unconventional Monetary Policy Announcements by the Federal Reserve, 2009–2015

March 18, 2009	FOMC announces it expects to keep the federal funds rate between 0 and 25 basis points (bp) for "an extended period", and that it will purchase $750B of mortgage-backed securities, $300B of longer-term Treasuries, and $100B of agency debt (a.k.a. "QE1")
November 3, 2010	FOMC announces it will purchase an additional $600B of longer-term Treasuries (a.k.a. "QE2")
August 9, 2011	FOMC announces it expects to keep the federal funds rate between 0 and 25 bp "at least through mid-2013"
September 21, 2011	FOMC announces it will sell $400B of short-term Treasuries and use the proceeds to buy $400B of long-term Treasuries (a.k.a. "Operation Twist")
January 25, 2012	FOMC announces it expects to keep the federal funds rate between 0 and 25 bp "at least through late 2014"
September 13, 2012	FOMC announces it expects to keep the federal funds rate between 0 and 25 bp "at least through mid-2015", and that it will purchase $40B of mortgage-backed securities per month for the indefinite future
December 12, 2012	FOMC announces it will purchase $45B of longer-term Treasuries per month for the indefinite future, and that it expects to keep the federal funds rate between 0 and 25 bp at least as long as the unemployment remains above 6.5 percent and inflation expectations remain subdued
December 18, 2013	FOMC announces it will start to taper its purchases of longer-term Treasuries and mortgage-backed securities to paces of $40B and $35B per month, respectively
December 17, 2014	FOMC announces that "it can be patient in beginning to normalize the stance of monetary policy"
March 18, 2015	FOMC announces that "an increase in the target range for the federal funds rate remains unlikely at the April FOMC meeting"

economy further. By far the two most extensively used such policies were "forward guidance"—communication by the FOMC about the likely future path of the federal funds rate over the next several quarters or years— and "large-scale asset purchases", or LSAPs—purchases by the Federal Reserve of hundreds of billions of dollars of longer-term U.S. Treasury bonds and mortgage-backed securities. The goal of both policies was to lower longer-term U.S. interest rates by methods other than changes in the current federal funds rate, and thereby stimulate the economy.

Table 1 reports some of the most notable examples of the FOMC's forward guidance and LSAP announcements during this period. In addition to the examples in the table, incremental news about these policies was released to financial markets at virtually every FOMC meeting, such as updates that a policy was ongoing, was likely to be continued, or might be adjusted. Throughout 2015, for example, the FOMC gave numerous updates about whether a tightening of the federal funds rate was likely to take place at the next one or two FOMC meetings. Finally, the

U.S. zero lower bound period ended on December 16, 2015, when the FOMC raised the federal funds rate for the first time since the financial crisis, to a range of 0.25 to 0.5 percent.

It's apparent from Table 1 that separately identifying the effects of forward guidance and LSAPs is difficult, because many of the FOMC's announcements provided information about both types of policy simultaneously. Moreover, even in the case of a seemingly clear-cut announcement, such as the LSAP-focused "QE2" announcement on Nov. 3, 2010, both types of policies may still have been at work: in particular, several authors have argued that LSAPs affect the economy either partly or wholly by changing financial markets' expectations about the future path of the federal funds rate (e.g., Woodford, 2012; Bauer and Rudebusch, 2014). To the extent that this "signaling" channel is operative, even a pure LSAP announcement would have important forward guidance implications. This makes disentangling the two types of policies even more difficult than it might at first seem.

A second major challenge in estimating the effects of unconventional monetary policy announcements is that financial markets are forward-looking, and thus should not react to the component of an FOMC announcement that is expected *ex ante*; only the unanticipated component should have an effect. But determining the size of the unexpected component of each announcement in Table 1 is very difficult, because there are no good data on what financial markets expected the outcome of each FOMC announcement to be.[2]

A third, related challenge is that the FOMC can sometimes surprise markets through its *in*action rather than its actions. For example, on September 18, 2013, financial markets widely expected the FOMC to begin tapering its LSAPs, but the FOMC decided not to do so, surprising markets and leading to a large effect on asset prices despite the fact that no action was announced.[3] This implies that even dates *not* listed in Table 1 could have produced a significant surprise in financial markets and led to large effects on asset prices and the economy.

In this paper, I address these challenges by extending the high-frequency approach of Gürkaynak, Sack, and Swanson (2005, henceforth GSS). I first look at the high-frequency (30-minute) response of asset prices to FOMC announcements to identify the immediate causal effect of those announcements on financial markets. I then test for the number of dimensions underlying

[2] This is in sharp contrast to the case of conventional monetary policy—changes in the federal funds rate—for which we have very good data on financial market expectations *ex ante* through federal funds futures and other short-term financial market instruments, as discussed by Kuttner (2001), Gürkaynak, Sack, and Swanson (2005, 2007), and others.

[3] *The Wall Street Journal* (2013b,c) reported that "No Taper Shocks Wall Street," and "'Bernanke had a free pass to begin that tapering process and chose not to follow [through]... The Fed had the market precisely where it needed to be. The delay today has the effect of raising the benchmark to tapering..."

those announcement effects and show that they are well described by three dimensions over the period from 1991 to 2015. These dimensions represent the three aspects of FOMC announcements that had the greatest systematic effect on asset prices over the sample; intuitively, these three dimensions are likely to correspond to changes in the federal funds rate, changes in forward guidance, and changes in LSAPs.

I collect the 30-minute asset price responses to each FOMC announcement between 1991 and 2015 and compute the first three principal components of those asset price responses. This estimates the three factors that had the greatest explanatory power for these financial market responses. I search over all possible rotations of these three principal components to find one in which the first factor corresponds to the change in the federal funds rate, the second factor to the change in forward guidance, and the third factor to the change in LSAPs. I propose two different sets of identifying assumptions and show that both work very well, producing estimates that agree closely with each other and with observable characteristics of major FOMC announcements during the period. In this way, I separately identify the size of the federal funds rate, forward guidance, and LSAP component of every FOMC announcement from July 1991 to October 2015.

Once the different components of each FOMC announcement are identified, it's straightforward to estimate the response of different asset prices to each of those components using high-frequency (30-minute or 1-day) regressions. I find that both forward guidance and LSAPs had highly statistically significant effects on a wide variety of assets, including Treasuries, corporate bonds, stocks, exchange rates, and interest rate uncertainty as measured by options. The size of these effects is comparable to that of conventional monetary policy—changes in the federal funds rate—during the pre-ZLB period. Forward guidance was relatively more effective at moving short-term Treasury yields, while LSAPs were more effective at moving longer-term Treasury yields, corporate bond yields, and interest rate uncertainty (with an increase in LSAPs reducing interest rate uncertainty).

Finally, I investigate whether these effects were persistent—i.e., did they die out quickly as some models of slow-moving capital (e.g., Duffie, 2010; Fleckenstein, Longstaff, and Lustig, 2014) and some empirical work (Wright 2012) suggest, or were the high-frequency impact effects more permanent? I find that the effects of conventional monetary policy—changes in the federal funds rate—in the pre-ZLB period were completely persistent, with no tendency to die out over the next several months. For LSAPs, I also find that the effects were completely persistent, with the exception of the very influential March 2009 "QE1" FOMC announcement, after which bond yields fell sharply but then rebounded strongly over the subsequent weeks as financial markets turned around. Finally, I estimate that the effects of forward guidance died out quickly, with a half-life of about 1–4 months.

The remainder of the paper proceeds as follows. In Section 2, I describe the data and extend the analysis in GSS to allow for additional dimensions of monetary policy. I test for the number of dimensions underlying the financial market responses to FOMC announcements between 1991 and 2015, and propose two different sets of identifying assumptions to estimate the effects of the different types of monetary policy. In Section 3, I discuss the results of these identification methods and show that they are robust, corresponding closely to each other and to identifiable features of major FOMC announcements. In Section 4, I estimate the effects of forward guidance and LSAPs on Treasury yields, stock prices, exchange rates, and corporate bond yields and show that both policies were effective, as measured by their impact on financial markets. In Section 5, I investigate whether these effects were persistent. In Section 6, I estimate the effects of forward guidance and LSAPs on financial market uncertainty, as measured by options. Finally, in Section 7, I discuss the broader implications of my findings for U.S. monetary policy going forward and for estimating the effects of unconventional monetary policy in other economies. A technical Appendix contains mathematical details of the identifying restrictions used in Section 2.

2. Data and Identification of Forward Guidance and LSAPs

In order to separately identify the effects of forward guidance and asset purchases, we must first separately identify the forward guidance and LSAP components of each FOMC announcement. I do this using two different approaches, each of which extends earlier work by Gürkaynak, Sack, and Swanson (2005) in a different way.

I first extend the GSS dataset through October 2015 using data obtained from staff at the Federal Reserve Board. The combined dataset includes the date of each FOMC announcement from July 1991 through October 2015, and the change in a number of asset prices in a 30-minute window bracketing each announcement.[4] The asset prices include federal funds futures (the current-month contract rate and the contract rates for each of the next six months),

[4] The window begins 10 minutes before the FOMC announcement was released to the public and ends 20 minutes after the FOMC announcement was released. The dataset also includes the dates and times of FOMC announcements and some intraday asset price responses going back to January 1990, but the data for Treasury yield responses begins in July 1991, and those data are an important part of my analysis. Also, as is standard in the literature, I exclude the FOMC announcement on September 17, 2001, which took place after financial markets had been closed for several days following the September 11 terrorist attacks.

eurodollar futures (the current quarter contract rate and the contract rates for each of the next eight quarters), Treasury bond yields (for the 3-month, 6-month and 2-, 5-, 10-, and 30-year maturities), the stock market (as measured by the S&P 500), and exchange rates (yen/dollar and dollar/euro).

I collect these asset price responses into a $T \times n$ matrix X, with rows of X corresponding to FOMC announcements and columns of X corresponding to n different assets; each element x_{ij} of X then reports the 30-minute response of the jth asset to the ith FOMC announcement. As in GSS, we can think of these data in terms of a factor model,

$$X = F\Lambda + \varepsilon, \tag{1}$$

where F is a $T \times k$ matrix containing $k \leq n$ unobserved factors, Λ is a $k \times n$ matrix of loadings of the asset price responses on the k factors, and ε is a $T \times n$ matrix of white noise residuals. If $k = 0$, the data X would be well described by white noise; if $k = 1$, X would be well described as responding linearly to a single factor (such as the change in the federal funds rate) plus white noise; if $k = 2$, the data X would be responding to two underlying dimensions of FOMC announcements plus white noise; and so on. Natural candidates for the columns of F would be: i) the surprise component of the change in the federal funds rate around each FOMC meeting, ii) the surprise component of the change in forward guidance, iii) the surprise component of any LSAP announcements, and iv) any additional dimensions of news about monetary policy or the economy that are systematically revealed in FOMC announcements.

We are interested in estimating and identifying the columns of F. For this estimation, I take X to include the first and third federal funds futures contracts, the second, third, and fourth Eurodollar futures contracts, and the 2-, 5-, and 10-year Treasury yields, to focus on the assets that are the most closely related to monetary policy. The first and third federal funds futures contracts provide good estimates of the market expectation of the federal funds rate after the current and next FOMC meetings.[5] The second through fourth Eurodollar futures contracts provide information about the market expectation of the path of the federal funds rate over a horizon of about 4 months to 1 year ahead.[6] The 2-, 5-, and 10-year Treasury yields provide

[5] As in GSS and Kuttner (2001), these contracts are scaled by the number of days remaining in the month to provide the best estimate of the surprise change in the federal funds rate after the announcement. See GSS and Kuttner (2001) for details.

[6] I follow GSS and switch from federal funds futures to Eurodollar futures contracts at a horizon of about two quarters because Eurodollar futures were much more liquid over this sample than longer-maturity fed funds futures, and are thus likely to provide a better measure of financial market expectations at those longer horizons (see Gürkaynak, Sack, and Swanson, 2007).

information about interest rate expectations and risk premia over longer horizons, about 1 to 10 years. The reason for focusing on some rather than all possible futures contracts is to avoid overlapping contracts, since they are highly correlated for technical rather than policy-related reasons.[7] In the factor model (1), futures contracts that are highly correlated will tend to show up as a common factor—a column of F—which is not interesting if the correlation is generated by overlapping contracts rather than the way monetary policy is conducted.

Note that, to estimate the factors F, I do not need to take a stand on *why* the interest rates above moved in response to FOMC announcements, only that they did so systematically. For example, medium- or longer-term interest rates might change because interest rate expectations changed or because liquidity or risk premia changed, and these changes could partly be due to the FOMC statement changing expectations about the future path of output or inflation as well as the federal funds rate itself (e.g., Campbell et al., 2012; Nakamura and Steinsson, 2017). As long as the interest rate responses to FOMC announcements are systematic, they will be identified as responses to the monetary policy factors F. Of course, this implies that my estimates of the effects of the factors F, below, do not represent a "pure interest rate" channel, but rather the *total* impact of the FOMC announcement on interest rates through all of these possible channels.

To estimate and identify the factors F, I use two different approaches: a full-sample approach and a split-sample approach, discussed below.

2.1 Full-Sample Identification

In the first approach, I analyze the sample from July 1991 to October 2015 as a whole. There are 213 FOMC announcements over this period and eight different assets in X, as described above, so X has dimensions 213×8.

I first investigate the rank of F following Cragg and Donald (1997). Given a null hypothesis of rank k_0 versus an alternative $k > k_0$, the Cragg-Donald test searches over all possible factor models with k_0 factors to find the one that brings the residuals ε as close to white noise as possible; the test then measures the distance between the residuals and white noise using a Wald statistic.

The results of this test are reported in Table 2. The data overwhelmingly reject the hypothesis of rank zero (white noise), so clearly interest rates respond systematically to FOMC

[7] For example, FOMC announcements are spaced 6 to 8 weeks apart, so the second federal funds futures contract is essentially perfectly correlated with the first (once the latter has been scaled to represent the outcome of the FOMC meeting, as discussed above). Similarly, including the first Eurodollar futures contract provides essentially no additional information beyond the first and third federal funds futures contracts.

Table 2: Tests for the Number of Factors Underlying Interest Rate Responses to FOMC Announcements, 1991–2015

H_0: number of factors equals	degrees of freedom	Wald statistic	p-value
0	28	88.4	3.5×10^{-8}
1	20	52.7	.00009
2	13	26.7	.014
3	7	11.8	.108

Results from the Cragg-Donald (1997) test for the number of factors k underlying the 213×8 matrix X of 30-minute asset price responses to FOMC announcements from July 1991 to October 2015. The test is for H_0: $k = k_0$ vs. H_1: $k > k_0$. See text for details.

announcements. The hypothesis of rank one is also rejected very strongly, which implies that interest rates respond to FOMC announcements in a multidimensional way—in other words, the surprise change in the federal funds rate (or any other single dimension of monetary policy) is insufficient to explain the responses of interest rates to FOMC announcements.[8] The hypothesis that F has rank two is also rejected at standard significance levels (p-value of .014), suggesting that even two dimensions of monetary policy are insufficient to explain the response of interest rates. However, the hypothesis of rank three is not rejected at even the 10% level, suggesting that the data are well-explained by three dimensions of monetary policy underlying the FOMC's announcements. Intuitively, it's natural to think of these three dimensions as corresponding to (the surprise component of) changes in the federal funds rate, forward guidance, and LSAPs, since these were the features of FOMC announcements that received the most attention in financial markets and the financial press.

The results in Table 2 are interesting for several reasons. First, the finding that monetary policy cannot be summarized by any one-dimensional model casts doubt on some authors' use of changes in the 1- or 2-year Treasury yield as a sufficient statistic for monetary policy (e.g., Gertler and Karadi, 2015; Hanson and Stein, 2015; Nakamura and Steinsson, 2017). Monetary policy seems to have more than one dimension, at least in terms of its effects on financial markets. Second, as discussed by GSS, FOMC announcements are potentially very high-dimensional objects, containing information about the current and future path of interest rates, asset purchases, and the economy. Despite this, the effects of monetary policy on the yield curve are surprisingly well summarized by a factor model with just three factors. Third, even though each FOMC announcement is unique, there is enough commonality across announcements that one can still

[8] Gürkaynak, Sack, and Swanson (2005) showed that this was also the case for their sample, from 1991–2004.

estimate an "average forward guidance" factor and an "average LSAP" factor, below. Thus, even though any particular FOMC announcement may have effects that deviate from these averages, those deviations are not systematic enough to require additional factors to explain them.

Now, the factors F are unobserved and must be estimated. The data suggest that F has rank three, so I begin by extracting the first three principal components of the data X.[9] These principal components correspond to the three elements of FOMC announcements that had the greatest systematic impact on the assets in X over the sample, and together explain about 94% of the variation in X.

Although principal components explain a maximal fraction of the variation in X, they are just a statistical decomposition and do not have a structural interpretation. For example, there is no reason why the first principal component should correspond to the surprise change in the federal funds rate, or forward guidance, or LSAPs—instead, the first principal component is likely to be some combination of all three of these types of announcements. Mathematically, if F and Λ characterize the data X in equation (1), and U is any 3×3 orthogonal matrix, then the matrix $\widetilde{F} \equiv FU$ and loadings $\widetilde{\Lambda} \equiv U'\Lambda$ represent an alternative factor model that fits the data X exactly as well as F and Λ, since it produces exactly the same residuals ε in equation (1).[10]

Among all these observationally equivalent factor models, we would like to find one in which the three columns of F correspond to (the surprise component of) changes in the federal funds rate, forward guidance, and LSAPs, respectively. This amounts to choosing a rotation matrix U such that the rotated factors $\widetilde{F}$ have this structural interpretation. A 3×3 orthogonal matrix U is completely determined by three parameters, so identification of U (and hence $\widetilde{F}$ and $\widetilde{\Lambda}$) requires three restrictions.

First, I impose that changes in LSAPs have no effect on the current federal funds rate—i.e., $\widetilde{\lambda}_{31} = 0$, where $\widetilde{\lambda}_{ij}$ denotes the (i, j)th element of $\widetilde{\Lambda}$. Since the FOMC's major LSAP announcements all occurred during the ZLB period after 2008, this should be relatively uncontroversial.

Second, following GSS, I impose that changes in forward guidance also have no effect on the current federal funds rate—i.e., $\widetilde{\lambda}_{21} = 0$. Although there are important examples of forward guidance before the ZLB period, as discussed in GSS, this identifying assumption is justified by defining forward guidance to be the component of FOMC announcements that conveys informa-

[9] The factors F are not required to have any dynamic relationship over time, so Kalman filtering is not a feasible approach to estimating F.

[10] The scale of F and Λ are also indeterminate: if α is any scalar, then αF and Λ/α also fit the data X exactly as well as F and Λ. Traditionally, the scale of F is normalized so that each column has unit variance.

tion about the future path of short-term interest rates *above and beyond* changes in the target federal funds rate itself.[11] This is the definition of forward guidance (or the path factor) used by GSS and that I also use in the present paper.

Third and finally, I impose the restriction that the LSAP factor is as small as possible in the pre-ZLB period. In other words, I compute the sum of squared values of the third factor, $\widetilde{F}_3 = FU_3$, where U_3 denotes the third column of U, over the period from 1991 to 2008, and choose the elements of U_3 to minimize this sum of squares subject to the first two constraints above. The idea is that FOMC announcements before the ZLB did not have significant LSAP implications and thus the LSAP factor should be small during this period.[12]

Together, these three restrictions uniquely identify U, and hence $\widetilde{F}$ (up to a sign normalization for each column).[13] Mathematical details of these restrictions are provided in the Appendix.

2.2 Split-Sample Identification

My second approach to identification divides the sample into two sub-periods: the pre-ZLB period from 1991–2008 and the ZLB period from 2009–2015. I then perform the factor estimation and identification separately on each sub-period, assuming that there are only two factors (changes in the federal funds rate and forward guidance) in the first sub-period and two factors (changes in forward guidance and LSAPs) in the second. This approach serves as a robustness check on the full-sample identification results above.

For the first sub-period, July 1991 to December 2008, I collect the same eight interest rate responses as above to the 158 FOMC announcements over this period into a 158×8 matrix X. I extract the first two principal components of X and look for a 2×2 rotation matrix U that gives the first rotated factor an interpretation as the (surprise component of the) change in the

[11] An increase in the federal funds rate is typically not a one-off decision, but is usually followed by additional funds rate hikes down the road. Thus, a surprise change in the federal funds rate today has implications for future values of the federal funds rate as well. What distinguishes the forward guidance factor is that it moves market expectations of future values of the federal funds rate *without* any change in the current federal funds rate target.

[12] Note that we cannot impose the federal funds rate factor—the first column of $\widetilde{F}$—is as small as possible during the ZLB period from 2009 to 2015, minimizing the sum of squares of $\widetilde{F}_1$ over this later period. The first two restrictions already identify the federal funds rate factor, so this third restriction would not help to separate forward guidance from LSAPs.

[13] One can also regard the orthogonality of U and the columns of $\widetilde{F}$ as additional assumptions that help achieve identification. Intuitively, this orthogonality assumption is just part of the definition of each factor—i.e., changes in the federal funds rate factor typically have implications for future interest rates, but those changes are part of the effects of the fed funds rate factor itself; the forward guidance factor captures effects on longer-term interest rates that are *above and beyond* the usual effects of changes in the fed funds rate factor. Similarly, the LSAP factor captures effects on the yield curve that are above and beyond the usual effects of changes in the forward guidance factor, etc.

federal funds rate and the second rotated factor the change in forward guidance. Following GSS, I impose the restriction that changes in forward guidance have no effect on the current federal funds rate, which uniquely identifies U up to a sign normalization for each column. Mathematically, if $\widetilde{F} \equiv FU$ and $\widetilde{\Lambda} \equiv U'\Lambda$, I choose U such that $\tilde{\lambda}_{21} = 0$. The first rotated factor, $\widetilde{f}_1$, then corresponds to all information in the FOMC announcement that systematically moves the federal funds rate. The second rotated factor, $\widetilde{f}_2$, corresponds to all information in the FOMC announcement, other than the change in the federal funds rate itself, that systematically moves intermediate-maturity interest rates. This is the definition of forward guidance (or the "path factor") adopted by GSS and that I use here.

Next, I adapt this methodology to the ZLB period from January 2009 to October 2015. I collect the interest rate response data into a 55×5 matrix X^{zlb}, with the 55 rows corresponding to FOMC announcements over this period and the 5 columns corresponding to the third and fourth Eurodollar futures contracts and the 2-, 5-, and 10-year Treasury yield responses to each announcement; note that I exclude the first and third federal funds futures contracts and the second Eurodollar futures contract from the analysis in this sub-period because those contracts have such short maturities that the ZLB essentially prevents them from responding to news.[14]

I then extract the first two principal components from the matrix X^{zlb}, which are the two features of FOMC announcements over this period that moved these interest rates the most. Let F^{zlb} denote the 55×2 matrix of principal components, let U^{zlb} be a 2×2 orthogonal matrix, let $\widetilde{F}^{\text{zlb}} \equiv F^{\text{zlb}} U^{\text{zlb}}$, and let $\tilde{f}_1^{\text{zlb}}$ and $\tilde{f}_2^{\text{zlb}}$ denote the first and second columns of $\widetilde{F}^{\text{zlb}}$. I search over all possible rotation matrices U^{zlb} to find the one where the first rotated factor $\tilde{f}_1^{\text{zlb}}$ is as close as possible (in terms of its asset price effects) to the "forward guidance factor" $\tilde{f}_2$ estimated previously over the 1991–2008 sample.[15] The identifying assumption is thus that the effect of forward guidance on medium- and longer-term interest rates during the ZLB period is about the same as it was during the pre-ZLB period from 1991–2008. The remaining factor, $\tilde{f}_2^{\text{zlb}}$, then corresponds to all information in FOMC announcements, other than the change in forward guidance itself, that systematically moved medium- and longer-term interest rates over

[14] The first and third federal funds futures contracts correspond to federal funds rate expectations 1 and 3 months ahead, respectively, and the second Eurodollar futures contract corresponds to funds rate expectations from about three to six months ahead. As shown and discussed by Swanson and Williams (2014), interest rates at these short maturities essentially stopped responding systematically to news from 2009 to 2012 (the end of their sample), and this remains true through mid-2015.

[15] In other words, I choose the rotation matrix U^{zlb} that matches the factor loadings $\tilde{\lambda}_{11}^{\text{zlb}}$, $\tilde{\lambda}_{12}^{\text{zlb}}$, $\tilde{\lambda}_{13}^{\text{zlb}}$, $\tilde{\lambda}_{14}^{\text{zlb}}$, and $\tilde{\lambda}_{15}^{\text{zlb}}$ from the ZLB period to $\tilde{\lambda}_{24}$, $\tilde{\lambda}_{25}$, $\tilde{\lambda}_{26}$, $\tilde{\lambda}_{27}$, and $\tilde{\lambda}_{28}$ from the pre-ZLB period as closely as possible, in the sense of minimum Euclidean distance.

this period. It is natural to interpret this second factor as the FOMC's large-scale asset purchase announcements.

The crucial assumption underlying this identification is that forward guidance has essentially the same effects on medium- and longer-term interest rates before and during the ZLB. This assumption is debatable—the effects of forward guidance might not be *exactly* the same before and after the ZLB—but I show below that it works very well, and gives results that are quite similar to the full-sample identification approach above. Intuitively, the effects of LSAPs seem to be very different from those of forward guidance (see below), so the identifying assumption is sufficient to cleanly separate the two types of announcements in the data in a robust way.

3. The FOMC's Forward Guidance and LSAP Announcements

Table 3 reports the identified loading matrices $\widetilde{\Lambda}$ from the full-sample and split-sample identifications described above. The first three rows report results from the full-sample identification. Each rotated factor is normalized to have a unit standard deviation, so the coefficients in the table are in units of basis points (bp) per standard deviation change in the monetary policy instrument.[16]

A one-standard-deviation increase in the federal funds rate factor is estimated to raise the current federal funds rate by about 8.8bp, the expected federal funds rate at the next FOMC meeting by about 6.2bp, the second through fourth Eurodollar futures rates by 5.6, 5.2, and 4.4bp, respectively, and the 2-, 5-, and 10-year Treasury yields by about 3.7, 2, and 1bp, respectively. The effects of a surprise change in the federal funds rate are thus largest at the short end of the yield curve and die off monotonically as the maturity of the interest rate increases.

The effects of forward guidance, in the second row, are quite different. By construction, a shock to the forward guidance factor has *no* effect on the current federal funds rate. At longer maturities, however, the forward guidance factor's effects increase, peaking at a horizon of about one year and diminishing at longer horizons.[17]

[16] I normalize the scale of the federal funds rate factor to have a unit standard deviation from July 1991 to December 2008, because the federal funds rate essentially does not change after December 2008. This scale convention is more intuitive than a full-sample unit standard deviation would be, and also facilitates comparison to the split-sample results below. Similarly, I normalize the LSAP factor to have a unit standard deviation over the period from January 2009 to October 2015. I normalize the forward guidance factor to have a unit standard deviation over the whole sample.

[17] Note that a surprise change in the federal funds rate factor also has implications for future values of the federal funds rate, as can be seen in the intermediate- and longer-maturity yield responses in the first row of Table 3. What distinguishes the forward guidance factor is that it moves market expectations of future values of the federal funds rate *independently* of any change in the current federal funds rate target, as discussed earlier. Also recall that the estimates in the second row of Table 3 represent an average forward guidance effect over the sample. Some FOMC announcements may have had an earlier or later peak effect than the average estimated in row 2, but these differences were not large enough or systematic enough to require another factor to fit the data.

Table 3: Estimated Effects of Conventional and Unconventional Monetary Policy Announcements on Interest Rates, 1991–2015

	MP1	MP2	ED2	ED3	ED4	2y Tr.	5y Tr.	10y Tr.
Full-Sample Identification:								
(1) change in federal funds rate	8.78	6.22	5.55	5.21	4.43	3.68	2.04	0.95
(2) change in forward guidance	0.00	1.21	4.16	5.32	6.02	4.85	5.09	3.92
(3) change in LSAPs	0.00	0.85	1.42	1.37	1.04	−0.32	−3.71	−5.68
Split-Sample Identification:								
July 1991–Dec. 2008:								
(4) change in federal funds rate	8.58	6.26	5.90	5.61	4.82	3.81	1.93	0.68
(5) change in forward guidance	0.00	1.18	4.20	5.39	6.09	5.10	5.21	4.03
Jan. 2009–October 2015:								
(6) change in forward guidance	—	—	—	3.53	4.46	3.78	4.59	2.62
(7) change in LSAPs	—	—	—	−0.76	−1.02	−1.29	−4.79	−7.32
memo:								
(8) row 6, rescaled	—	—	—	4.74	5.98	5.07	6.14	3.51

Coefficients in the table correspond to elements of the structural loading matrix $\widetilde{\Lambda}$, in basis points per standard deviation change in the monetary policy instrument (except for row 8, which is rescaled). MP1 and MP2 denote scaled changes in the first and third federal funds futures contracts, respectively; ED2, ED3, and ED4 denote changes in the second through fourth Eurodollar futures contracts; and 2y, 5y, and 10y Tr. denote changes in 2-, 5-, and 10-year Treasury yields. See text for details.

The effects of LSAPs, reported in the third row, differ substantially from the first two rows. Like forward guidance, a change in the LSAP factor has *no* effect on the current federal funds rate, by construction. Unlike forward guidance and the federal funds rate, the effect of LSAPs is small at short maturities and much larger at the long end of the yield curve. A one-standard deviation increase in the LSAP factor causes 5- and 10-year Treasury yields to fall by about 3.7 and 5.7bp, respectively, on average. An increase in LSAPs also causes short-term yields to rise slightly, on average, although this effect is quantitatively small.

There are already several interesting conclusions to draw from the first three rows of Table 3. First, the general pattern of coefficients is consistent with earlier estimates from Kuttner (2001) and GSS for changes in the federal funds rate and forward guidance, and with previous authors' findings that LSAPs have a substantial impact on longer-term Treasury yields (e.g., Gagnon et al., 2011; Swanson, 2011; and Krishnamurthy and Vissing-Jorgensen, 2012). This provides some initial confirmation of the methods and identifying assumptions above.

Second, the results imply that unconventional monetary policy was effective, at least in terms of its high-frequency impact on the yield curve. Both types of unconventional monetary policy—forward guidance and LSAPs—were about as effective as the federal funds rate itself in terms of their effects per standard deviation. Even though each type of policy has a peak effect at a different point along the yield curve, the overall magnitudes of the coefficients are broadly similar across rows. This is an important confirmation of these unconventional policies.

Third, the effects of LSAPs are estimated to be very different from those of forward guidance. Indeed, it is this strong contrast that makes identification of these two factors empirically robust. These differences imply that the LSAP factor affected financial markets through more than just a "signaling channel" (e.g., Woodford, 2012; Bauer and Rudebusch, 2014). Recall that, according to the pure signaling view, LSAPs affect financial markets only because they increase the central bank's commitment to follow through with its forward guidance (because the bank would lose money on those LSAPs if it raised interest rates sooner than financial markets expect). If that were the case, then the second and third rows of Table 3 should be much more similar in terms of their relative effects on yields. Instead, the effects are markedly different. This observation is also supported by the results in Table 2, which imply that changes in the federal funds rate and forward guidance factors alone are generally not sufficient to explain financial markets' reactions to FOMC announcements—a third factor is necessary.

Fourth, the differences across the first three rows in Table 3 cast doubt on some authors' use of the 1- or 2-year Treasury yield as a sufficient statistic for monetary policy (e.g., Gertler and Karadi, 2015; Hanson and Stein, 2015; Nakamura and Steinsson, 2017). A 10bp change in the 2-year Treasury yield has very different effects on short- and long-term interest rates (and other financial market assets, as shown below) if it is caused by a change in the current federal funds rate as opposed to a change in forward guidance or a change in LSAPs. For example, a 23.9bp (2.7-standard deviation) change in the federal funds rate has a 10bp effect on the 2-year Treasury yield and a 2.6bp effect on the 10-year yield, while a 2.1-standard deviation change in forward guidance has the same effect on the 2-year Treasury but more than triple the effect on the 10-year yield (8.1bp) and on corporate bond yields, as shown below. A change in LSAPs that caused the 2-year Treasury yield to fall by 10bp would cause the 10-year yield to fall by 177bp. Estimates by these other authors capture a weighted average of the effects of these three different types of monetary policy, but the effects of a given change in the 2-year Treasury yield in practice is likely to depend on how the change in that yield is implemented.

Returning to Table 3, the results of the split-sample identification are reported in rows 4–8. The fourth and fifth rows report the loadings $\widetilde{\Lambda}$ for the rotated pre-ZLB factors during the pre-ZLB period, 1991–2008. The sixth and seventh rows report the loadings $\widetilde{\Lambda}^{zlb}$ for the ZLB period, 2009–15. By construction, the coefficients in the sixth row match those in the fifth row as closely as possible, up to a constant scale factor.[18] (For reference, the last row of Table 3 rescales the coefficients in row 5 to show the best-fitting coefficient values, including scale.) Finally, the seventh row reports the effects of LSAPs. The coefficients in row 7 are generally similar to row 3, although the split-sample estimates are a bit larger for the 5- and 10-year yields, and slightly negative rather than slightly positive for the third and fourth Eurodollar futures contract. But overall, the results from the two identification procedures are quite similar, suggesting that both sets of identifying assumptions work well.

In Figure 1, I directly compare the two sets of estimates for each monetary policy factor from 1991 to 2015. I plot the federal funds rate factor estimates in the top panel, forward guidance factor estimates in the middle panel, and LSAP factor estimates in the bottom panel. In each panel, the solid blue line depicts the full-sample identification estimate and the dashed red line the split-sample estimate. In each panel, the two sets of estimates overlap almost perfectly—the correlation is .98, .945, and .996 in the three panels, respectively.

The main conclusion from Figure 1 is thus that both sets of identifying assumptions produce very similar results. The significantly different shapes of the forward guidance and LSAP effects in the data make the identification of these factors robust across reasonable differences in identifying assumptions.

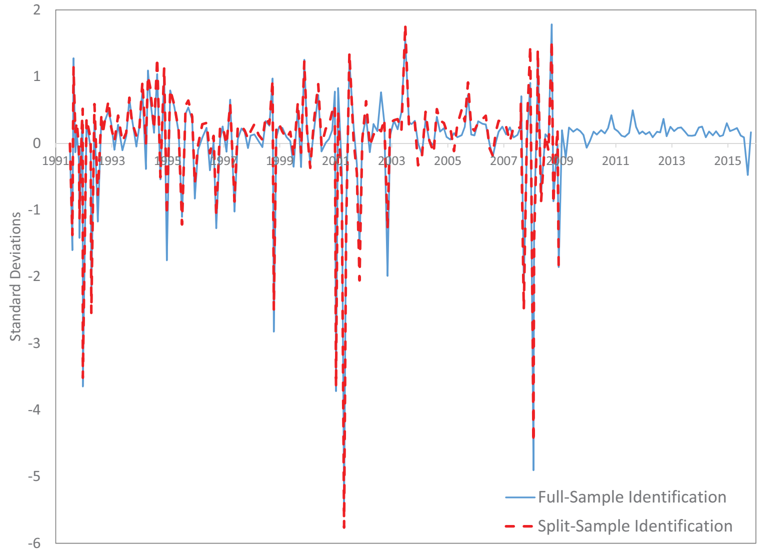
3.1 Correspondence of Factors to Notable FOMC Announcements

Figure 2 reports how well these estimated factors correspond to observable characteristics of major FOMC announcements during the ZLB period, January 2009 to October 2015. (For a similar analysis of the federal funds rate and forward guidance factors in the pre-ZLB period, see GSS.) The dashed blue line in the figure depicts the full-sample estimate of the forward guidance factor, and the solid orange line the full-sample LSAP factor multiplied by -1. This sign renormalization

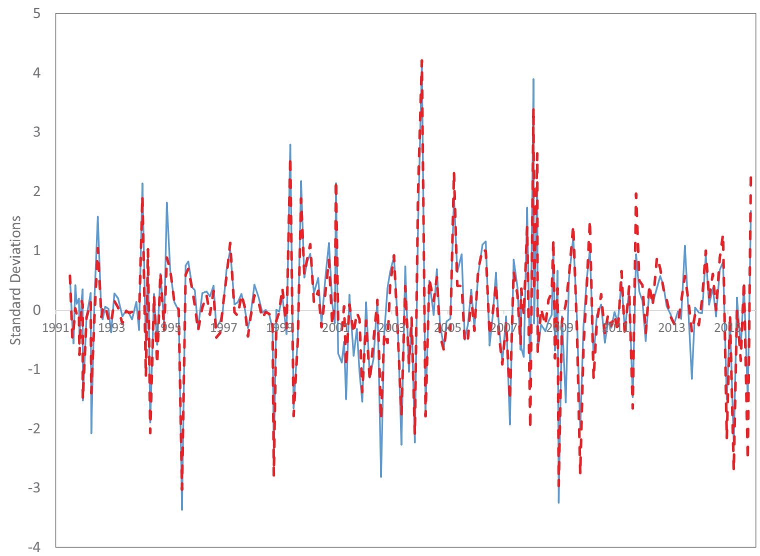
[18] It's interesting that the relative effect of forward guidance on the 5-year Treasury yield is larger in the sixth row of Table 3 than in the fifth row. This is consistent with the view that the FOMC's forward guidance extended out to a longer horizon, on average, during the ZLB period than before. Nevertheless, the identifying assumption that the effects of forward guidance are similar in the pre-ZLB and ZLB periods seems to work well because the effects of the FOMC's asset purchases contrast so sharply with those of forward guidance. It's also interesting that the size of the forward guidance factor is somewhat smaller during the ZLB period than it was before, with an effect of about 4.5bp on the 4-quarter ahead Eurodollar future rate vs. 6.1bp in the pre-ZLB period. A significant change in forward guidance during the ZLB period was often followed by many months with no changes to that forward guidance, resulting in a smaller average forward guidance surprise than before the ZLB. Recall that there were numerous examples of significant forward guidance in the pre-ZLB period, as discussed by GSS.

FIGURE 1: FULL-SAMPLE VS. SPLIT-SAMPLE FACTOR ESTIMATES, 1991–2015

(a) Federal Funds Rate Factor



(b) Forward Guidance Factor



(c) LSAP Factor

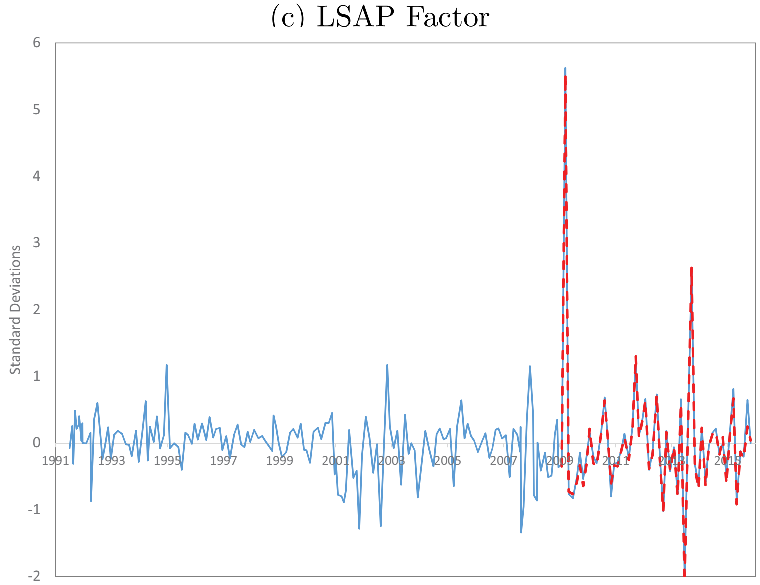
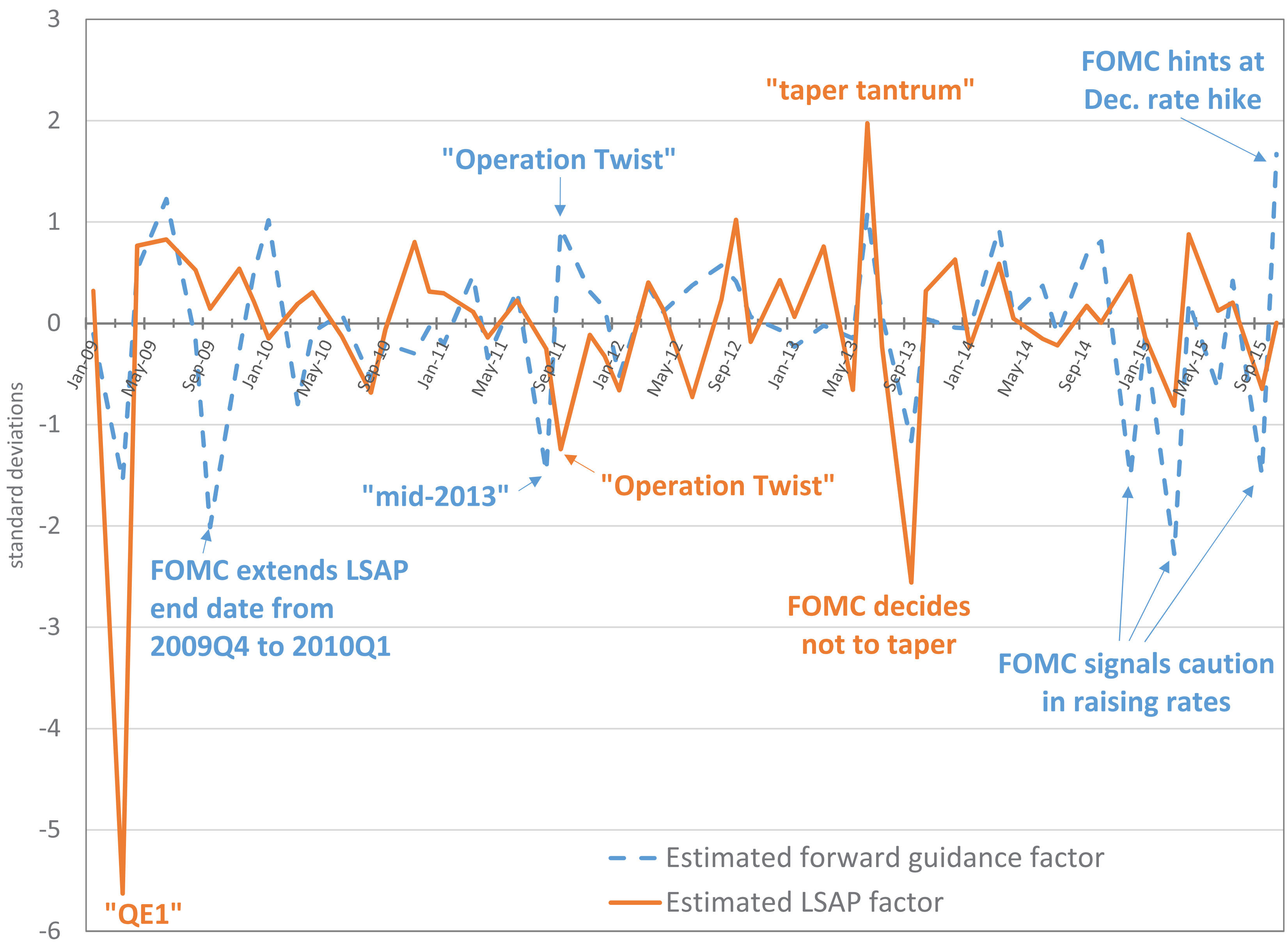


Figure 2: Estimated Forward Guidance and LSAP Factors, 2009–2015



Plot of estimated forward guidance (dashed blue line) and LSAP (solid orange line) factors over time. Notable FOMC announcements are labeled in the figure for reference. The LSAP factor is multiplied by -1 in the figure so that positive values in the figure correspond to interest rate increases. See text for details.

for the LSAP factor makes its behavior in the figure more intuitive—i.e., positive values in the figure correspond to monetary policy tightenings and negative values to monetary policy easings. Figure 2 also contains brief annotations that help to explain some of the larger observations.

The most striking observation in Figure 2 by far is the negative 5.6-standard-deviation LSAP announcement on March 18, 2009, near the beginning of the ZLB sample. This observation corresponds to the announcement of the FOMC's first LSAP program, often referred to as "QE1" in the press.[19] The key elements of this program are listed in Table 1, and the announcement seems to have been a major surprise to financial markets, given the huge estimated size of the factor on that date. According to my identification(s), this announcement is dominated by its LSAP implications, although I also estimate a negative 1.5-standard-deviation forward guidance easing as well. Given that this FOMC announcement placed such a large emphasis on asset purchases, these results seem very reasonable.[20]

Three occasions near the end of the sample—December 17, 2014, March 18, 2015, and September 17, 2015—are also very striking. On these dates, markets expected the FOMC to signal that a hike in the federal funds rate would be coming in the near future. In each of these cases, the FOMC surprised markets by signaling additional caution in raising the funds rate.[21] My identification attributes each of these announcements to changes in FOMC forward guidance, which is very much in line with the market commentary.

The last observation in Figure 2, October 28, 2015, is also very supportive. On that date, the FOMC kept the federal funds rate at zero, but explicitly stated that a rate hike in December

[19] The "QE1" program began on November 25, 2008, when the Federal Reserve Board (rather than the FOMC) announced it would purchase $600 billion of mortgage-backed securities and $100 billion of debt issued by the mortgage-related government-sponsored enterprises. The term "QE1" typically refers to both this earlier program and the huge expansion of that program announced on March 18, 2009. My analysis in this paper excludes the 11/25/08 announcement because it is not an FOMC announcement, but my results are not sensitive to its inclusion.

[20] It's interesting to note that the FOMC's subsequent "QE2" program, described in Table 1, does not show up as a major event in Figure 2, probably becuase it was anticipated by financial markets in advance (see, e.g., *Forbes* 2010). Looking at Figure 2 around the November 3, 2010, announcement date of the program, there is essentially no estimated effect, because the interest rates included in the estimation responded very little to the announcement. Thus, even though the QE2 announcement was roughly one-half as large as the earlier QE1 announcement in terms of the quantity of purchases, the surprise component of that announcement appears to have been dramatically smaller.

[21] On Dec. 17, 2014, markets expected the FOMC to remove its statement that it would keep the federal funds rate at essentially zero "for a considerable time". Not only did the FOMC leave that phrase intact, it announced that "the Committee judges it can be patient in beginning to normalize the stance of monetary policy," which was substantially more dovish than markets had expected (e.g., "U.S. stocks surged...after the Federal Reserve issued an especially dovish policy statement," *The Wall Street Journal*, 2014). On Mar. 18, 2015, the FOMC revised its projections for U.S. output, inflation, and the federal funds rate substantially below what markets had expected. The revised forecast was read by financial markets "as a sign that the central bank would take its time in raising [rates]" (*The Wall Street Journal*, 2015a,b). And on Sep. 17, 2015, the FOMC declined to raise the federal funds rate, issued a statement that was widely regarded as more dovish than expected, and released interest rate forecasts that were substantially lower than before (*The Wall Street Journal*, 2015c,d,e).

was being considered—an unusually explicit signal that significantly altered market's expectations of a rate hike at the upcoming meeting (*The Wall Street Journal*, 2015f,g). The Fed's statement caused short- and medium-term interest-rate futures and Treasury yields to jump, and is thus identified by my estimation as a significant increase in forward guidance, with no change in LSAPs.

The middle of 2013 corresponds to the so-called "taper tantrum" in financial markets. On June 19, I estimate a substantial, two-standard-deviation decrease in the LSAP factor (which is positive in Figure 2 becuase it represents a monetary policy tightening). There is little change in the FOMC statement on that date, but as reported by *The Wall Street Journal,* the FOMC released economic projections along with the statement that showed a substantial increase in the FOMC's economic outlook. Given earlier remarks by then-Chairman Bernanke that the FOMC could begin tapering its asset purchases soon, markets interpreted this as a signal that a tapering was imminent: for example, *The Wall Street Journal* (2013a) reported that "Bond prices slumped, sending the yield on the 10-year Treasury note to its highest level in 15 months, as the Federal Reserve upgraded its growth projections for the U.S. economy... Stronger U.S. growth is widely perceived in the market as heralding an earlier end to the Fed's program of purchasing $85 billion in bonds each month..." The flip side of this announcement occurred on September 18, 2013, when the FOMC was widely expected to begin tapering its asset purchases but opted not to do so. *The Wall Street Journal* (2103b,c) reported that "No Taper Shocks Wall Street," and "The move, coming after Fed officials spent months alerting the public that they might begin to pare their $85 billion-a-month bond-buying program at the September policy meeting, marks the latest in a string of striking turnabouts from Washington policy makers that have whipsawed markets in recent days."[22] I estimate this announcement to be a very large, 2.6-standard-deviation LSAP easing. Thus, both of these "taper tantrum" announcements seem to be correctly identified as movements in the LSAP factor.

There are a number of other notable observations in Figure 2 as well. August 9, 2011, marked the first time the FOMC gave explicit (rather than implicit) forward guidance about the likely path of the federal funds rate over the next several quarters. In that announcement, described in Table 1, the FOMC stated that it expected the current (essentially zero) level of the federal funds rate would be appropriate "at least through mid-2013", a date almost two years in the future. My estimates imply the announcement on this date was a negative 1.5-standard-

[22] *The Wall Street Journal* (2013b,c) also reported that "'Bernanke had a free pass to begin that tapering process and chose not to follow [through]... The Fed had the market precisely where it needed to be. The delay today has the effect of raising the benchmark to tapering..."

deviation surprise in forward guidance, with essentially no LSAP component.

September 21, 2011, corresponds to "Operation Twist", a program where the FOMC sold about $400 billion of short-term Treasury securities in its portfolio and used the proceeds to purchase a like quantity of long-term Treasuries. As can be seen in Figure 2, my identification estimates this announcement to have both LSAP and forward guidance components: a negative 1.2-standard-deviation LSAP effect (which is intuitive), and a *positive* 1-standard-deviation forward guidance effect, which is perhaps surprising. This latter effect is due to the fact that shorter-maturity interest rates rose in response to the FOMC announcement—presumably due to a change in risk premia on those securities resulting from the large increase in expected sales by the Fed. Although this is probably not an example of forward guidance by the FOMC per se, it nevertheless looks like forward guidance in the data because of the unusual implication of the announcement for short-term Treasury yields. Thus, even though my identification is arguably missing this subtle distinction on this particular date, the estimates coming out of the identification are sensible.

Finally, I estimate a negative two-standard-deviation forward guidance announcement on September 23, 2009. On this date, the FOMC stated it would extend its asset purchase program by an additional three months, through 2010Q1. From the text of the FOMC statement alone, it's unclear whether the announcement should be regarded as forward guidance or LSAPs, or both. My estimates characterize this announcement as forward guidance, based on the way financial markets responded (i.e., shorter-term interest rates moved more than longer-term interest rates). It's important to bear in mind that the U.S. economy was beginning to recover by late 2009 and financial markets expected the FOMC to begin raising the federal funds rate in just a few quarters (Swanson and Williams, 2014), but not until a few meetings after completing its asset purchase program. Thus, an extension of the end date of the LSAP program was taken by markets to imply a correspondingly later liftoff date for the federal funds rate.

3.2 Scale of Forward Guidance and LSAP Factors

The forward guidance and LSAP factors estimated above and plotted in Figure 2 have been normalized to have a unit standard deviation over the sample. Similarly, the loadings in Table 3 are for these normalized factors and thus represent a basis points per standard deviation effect. For practical policy applications, however, it's useful to relate these factors to a scale that is more tangible and observable.

For forward guidance, it's natural to think of the factor in terms of a 25bp effect on the Eurodollar future rate one year ahead, ED4. Note that a forward guidance announcement of this size would be very large by historical standards, equal to about a 6-standard-deviation surprise during the ZLB period, or a 4-standard-deviation surprise in the pre-ZLB period. To estimate the effects of a forward guidance announcement of this magnitude, we can multiply the coefficients in the second row of Table 3 by a factor of about 4, which implies that the effects on the 5- and 10-year Treasury yields would be about 20.5 and 15.5bp, respectively. The interpretation is that, if the FOMC gave forward guidance for the federal funds rate that was about 25bp lower one year ahead than financial markets expected, then the 5- and 10-year Treasury yields would decline by about 20.5 and 15.5bp on average.

For LSAPs, we would like the units to be in billions of dollars of purchases, which is a more difficult transformation than a simple renormalization of the coefficients in Table 3. Nevertheless, a number of estimates in the literature suggest that a $600 billion LSAP operation in the U.S., distributed across medium- and longer-term Treasury securities, leads to a roughly 15bp decline in the 10-year Treasury yield (see, e.g., Swanson, 2011, and Table 1 of Williams, 2013). Using this estimate as a benchmark implies that the coefficients in the third row of Table 3 correspond to a roughly $250 billion surprise LSAP announcement. Thus, it seems reasonable to interpret the coefficients in that row of Table 3 as corresponding to a $250 billion change in purchases. The interpretation is thus that, if the FOMC announced a new LSAP program that was about $250 billion larger than markets expected, the effects would be about as large those provided in the third row of Table 3.

4. The Effects of Forward Guidance and LSAPs on Asset Prices

Once we've estimated and identified the forward guidance and LSAP components of each of FOMC announcement, it's relatively straightforward to estimate the effects of those policies on asset prices using high-frequency regressions, as follows. The tables and figures below report results for the factors estimated using the full-sample identification method, but results are very similar for the split-sample identification.

4.1 Treasury Yields

Table 4 reports the responses of 6-month and 2-, 5-, 10-, and 30-year Treasury yields to changes in the federal funds rate and forward guidance from July 1991 to December 2008, and changes in

Table 4: Estimated Effects of Changes in the Federal Funds Rate, Forward Guidance, and LSAPs on U.S. Treasury Yields

	6-month	2-year	5-year	10-year	30-year
(A) estimated effects of federal funds rate and forward guidance, Jul. 1991–Dec. 2008					
change in federal funds rate	4.11***	3.70***	2.02***	0.82***	0.05
(std. err.)	(.397)	(.153)	(.213)	(.222)	(.175)
[t-stat.]	[10.36]	[24.22]	[9.47]	[3.70]	[0.30]
change in forward guidance	2.87***	4.81***	4.59***	3.44***	2.22***
(std. err.)	(.414)	(.191)	(.223)	(.169)	(.206)
[t-stat.]	[6.93]	[25.17]	[20.56]	[20.33]	[10.77]
Regression R^2	.80	.95	.87	.80	.53
# Observations	158	158	158	158	158
(B) estimated effects of forward guidance and LSAPs, Jan. 2009–Oct. 2015					
change in forward guidance	1.19***	5.14***	6.22***	3.06***	0.14
(std. err.)	(.322)	(.323)	(.363)	(.299)	(.886)
[t-stat.]	[3.69]	[15.91]	[17.13]	[10.24]	[0.16]
change in LSAPs	0.19**	0.20	−2.92***	−6.49***	−5.77***
(std. err.)	(.094)	(.118)	(.514)	(.343)	(.554)
[t-stat.]	[2.07]	[1.66]	[−5.69]	[−18.91]	[−10.42]
Regression R^2	.40	.93	.95	.98	.81
# Observations	55	55	55	55	55

Coefficients β from regressions $\Delta y_t = \alpha + \widetilde{F}_t\beta + \varepsilon_t$, where t indexes FOMC announcements, y denotes a given Treasury yield, $\widetilde{F}$ denotes the monetary policy factors estimated previously, and Δ is the intraday change in a 30-minute window bracketing each FOMC announcement. Coefficients are in units of basis points per standard deviation change in the monetary policy instrument. Huber-White heteroskedasticity-consistent standard errors in parentheses; t-statistics in square brackets; *** and ** denote statistical significance at the 1% and 5% levels, respectively. See text for details.

forward guidance and LSAPs from January 2009 to Occtober 2015.[23] As in previous tables and figures, the coefficients here are in units of basis points per standard deviation surprise in the announcement. Each column of the table reports estimates from an OLS regression of the form

$$\Delta y_t = \alpha + \widetilde{F}_t + \varepsilon_t, \tag{2}$$

where t indexes FOMC announcements, y denotes the corresponding Treasury yield, Δ denotes the change in a 30-minute window bracketing each FOMC announcement, $\widetilde{F}$ denotes the monetary policy factors as estimated above, ε is a regression residual, and α and β are parameters.

[23] Results for the 3-month Treasury yield are not reported, since the 3-month Treasury yield generally did not respond to news during the ZLB period—see Swanson and Williams (2014)—and is thus less interesting.

The estimates in the top panel of Table 4 are similar to those that have been estimated previously by GSS and others, and are included here for completeness. Huber-White heteroskedasticity-consistent standard errors and t-statistics are reported for each coefficient, from which we can see that the responses of yields to FOMC announcements about the federal funds rate and forwward guidance are extraordinarily statistically significant, with t-statistics often as high as 10 or even 20 or more. There is no doubt that Treasury yields respond systematically to these announcements by the FOMC. As discussed in the previous section and in GSS, the effect of changes in the federal funds rate declines steadily with maturity, while those of forward guidance are hump-shaped, peaking at an intermediate maturity of about 2 years.

The second panel of Table 4 reports results for changes in forward guidance and LSAPs during the ZLB period from 2009 to 2015. Again, both of these announcements have extraordinarily statistically significant effects on Treasury yields, with t-statistics often above 10 or even 15. The regression R^2 values are also very high during this period, over 94 percent, so these two factors explain a very large share of the variation in Treasury yields around FOMC announcements. The effects of forward guidance are hump-shaped during this later period as well, but with a peak effect that is a little bit larger and later than in the pre-ZLB period, consistent with the FOMC's greater emphasis on longer-dated forward guidance during the ZLB. The effect of forward guidance on the 6-month Treasury yield is smaller than in the pre-ZLB period, due to that yield being so close to zero and so much less sensitive to news for much of the ZLB period (Swanson and Williams, 2014). Finally, the effects of forward guidance diminish rapidly at longer maturities, falling to essentially zero for the 30-year Treasury yield during this period.

As noted previously, LSAPs have their greatest effect on the longest maturities, particularly the 10-year Treasury yield, likely because the FOMC targeted its bond purchases around that particular maturity. The effect on the 30-year yield is also quite large and extraordinarily statistically significant. In contrast, I estimate that LSAPs had a small *positive* effect on the short end of the yield curve, amounting to about 0.2bp per standard deviation. One explanation for this result is that the Federal Reserve or other market participants may have reduced their demand or sold off short-term Treasuries in order to buy those at the longer maturities, such as in the Federal Reserve's "Operation Twist" period from late 2011 through 2012.

Taken together, these results show that both forward guidance and LSAPs were effective during the ZLB period, both statistically and quantitatively. Their effects on the Treasury yield curve have very different shapes than conventional monetary policy—changes in the federal funds

Table 5: Estimated Effects of Changes in the Federal Funds Rate, Forward Guidance, and LSAPs on Stock Prices and Exchange Rates

	S&P500	\$/euro	\$/yen
(A) estimated effects of federal funds rate and forward guidance, Jul. 1991–Dec. 2008			
change in federal funds rate	-0.32^{***}	-0.11^{**}	-0.13^{***}
(std. err.)	(.106)	(.046)	(.032)
[t-stat.]	[−2.98]	[−2.41]	[−4.02]
change in forward guidance	-0.16^{**}	-0.16^{***}	-0.14^{***}
(std. err.)	(.068)	(.033)	(.031)
[t-stat.]	[−2.37]	[−4.64]	[−4.53]
Regression R^2	.31	.15	.14
# Observations	158	158	158
(B) estimated effects of forward guidance and LSAPs, Jan. 2009–Oct. 2015			
change in forward guidance	-0.26^{***}	-0.37^{***}	-0.24^{***}
(std. err.)	(.100)	(.057)	(.050)
[t-stat.]	[−2.61]	[−6.46]	[−4.86]
change in LSAPs	0.12^{*}	0.21^{***}	0.29^{***}
(std. err.)	(.059)	(.053)	(.048)
[t-stat.]	[1.99]	[4.00]	[6.08]
Regression R^2	.28	.68	.79
# Observations	55	55	55

Coefficients β from regressions $\Delta \log x_t = \alpha + \widetilde{F}_t \beta + \varepsilon_t$, where t indexes FOMC announcements, x is the asset price, $\widetilde{F}$ denotes the monetary policy factors estimated previously, and Δ is the intraday change in a 30-minute window bracketing each FOMC announcement. Coefficients are in units of percentage points per standard deviation change in the monetary policy instrument. Huber-White heteroskedasticity-consistent standard errors in parentheses; t-statistics in square brackets; ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively . See text for details.

rate target—but nevertheless are similar in magnitude.

4.2 Stock Prices and Exchange Rates

Table 5 reports analogous results for the S&P 500 stock index and dollar-euro and dollar-yen exchange rates. The form of the regressions is the same as in equation (2), except the dependent variable in each regression is now 100 times the log change in the asset price in each column.

As before, the results for changes in the federal funds rate and forward guidance in the pre-ZLB period are included for reference and completeness. A one-standard-deviation increase in the federal funds rate causes stock prices to fall about 0.3 percent and the dollar to appreciate by about 0.1 percent, with t-statistics of 2.4 or greater. A one-standard-deviation tightening of forward guidance causes stocks to fall a bit less, about 0.15 percent, but the dollar to appreciate by a bit more, also about 0.15 percent, and these effects are also statistically significant with t-statistics of 2.4 or above.

During the ZLB period, I estimate that the effects of forward guidance were somewhat larger, leading to a drop in stock prices of about 0.25 percent and an appreciation of the dollar of about 0.25–0.35 percent. The t-statistics are even larger than for the pre-ZLB period. For LSAPs, I estimate that a one-standard-deviation increase—which causes interest rates to fall—leads stock prices to rise about 0.1 percent and the dollar to depreciate by 0.2–0.3 percent. The effects on the dollar are much more highly statistically significant and have a much higher R^2 than the results for stocks or the pre-ZLB exchange rate results. The R^2 for the stock price regression is much lower than those for Treasury yields, due to the high and idiosyncratic volatility of stock prices after FOMC announcements.

These effects are all intuitive. For the dollar, the effects have the signs one would expect from uncovered interest parity, given the response of interest rates in Table 4. That is, an increase in U.S. interest rates makes U.S. dollar investments more attractive relative to foreign investments, and tends to drive the value of the dollar up. For stocks, the effects are consistent with increases in interest rates reducing the present value of stocks' future dividends through both a discounting channel and a weaker economy.

The results in Table 5 show that forward guidance and LSAPs were also effective at moving stock prices and exchange rates. Their effects on the dollar seem to be even greater than for conventional monetary policy—changes in the federal funds rate—but the effects on stock prices seem to be a bit less, though still statistically significant. Forward guidance and LSAPs seem to be about equally effective at moving exchange rates, while forward guidance is a bit better at moving stock prices.

4.3 Corporate Bond Yields and Spreads

Table 6 reports analogous results for corporate bond yields and spreads. Corporate bonds are less frequently traded than U.S. Treasuries, stocks, and foreign exchange, so only daily frequency corporate bond yield data are available. Thus, the regressions in Table 6 use the one-day change in corporate bond yields or spreads around each FOMC announcement as the dependent variable. To measure corporate yields, I consider both the Aaa and Baa indexes of long-term seasoned

Table 6: Estimated Effects of Changes in the Federal Funds Rate, Forward Guidance, and LSAPs on Corporate Bond Yields and Spreads

	Corporate Yields		Spreads	
	Aaa	Baa	Aaa−10-yr.	Baa−10-yr.
(A) estimated effects of federal funds rate and forward guidance, Jul. 1991–Dec. 2008				
change in federal funds rate	0.32	0.41	−0.41	−0.32
(std. err.)	(.388)	(.421)	(.548)	(.461)
[t-stat.]	[0.83]	[0.98]	[−0.76]	[−0.70]
change in forward guidance	2.08***	1.96***	−0.60	−0.72**
(std. err.)	(.396)	(.402)	(.402)	(.315)
[t-stat.]	[5.24]	[4.87]	[−1.52]	[−2.30]
Regression R^2	.18	.18	.04	.07
# Observations	158	158	158	158
(B) estimated effects of forward guidance and LSAPs, Jan. 2009–Oct. 2015				
change in forward guidance	0.48	−0.51	−1.64**	−2.63***
(std. err.)	(.765)	(.922)	(.780)	(.959)
[t-stat.]	[0.63]	[−0.56]	[−2.10]	[−2.74]
change in LSAPs	−4.51***	−5.25***	3.56***	2.81***
(std. err.)	(.427)	(.756)	(.633)	(1.030)
[t-stat.]	[−10.56]	[−6.96]	[5.62]	[2.73]
Regression R^2	.45	.50	.53	.55
# Observations	55	55	55	55

Coefficients β from regressions $\Delta y_t = \alpha + \widetilde{F}_t\beta + \varepsilon_t$, where t indexes FOMC announcements, y denotes the corporate bond yield or spread, $\widetilde{F}$ denotes the monetary policy factors estimated previously, and Δ is the change in a one-day window bracketing each FOMC announcement. Coefficients are in units of basis points per standard deviation change in the monetary policy instrument. Huber-White heteroskedasticity-consistent standard errors in parentheses; t-statistics in square brackets; *** and ** denote statistical significance at the 1% and 5% levels, respectively. See text for details.

corporate bond yields from Moody's.

The top panel reports the effects of changes in the federal funds rate and forward guidance before the ZLB. FOMC changes in the federal funds rate have no significant effect on either corporate bond yields or spreads. Forward guidance has a larger and highly statistically significant effect, about 2bp per standard deviation for Aaa and Baa bond yields, with t-statistics of about 5. The effect of forward guidance on spreads, however, is negative as the 10-year Treasury yield responds to the announcement by more than the corporate bond yields.

The bottom panel reports the effects of changes in forward guidance and LSAPs on corporate bonds during the ZLB period. Surprisingly, changes in forward guidance have essentially no effect on corporate bond yields during the ZLB. The point estimates for both Aaa and Baa yields are small (about 0.5bp per standard deviation change in forward guidance) and statistically insignificant. Because 10-year Treasury yields rise modestly in response to an increase in forward guidance, the effect on the corporate-Treasury yield spread is thus modestly negative, falling about 1.5 to 2.5bp in response to an increase in guidance, and this effect is statistically significant, with t-statistics of 2.1 and 2.7.

The effect of LSAPs on corporate bond yields is much larger and more significant. A one-standard-deviation increase in LSAPs causes the Aaa and Baa yields both to fall about 5bp, and the effect is very highly statistically significant. However, the effect of LSAPs on the 10-year Treasury yield is larger than the effect on corporate bond yields, so the spread between corporate bonds and Treasuries actually *increases* in response to the LSAP program.[24] This result echoes findings in Krishnamurthy and Vissing-Jorgensen (2012) and Swanson (2011) that the Fed's LSAP programs—which tended to be concentrated in U.S. Treasury securities—pushed down Treasury yields more than they did private-sector yields. Nevertheless, the effect on corporate bond yields I estimate here is bigger than those authors found in their studies. For example, Swanson (2011) estimated corporate yields fall about 4–5bp in response to a \$600 billion Treasury LSAP, while the estimates in Table 6 are closer to 11–12bp for the same size operation (assuming this is a roughly 2.5-standard-deviation announcement, as discussed earlier). One reason for the larger estimates here may be that the FOMC's recent LSAP programs often included a substantial quantity of mortgage-backed securities (MBS) as well as Treasuries, while the earlier estimates in Krishnamurthy and Vissing-Jorgensen (2012) and Swanson (2011) were for the case of a Treasury-only LSAP. Those MBS are likely to be closer substitutes for corporate bonds than are Treasuries, so we should expect purchases of MBS to have a relatively larger effect on corporate bond yields than purchases of Treasuries alone.

5. The Persistence of Forward Guidance and LSAP Effects

The regressions above measure the 30-minute or one-day responses of different yields and asset

[24] The 10-year yield response in Table 3 is estimated to be about −6.5bp, while the effect implied in Table 6 is a bit larger, about −8.1bp. There are two reasons for this difference: first, the responses in Table 3 are 30-minute responses, while those in Table 6 are one-day responses. Second, Table 3 uses the on-the-run coupon-bearing 10-year Treasury bond, while in Table 6 I use the 10-year zero-coupon yield estimate by Gürkaynak, Sack, and Wright (2007). The latter yield has a longer duration than the coupon-bearing 10-year security, which should be a better match to the long-term corporate bonds in the Moody's indexes.

prices to FOMC announcements. If yields and asset prices are martingales, then these very short-term responses are representative of the responses of those assets over longer windows as well. However, some recent studies suggest the effects of unconventional monetary policy may not be persistent. For example, Duffie (2010) cites several examples where large movements of captial (e.g., due to stocks entering or leaving the S&P500, or auctions of new Treasury securities) can have transitory effects on asset prices that dissipate over a period of time, up to several months in length. The idea is that arbitrage capital can be "slow-moving" and is not reallocated instantaneously to take advantage of asset price distortions caused by idiosyncratic changes in demand or supply for the asset. Fleckenstein, Longstaff, and Lustig (2014) find support for this theory in the pricing of TIPS securities during the 2007–09 global financial crisis.

Taylor (2012) and Woodford (2012) argue against the effectiveness of the Federal Reserve's LSAPs for essentially the same reasons. Although the FOMC's announcement of an LSAP causes high-frequency movements in yields or asset prices around the time of the announcement, the argument goes, these changes in risk premia will be arbitraged away eventually as arbitrageurs react to the announcement and adjust their positions, but this process takes time because the Fed's expected asset purchases are so large, amounting to hundreds of billions of dollars. The empirical evidence in Wright (2012) supports this view: using a dailiy-frequency VAR, Wright (2012) estimates that the effects of the FOMC's unconventional monetary policy on U.S. long-term bond yields had a half-life of only about 2–3 months.

5.1 Unconstrained h-Day Yield Changes

To get a first look at the persistence of the effects of the FOMC's forward guidance and LSAP announcements, I run a series of daily regressions at multiple horizons, of the form

$$y_{t-1+h} = \alpha_h + \beta_h y_{t-1} + \gamma_h \widetilde{F}_t + \varepsilon_t^{(h)}, \tag{3}$$

where each forecast horizon h is associated with a different regression, y denotes a given bond yield or log asset price, t indexes business days from January 2009 through October 2015, $\widetilde{F}$ denotes the forward guidance and LSAP components of FOMC announcements as estimated above (and is set equal to zero on non-FOMC announcement days), $\varepsilon_t^{(h)}$ is a residual, and α_h, β_h, and γ_h are parameters that may vary across regressions h. This is essentially Jordà's (2005) "direct projections" method of estimating impulse response functions, with a lag length of zero for the lagged endogenous variable y on the right-hand side, since I find that additional lags aren't needed. As discussed by Jordà (2005), the direct projections in (3) have several advantages over extrapolating the results of a daily-frequency VAR(1) as in Wright (2012). In particular, the results of extrapolation compound any errors in the parameter estimates as the horizon h increases, while the direct projections method avoids extrapolation and compounding and is thus more robust to model misspecification.

I estimate that the coefficients α_h and β_h are essentially always close to zero and one, respectively, so I impose those restrictions in the analysis. Then (3) is just a regression of the h-day difference, $y_{t-1+h} - y_{t-1}$, on the factors $\widetilde{F}_t$. The estimated coefficients $\hat{\gamma}_h$ vary across forecast horizons h, so we can plot those coefficients as a function of the horizon h to see whether those coefficients tend to diminish as h increases. Of course, for longer horizons h, there will also be a greater amount of non-monetary-policy news that impacts yields and asset prices, so the residuals $\varepsilon_t^{(h)}$ and standard errors surrounding the coefficient estimates $\hat{\gamma}_h$ will tend to be larger.

Figure 3 plots the results of these regressions for 2- and 10-year Treasury yields. The solid blue line in each panel plots the point estimates of $\hat{\gamma}_h$ as a function of horizon h, and dotted red lines plot Newey-West (1987) $\pm$1.96-standard-error bands around those point estimates, allowing for $h-1$ lags of autocorrelation.[25]

The estimated effect of a one-standard-deviation change in forward guidance on the 2-year Treasury yield is about 3bp on the first day (top-left panel of Figure 3), slightly less than the estimated effect in Table 4 that used intradaily data, and this one-day response is highly statistically significant. For horizons h out to about 50 business days, the point estimates remain between 2.5 and 5.5bp, and are statistically significant out to horizons of about 35 days. At horizons beyond about 50 days, the point estimates are typically smaller.

The effect of forward guidance on the 10-year Treasury yield (top-right panel of Figure 3) is about 2bp on the first day, and is statistically significant. For horizons out to about 35 days, the effect is actually somewhat larger, around 5–8bp, and is typically highly statistically significant. After about 40 days, the effects of forward guidance on the 10-year yield are close to zero.

The effect of a one-standard-deviation increase in LSAPs on the 2-year Treasury yield (bottom-left panel of Figure 3) is about -2.5bp on the first day, and this effect is statistically significant.[26] However, the effect diminishes almost monotonically with the horizon h, fluctuating

[25] Alternatively, one can drop all observations for which $\widetilde{F}_t = 0$, which leaves a sample of size 55 (or 54 or 53 for longer horizons h) and reduces the number of autocorrelated lags to about $h/32$ (FOMC meetings average about 32 business days apart), rounded down. All results below are essentially identical using this approach.

[26] The estimated effect in Table 4 is smaller and statistically insignificant, but that estimate is for an on-the-

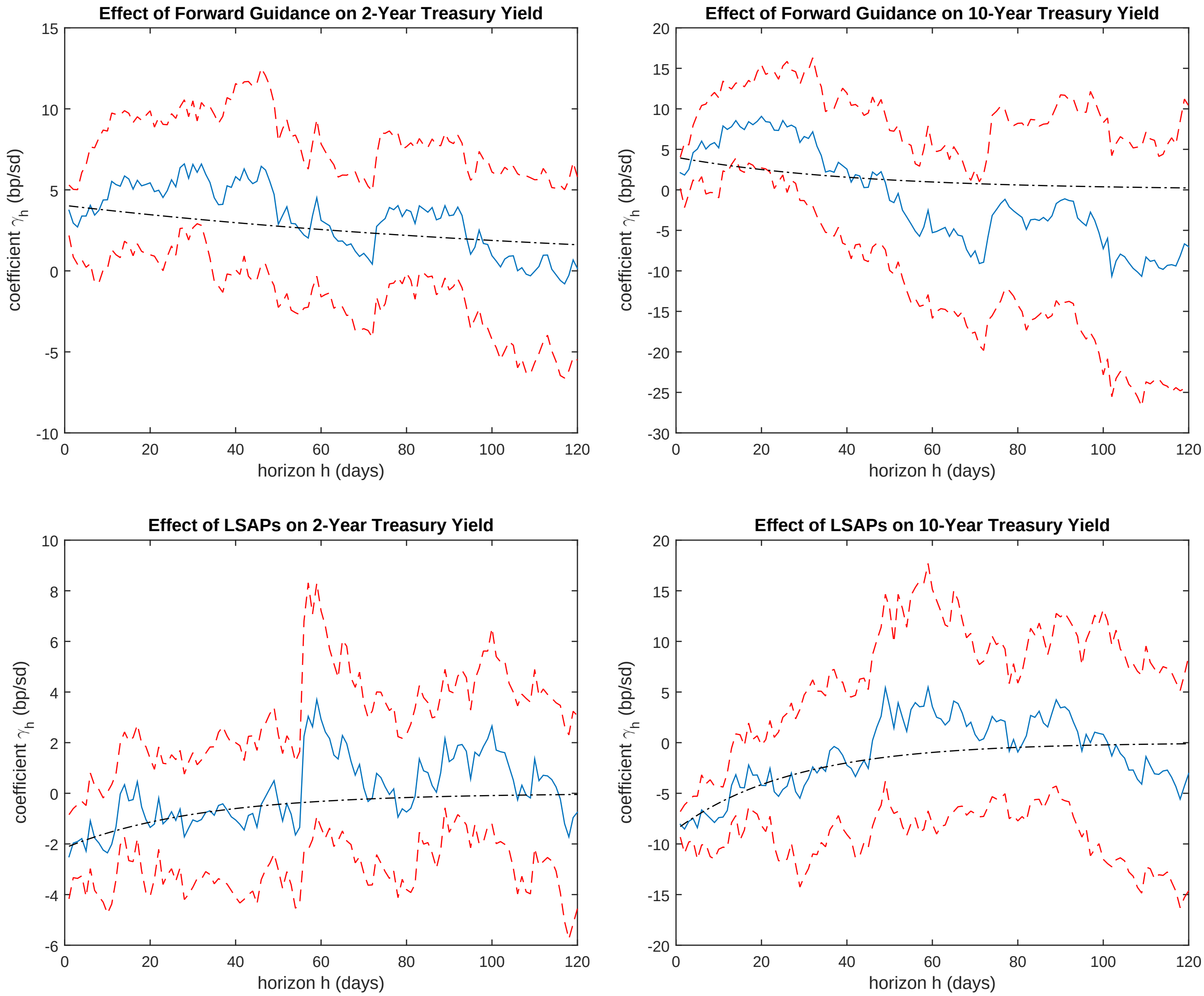


Figure 3. Estimated effects of forward guidance and LSAPs on 2- and 10-year zero-coupon Treasury yields, for different horizons h ranging from 1 to 120 business days. Estimated coefficients $\hat{\gamma}_h$ (solid blue line) and HAC ±1.96-standard-error bands (dashed red lines) are from regressions $y_{t-1+h} - y_{t-1} = \gamma_h \widetilde{F}_t + \varepsilon_t^{(h)}$. Restricted coefficient estimates $\gamma_h = ae^{-b(h-1)}$ (dash-dotted black lines) are from the same set of regressions estimated jointly via nonlinear least squares. See text for details.

around zero after about 55 days. The standard error bands are somewhat narrower than for forward guidance. For the 10-year Treasury yield in the bottom-right panel, the estimated effect is nearly 9bp on impact, and again the effect diminishes almost monotonically over time, fluctuating around zero after about 50 days.

run (i.e., most recently issued, most liquid, and most heavily traded) coupon-bearing 2-year Treasury, while the estimates in Figure 4 are for a zero-coupon 2-year Treasury, which has a longer Macauley duration. Since the effects of LSAPs generally increase with duration, we should expect the effect on the zero-coupon 2-year Treasury to be larger. Zero-coupon yields are from the Gürkaynak et al. (2007) database and keep the maturity constant even as the horizon h and time t change.

Table 7: Estimated Persistence Coefficients

	Forward Guidance		LSAPs	
	a	b	a	b
Jan. 2009–Oct. 2015:				
2-year Treasury yield	4.0***	0.0077***	−2.2***	0.032**
[t-stat.]	[10.26]	[4.41]	[−4.94]	[2.54]
10-year Treasury yield	4.0***	0.024**	−8.6***	0.037***
[t-stat.]	[5.40]	[2.02]	[−16.34]	[5.30]
Jan. 2009–Oct. 2015, excluding March 18, 2009:				
2-year Treasury yield	4.1***	0.0081***	−0.3	15.26
[t-stat.]	[11.10]	[4.98]	[−0.56]	[0.00]
10-year Treasury yield	3.6***	0.022**	−4.9***	0.0018
[t-stat.]	[4.97]	[1.97]	[−9.58]	[1.37]

Coefficients a and b for restriction $\gamma_h = ae^{-b(h-1)}$ in regressions (3), estimated via nonlinear least squares. HAC t-statistics in square brackets; *** and ** denote statistical significance at the 1% and 5% levels, respectively. See text for details.

5.2 Persistence Estimates

To estimate the degree of attenuation in these figures, and the statistical significance of that attenuation, I fit an exponential function to the coefficients γ_h,

$$\gamma_h \;=\; ae^{-b(h-1)}\,, \tag{4}$$

where a and b are parameters, with a denoting the impact effect and b the exponential decay rate. I stack the regressions (3) into a single system, impose the restriction (4) on the coefficients γ_h, and estimate the parameters a and b in a single step via weighted nonlinear least squares.[27] The dash-dotted black lines in Figure 3 depict the results of this restricted specification.

Table 7 reports the estimated values of a and b for the effects of forward guidance and LSAPs on the 2- and 10-year Treasury yields.[28] The impact effects a in the top panel are all highly statistically significant, with t-statistics of 4 or more. The standard martingale view of

[27] The observations for each horizon h are weighted by σ_h^{-1}, where σ_h denotes the estimated variance of the residuals for the unrestricted horizon h regression (3). I also impose two restrictions on this estimation: First, the coefficient a cannot be more than 25% greater or less than the average unconstrained effect γ_h over the first 5 days. Second, the coefficient $b \geq 0$. These restrictions prevent the estimation from picking values of a and b that are implausible *a priori*. Finally, the regressions in (4) are stacked and run out to a 180-business-day horizon h, to help estimate the decay parameter b.

[28] The t-statistics in Table 7 are corrected for heteroskedasticity and autocorrelation according to Newey and West (1987), with 119 lags, since the maximum horizon h considered in these regressions is 120. Results are very similar using a lower number of lags, or no lags and a Huber-White heteroskedasticity correction.

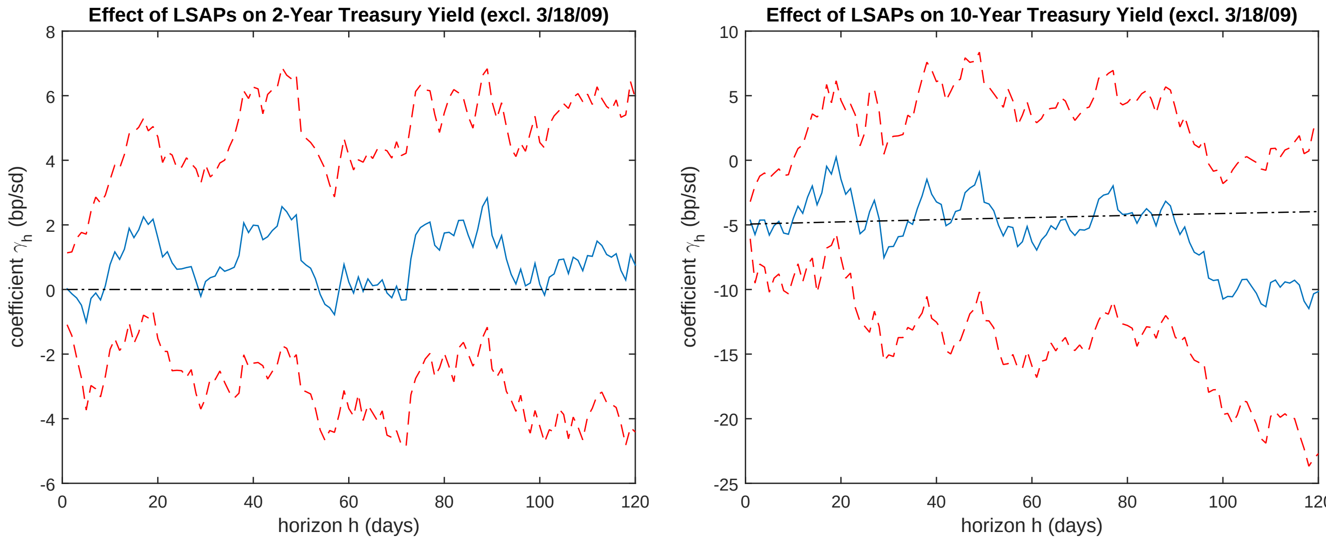


Figure 4. Estimated effects of LSAPs on 2- and 10-year zero-coupon Treasury yields for different horizons h, excluding the large and influential March 18, 2009, FOMC announcement. (Results for forward guidance are essentially identical to Figure 3 and are not reported.) See notes to Figure 3 and text for details.

asset price responses would imply that $b = 0$, but in Table 7, the decay rates b are all significantly larger than zero, which supports the slow-moving capital view and suggests that the attenuation in Figure 3 is important. The half-lives of the effects range from as long as 90 business days (for the effect of forward guidance on the 2-year yield) down to 19 business days (for the effect of LSAPs on the 10-year yield).

These estimates suggest that the effects of unconventional monetary policy are not very persistent, particularly for LSAPs and for longer-term yields. However, it's important to note that the significance of the estimates for LSAPs in Table 7 are very sensitive to whether or not the extremely large and influential March 18, 2009, FOMC announcement is included in the analysis. (Recall that announcement was about 5.5 standard deviations, corresponding to over \$1.1 trillion of new long-term bond purchases and implicitly raising the possibility that there could be additional such operations in the future.) The bottom panel of Table 7 reports results for the same regressions, excluding that one observation from the sample. In this case, the results for forward guidance are essentially unchanged, while the results for LSAPs no longer show any evidence of attenuation. The effect of LSAPs is no longer significant on impact for the 2-year Treasury yield, omitting that large March 2009 observation, but the effect on the 10-year yield remains extremely statistically significant, albeit with a smaller magnitude.

Figure 4 repeats the analysis in Figure 3, but excluding the March 18, 2009, observation from the sample. The results for forward guidance are essentially identical to Figure 3 and are

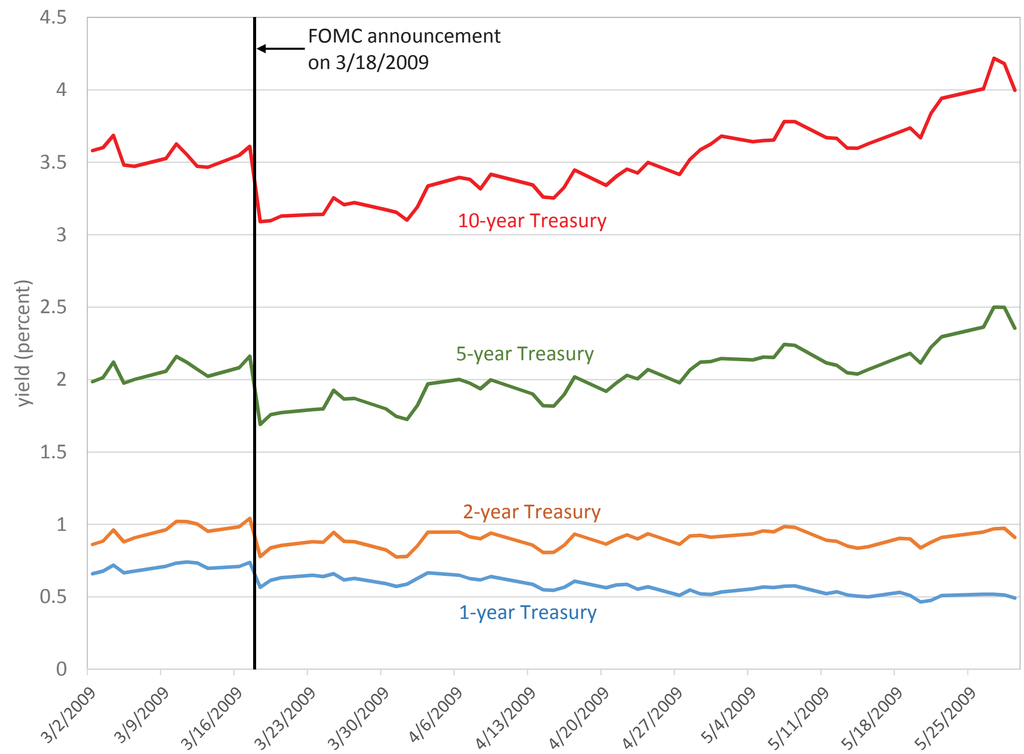


Figure 5. 1-, 2-, 5-, and 10-year zero-coupon Treasury yields from March 1 to May 31, 2009. See text for details.

not reported. However, the results for LSAPs are very different: for the 2-year Tresury yield, the effects are no longer significant at any horizon, and for the 10-year yield, there is no longer any evidence of attenuation. The effects of LSAPs look completely persistent.

For reference, Figure 5 reports the behavior of Treasury yields around the March 18, 2009, announcement. Yields of all maturities fell dramatically on the day of the announcement, but 5- and 10-year yields began to drift back up over the ensuing weeks, erasing the entire decline in long-term yields by about the 30th business day following the announcement. The very large size of the LSAP factor for this FOMC announcement gives these responses a very large weight in the regression analysis above.

Thus, the low persistence estimates for the effects of LSAPs seem to be driven entirely by the behavior of long-term bond yields after the March 18, 2009, FOMC announcement. Having influential observations is good for econometric power, but can be a problem if the behavior around that observation is not representative, which appears to be the case here. *A priori,* there is little reason to exclude that announcement, except that it is very close to the U.S. stock market trough and may have been a period of poor market functioning in general (e.g., Fleckenstein et al., 2014); if the March 2009 FOMC announcement had unusual effects because of these background

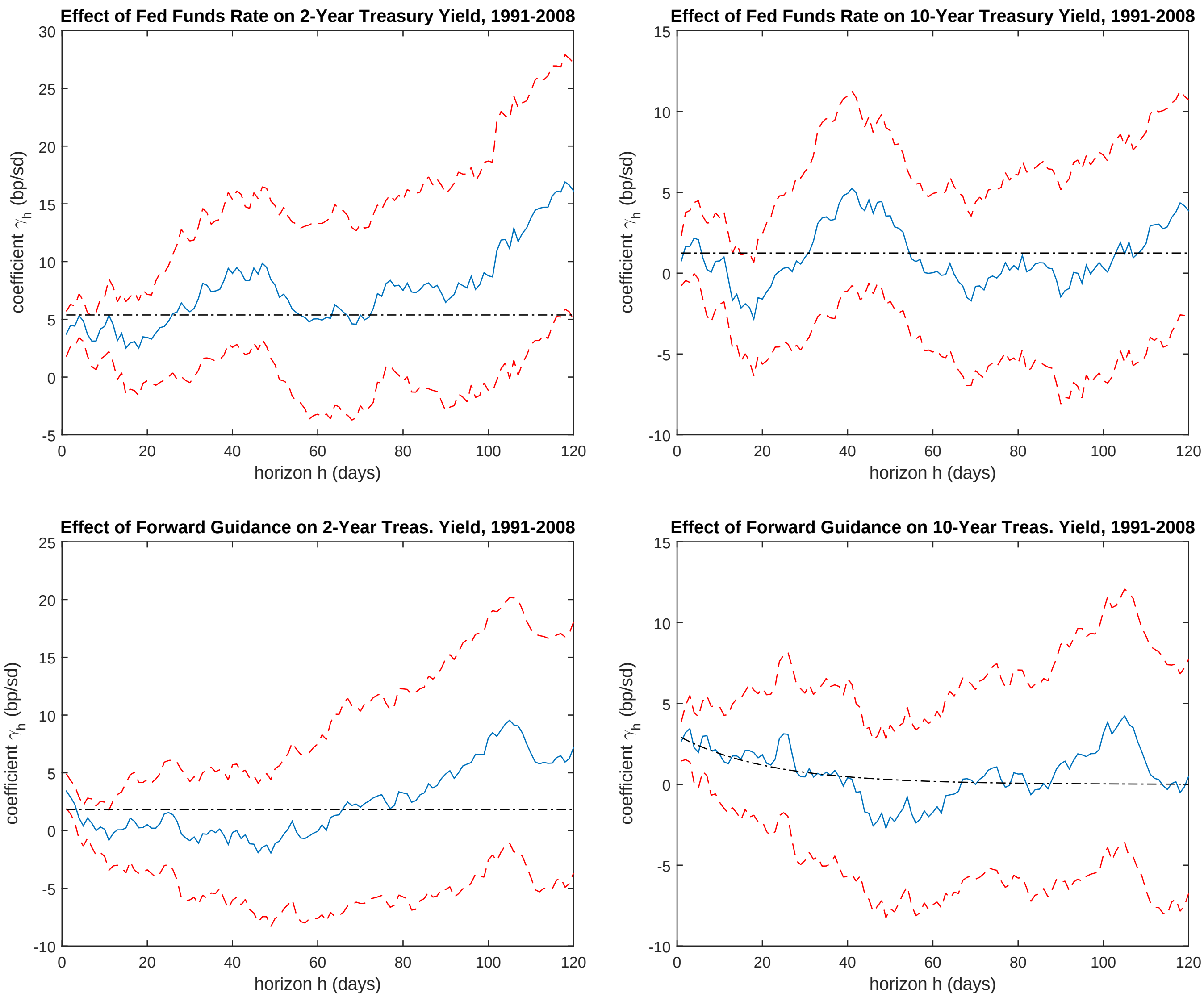


Figure 6. Estimated effects of changes in the federal funds rate and forward guidance on 2- and 10-year zero-coupon Treasury yields for different horizons h ranging from 1 to 120 business days, over the period 1991 to 2008. See notes to Figure 3 and text for details.

factors and the sheer size of the announcement, then that would tend to argue for excluding it. In any case, the fact that the low persistence estimates for LSAPs are so dependent on this one observation does suggest those results should be discounted.

In contrast, the low persistence estimates for forward guidance seem to be more robust. Unlike LSAPs, there is no one forward guidance announcement that has such an influential effect on the results.

In Figure 6, I check whether this low persistence of forward guidance was also a feature of the pre-ZLB period, and whether conventional monetary policy—i.e., changes in the federal funds rate—had persistent effects. Parameter estimates a and b for the restricted coefficient

Table 8: Estimated Persistence Coefficients for Conventional and Unconventional Monetary Policy, 1991–2008

	Federal Funds Rate		Forward Guidance	
	a	b	a	b
July 1991–Dec. 2008:				
2-year Treasury yield	5.4***	0.000	1.8***	0.000
[t-stat.]	[12.82]	[0.00]	[6.07]	[0.00]
10-year Treasury yield	1.2***	0.000	3.0***	0.047**
[t-stat.]	[3.69]	[0.00]	[6.97]	[2.41]

Coefficients a and b for restriction $\gamma_h = ae^{-b(h-1)}$ in regressions (3), estimated via nonlinear least squares. HAC t-statistics in square brackets; *** and ** denote statistical significance at the 1% and 5% levels, respectively. See text for details.

specification, $\gamma_h = ae^{-b(h-1)}$, are reported in Table 8. The effects of conventional monetary policy (top panels of Figure 6) are highly statistically significant for the 2-year yield and show no evidence of attenuation for either the 2- or 10-year yield. These observations are confirmed by the coefficient estimates in Table 8.

For forward guidance (bottom panels of Figure 6), however, the effects seem to die out quickly. The estimated half-life of the effect on the 10-year Treasury yield in Table 8 is just 15 business days. Although the estimates in Table 8 for the 2-year yield suggest the effects are persistent, the bottom-left panel of Figure 6 actually shows very rapid attenuation over the first 5 or 6 days after the announcement, with essentially a zero effect thereafter, suggesting very strong attenuation for that yield as well. Ending the sample before 2008 or excluding some of the larger and more influential forward guidance announcements has essentially no effect on this result; in fact, the estimated attenuation tends to be even stronger and more statistically significant in those cases.

Thus, the effects of forward guidance are relatively powerful on impact, but appear to be short-lived, both before and during the ZLB period. I estimate half-lives for the effects that range from about 15 to 90 business days, or about one to four months. Interestingly, this is similar to Jonathan Wright's (2012) estimated half-life of 2–3 months for unconventional monetary policy in a daily VAR over his 2008–11 sample. In contrast to Wright (2012), I use a different econometric method, I distinguish between LSAPs and forward guidance, and I find evidence that the effects of LSAPs are completely persistent if we exclude the influential March 2009 FOMC announcement.

6. Effects of Forward Guidance and LSAPs on Interest Rate Uncertainty

Unconventional monetary policy could also have substantial effects on interest rate uncertainty. Bernanke (2013) emphasizes that a major goal of forward guidance is to reduce financial market uncertainty about the path of the federal funds rate, not just financial market expectations about that path. In this section, I investigate whether the FOMC's forward guidance announcements achieved this former goal as well as the latter.

I also investigate whether LSAPs as well as forward guidance had effects on interest rate uncertainty. The effect of LSAPs on uncertainty is ambiguous and is ultimately an empirical question: on one hand, if LSAPs are a new source of shocks to long-term bond yields, that could increase uncertainty about those yields; alternatively, LSAPs could reduce uncertainty if they tended to be implemented in response to increases in long-term yields, because then LSAPs would be a stabilizing force.

To measure uncertainty about the federal funds rate over the next several months or quarters, I use Eurodollar options with five quarters to expiration, as in Swanson and Williams (2014). These data are available at daily frequency with a range of strike prices, which can be used to estimate the entire distribution of the federal funds rate in five quarters' time.[29] Following Swanson and Williams (2014), I use the distance between the 80$^{\text{th}}$ and 20$^{\text{th}}$ percentiles of that distribution on any given day as a measure of uncertainty on that day about the federal funds rate five quarters ahead.

The first column of Table 9 reports results from regression (3) with monetary policy uncertainty as the dependent variable y. In response to a one-standard-deviation increase in forward guidance, monetary policy uncertainty increases by about 4bp (as measured by the interquintile range in the options-implied PDF as described above), and this change is statistically significant with a t-statistic of about 2.3. Thus, the data support Bernanke's (2013) stated goal that reductions in forward guidance by the FOMC should reduce financial market uncertainty about the path of the federal funds rate. In contrast to forward guidance, LSAPs have no significant effect on monetary policy uncertainty on impact.

[29] We don't need to assume normality for these distributions because we observe option prices for multiple strikes. On each day from January 2008 through December 2015, I use the range of available Eurodollar option put and call prices with five quarters to expiration to estimate the implied distribution of the spot 3-month Eurodollar rate in five quarters' time, using a flexible functional form. Eurodollar options are the most liquid options on a short-term interest rate and thus provide the best measure of the distribution of possible short-term interest rate outcomes. I use the spread between overlapping federal funds futures and Eurodollar futures rates at a one-year horizon to convert these implied distributions for the 3-month Eurodollar rate into an implied distribution for the federal funds rate. These probability estimates ignore risk premia and thus represent implied risk-neutral probabilities.

Table 9: Estimated Effects of Forward Guidance and LSAPs on Monetary Policy Uncertainty, 2009–2015

	(1)	(2)	(3)
change in forward guidance	4.21**	3.78**	3.55*
[t-stat.]	[2.33]	[2.05]	[1.76]
change in LSAPs	1.14*	1.58	1.07
[t-stat.]	[1.72]	[1.27]	[0.81]
|change in forward guidance|	—	−2.09	—
[t-stat.]	—	[−0.87]	—
|change in LSAPs|	—	−0.38	—
[t-stat.]	—	[−0.30]	—
(change in forward guidance)^2	—	—	−1.03
[t-stat.]	—	—	[−0.88]
(change in LSAPs)^2	—	—	0.06
[t-stat.]	—	—	[0.25]
Regression R^2	.15	.17	.17
# Observations	55	55	55

Coefficients β from regressions of one-day changes in monetary policy uncertainty on forward guidance and LSAP factors, nonlinear transformations of those factors, and a constant (not reported). Monetary policy uncertainty is the interquintile range (in bp) for the federal funds rate distribution 5 quarters ahead, from Eurodollar options. Huber-White heteroskedasticity-consistent standard errors in parentheses; t-statistics in square brackets; ** and * denote statistical significance at the 5% and 10% levels, respectively. See text for details.

The second and third columns of Table 9 augment regression (3) to include nonlinear terms, since the direction of forward guidance may not matter for uncertainty so much as the fact that forward guidance is given. However, columns (2) and (3) provide no support for these nonlinearities—only the linear terms matter over this sample. During this period, forward guidance easings reduced uncertainty and forward guidance tightenings increased uncertainty, which is intuitive when one considers the presence of the zero lower bound on the funds rate and how this would have interacted with uncertainty about the future federal funds rate.

As in the preceding section, I consider the persistence of these uncertainty effects in Figure 7. Since the nonlinear terms in Table 9 were not statistically significant, the regressions in Figure 7 consider only the linear terms, as in previous figures. After the first day, there is little evidence that the effect of forward guidance dies out over time, although the standard errors grow so that the effect is not statistically significant after about 2 days. For LSAPs, interestingly, there is no effect on impact but the effect grows substantially over the next few days and becomes statistically

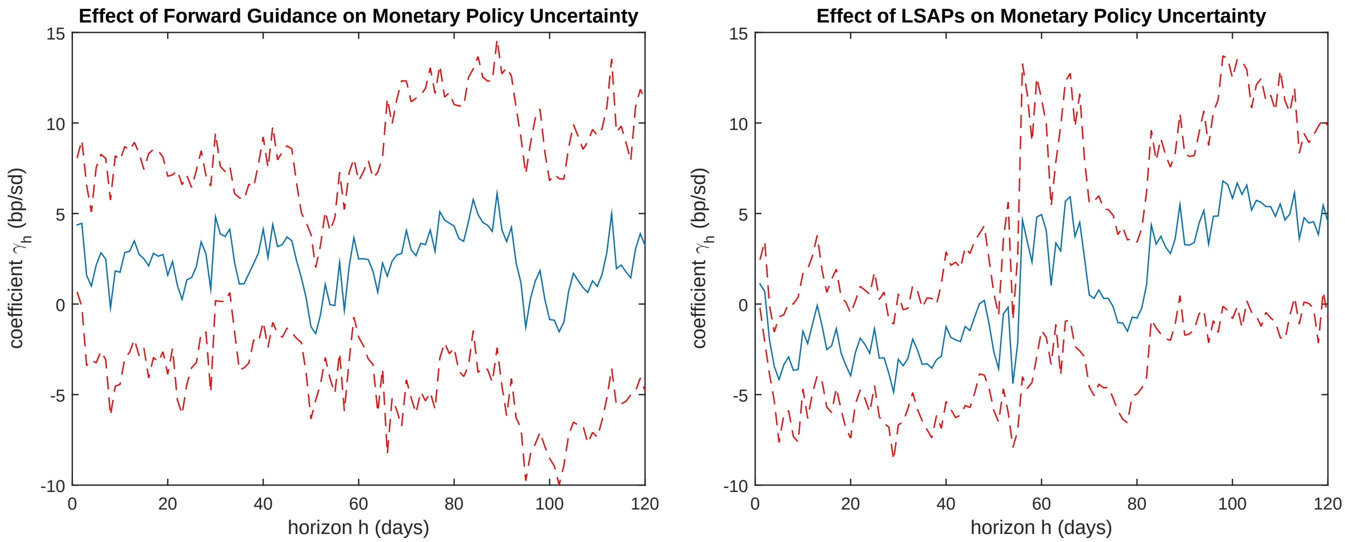


Figure 7. Estimated effects of forward guidance and LSAPs on monetary policy uncertainty, measured as the distance (in bp) between the 80^{th} and 20^{th} percentiles of the PDF for the federal funds rate 5 quarters ahead, implied by Eurodollar options. See notes to Figure 3 and text for details.

significant. A one-standard-deviation increase in LSAPs was typically followed by a 2–5bp decline in monetary policy uncertainty for most of the next 50 days, often statistically significantly so. Thus, the FOMC's asset purchases seem to have spoken more loudly than their words as far as convincing markets about their commitment to a future path for the federal funds rate. This finding seems in line with the discussion in Woodford (2012) and Bauer and Rudebusch (2014), that one channel through which LSAPs affected financial markets was by signalling the FOMC's commitment to keep the federal funds rate low for an extended period. Thus, even though my results in Tables 2 and 3 reject the hypothesis that LSAPs work *entirely* through the signalling channel, my results here do suggest that LSAPs have significant signalling effects.

In Figure 8, I plot similar results for the Bank of America/Merrill Lynch MOVE index of long-term bond yield uncertainty. The MOVE index is a composite of implied volatility on U.S. Treasury bonds with 2, 5, 10, and 30 years to maturity, measured using options on these securities, with most of the weight on the 5- and 10-year maturities. Overall, the results in Figure 8 look very similar to those in Figure 7 for shorter-term interest rate uncertainty: An increase in forward guidance raises longer-term bond yield uncertainty by a small amount, but the effect is not statistically significant and declines to zero after a few days. An increase in LSAPs, on the other hand, has essentially no effect on longer-term bond yield uncertainty on impact, but then leads to statistically significant declines in that uncertainty by about 4bp over the next few days, and this effect persists for about 45 days.

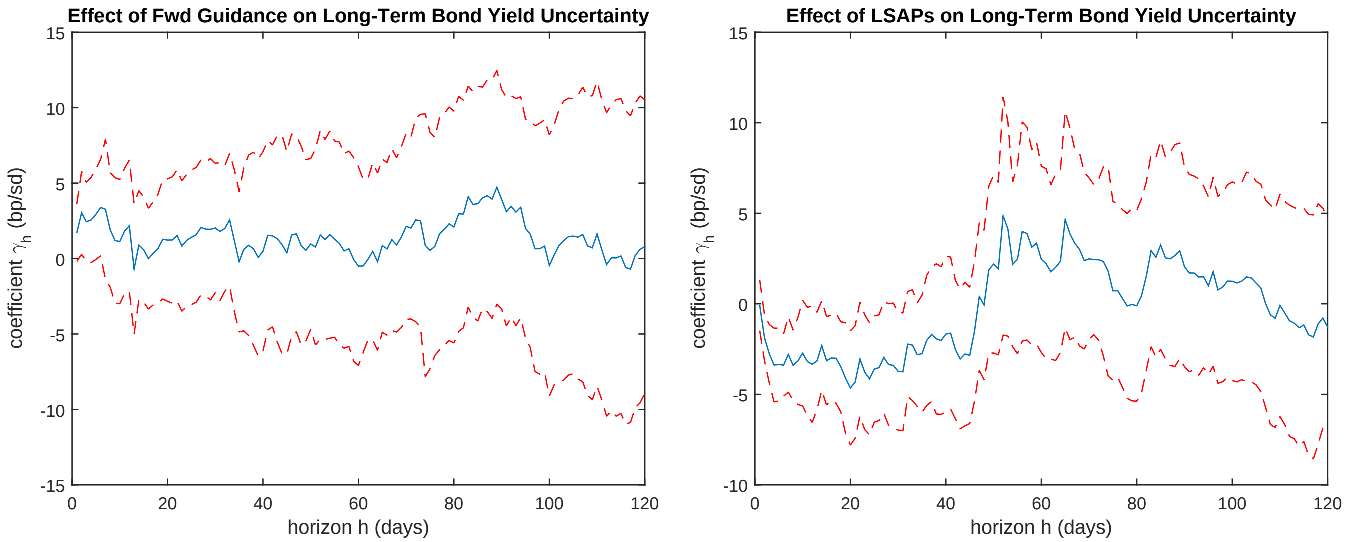


Figure 8. Estimated effects of forward guidance and LSAPs on long-term bond yield uncertainty, as measured by the Bank of America/Merrill Lynch MOVE index of implied volatility (in bp/year) from options on Treasury securities. See notes to Figure 3 and text for details.

Far from increasing longer-term bond yield uncertainty, an increase in LSAPs by the FOMC seems to have had a stabilizing effect on longer-term bond yields. This would be the case, for example, if the FOMC's LSAP operations were conducted in such a way as to "push back" against movements in long-term interest rates.

Finally, I investigate the effects of forward guidance and LSAPs on stock market uncertainty, as measured by the VIX, but find no statistically significant effects at any horizon (results not reported).

7. Conclusions

In this paper, I extend the methods of Gürkaynak, Sack, and Swanson (2005) to separately identify the forward guidance and large-scale asset purchase component of every FOMC announcement from January 2009 to October 2015, the zero lower bound period in the U.S. I show that this identification is robust and that my estimated forward guidance and LSAP announcements correspond to identifiable characteristics of notable FOMC statements.

I separately estimate the effects of forward guidance and LSAPs on a variety of assets, including Treasuries, stocks, exchange rates, corporate bonds, and interest rate uncertainty as measured by options. Both forward guidance and LSAPs had substantial and highly statistically significant effects on medium-term Treasury yields, stock prices, and exchange rates, with magnitudes comparable to the effects of changes in the federal funds rate before the zero lower bound (comparing magnitudes across instruments in terms of their asset price effects per standard deviation change in each policy). Thus, I find that both of these unconventional monetary policies "worked", at least on impact.

Forward guidance was more effective than LSAPs at moving shorter-term Treasury yields, while LSAPs were more effective than forward guidance and the federal funds rate at moving longer-term Treasury yields, corporate bonds, and interest rate uncertainty. To the extent that monetary policy affects the real economy through changes in private-sector interest rates like the corporate bond rate, this suggests that LSAPs were more effective than forward guidance at stimulating the real economy. LSAPs were also more effective at reducing interest rate uncertainty, which may also stimulate the real economy (e.g., Bloom, 2009).

Turning to persistence, I estimate that the effects of changes in the federal funds rate were completely persistent in the pre-ZLB period, lasting for several months with no sign of dying out. The effects of LSAPs also seem to have been completely persistent, with the exception of the very influential March 2009 "QE1" announcement. After that particular announcement, long-term bond yields fell sharply but then rebounded strongly over the next two months as financial markets turned around. Given that financial markets were functioning very poorly in March 2009, and the QE1 announcement was so large, the financial market responses to that announcement may not have been representative of LSAPs more generally.

Surprisingly, I find that the effects of forward guidance were not very persistent, with a half-life of 1–4 months, or even less. I find a similar lack of persistence before the ZLB period as during the ZLB. The reasons for this lack of persistence are not clear, since forward guidance is supposed to move financial market expectations of the future path of short-term interest rates rather than a risk premium. Nevertheless, the "slow-moving capital" view of Duffie (2010) and Fleckenstein et al. (2014) could be relevant even for forward guidance if movements in risk premia are related to changes in expectations: for example, in the "unspanned factor models" of Duffee (2011) and Joslin, Priebsch, and Singleton (2014), changes in an unspanned risk factor cause equal and offsetting movements in expectations and risk premia, which could lead to the low persistence I find above if the risk premia in those models move slowly rather than instantaneously.

Overall, I find there is relatively little reason for the Federal Reserve to raise its inflation target to avoid hitting the zero lower bound in the future, because the Fed has other monetary policy tools available. Both forward guidance and LSAPs have important effects on impact, and the effects of LSAPs seem to be persistent.

Going forward, there are many important issues that call out for further exploration. First, estimating the effects of forward guidance and LSAPs on macroeconomic variables such as the unemployment rate should be a top priority for future research—after all, the FOMC's stated goal in pursuing these unconventional policies was to boost the macroeconomy. Measuring the response of macroeconomic rather than financial variables to monetary policy announcements is difficult, however, because of the lower frequency and longer response lags of macroeconomic variables to those announcements. Second, answering why the effects of forward guidance do not seem to be persistent should be a high priority. In particular, is there something the FOMC could do that would increase the persistence of these effects? Third, studying the effects of unconventional monetary policy in other economies should be very fruitful, especially since the zero lower bound period in the U.S. has ended. The methods of the present paper should be very helpful for studying the effects of unconventional monetary policies in these other economies as well as the U.S.

Appendix: Details of Identifying Restrictions

As discussed in Section 2, the factor model (1) is not uniquely identified by the data. Here I provide the details of the full-sample and split-sample identifying restrictions in Section 2.

Full-Sample Identification

Given the $T \times n$ matrix X of n asset price responses to the T FOMC announcements in my sample, I first demean and scale each column of X to have zero mean and unit variance. I then extract the first three principal components of the standardized matrix to estimate the three latent factors that explain a maximal fraction of the variance of the (standardized) data. Let F denote the $T \times 3$ matrix of these first three principal components, and Λ the $3 \times n$ matrix of loadings of the data X on F (cf. eq. (1)).

It's straightforward to show that a 3×3 orthogonal matrix U is uniquely determined by three parameters. Thus, we require three identifying restrictions to uniquely identify the rotation U that maps the principal components F into three factors $F^* \equiv FU$ that have a structural interpretation as 1) the surprise change in the federal funds rate target, 2) the surprise change in forward guidance, and 3) the surprise change in LSAPs.

As discussed in Section 2, my first two identifying assumptions are that LSAPs and forward guidance have no effect on the current federal funds rate. These two zero restrictions can be written as

$$U'\Lambda_1 = \begin{bmatrix} \cdot \\ 0 \\ 0 \end{bmatrix}, \tag{A1}$$

where Λ_1 denotes the first column of Λ, the loadings of the current-month federal funds rate on the three factors F. Letting U_i denote the ith column of U, these restrictions correspond to $\Lambda_1' U_2 = 0$ and $\Lambda_1' U_3 = 0$. Effectively, these two restrictions imply that only the first factor has any systematic effect on the federal funds rate.

My third identifying restriction is that the variance of the LSAP factor is as small as possible over the sample from 1991 to 2008. The LSAP factor is given by FU_3, so this restriction amounts to minimizing $U_3'(F^{\text{pre}})'F^{\text{pre}}U_3$, where F^{pre} denotes the 158×3 matrix of values of F from 1990–2008. This is a constraint on U_3 that does not directly affect U_1 or U_2, except via the orthogonality conditions between the columns of U.

Computationally, I implement these three restrictions as follows. First, I implement restrictions one and three above in one step as a quadratic minimization problem subject to a linear constraint: I temporarily ignore the unit length requirement on U_3 and normalize the third element of U_3 to unity;[30] I then minimize

$$[\,u_{13} \quad u_{23} \quad 1\,]\,(F^{\text{pre}})'F^{\text{pre}} \begin{bmatrix} u_{13} \\ u_{23} \\ 1 \end{bmatrix}, \tag{A2}$$

subject to $\Lambda_1' \,[\,u_{13} \;\; u_{23} \;\; 1\,]' = 0$, where this last constraint ensures the minimization respects the first identifying assumption. After computing the minimizing vector $[\,u_{13} \;\; u_{23} \;\; 1\,]'$, I rescale it to have unit length and call the resulting vector U_3.

To implement the second identifying restriction, I again temporarily ignore the unit length requirement on U_2 and normalize its third element to unity. I then solve the equation

$$\begin{bmatrix} \Lambda_1' \\ U_3' \end{bmatrix} \begin{bmatrix} u_{12} \\ u_{22} \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{A3}$$

for u_{12} and u_{22}, which ensures that $[\,u_{12} \;\; u_{22} \;\; 1\,]'$ satisfies the identifying restriction and is orthogonal to U_3. I then rescale the vector $[\,u_{12} \;\; u_{22} \;\; 1\,]'$ to have unit length and call the result U_2.

[30] Note that there is nothing special about the third element here or in any of the normalizations below—if the third element happens to be close to zero, then the first or second element can be normalized to unity instead.

Finally, I compute U_1 by an analogous procedure, normalizing the third element of U_1 to unity, solving the equation

$$\begin{bmatrix} U_2' \\ U_3' \end{bmatrix} \begin{bmatrix} u_{11} \\ u_{12} \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \tag{A4}$$

and renormalizing $[\,u_{11} \;\; u_{12} \;\; 1\,]'$ to have unit length. This ensures U_1 is orthogonal to U_2 and U_3.

This uniquely identifies U and F^* up to a sign normalization for each column. I normalize the sign of the first column of F^* to have a positive effect on the current federal funds rate, the second column to have a positive effect on the four-quarter-ahead Eurodollar future contract ED4, and the third column to have a negative effect on the 10-year Treasury yield.

Split-Sample Identification

The identifying restrictions for the split-sample identification are simpler and are described in Section 2. For the pre-ZLB sample, the methods are exactly the same as in Gürkaynak, Sack, and Swanson (2005)—see the Appendix to that paper for details.

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