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Research article

Yield curve rotations, monetary shocks, and Greenspan's Conundrum

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Abstract: Between June 2004 and December 2005 the Federal Reserve conducted a relatively aggressive contractionary policy that saw a steady increase in the effective federal funds rate of over 300 basis points. Yet the 10-year treasury rate fluctuated little over 60 basis points and ultimately declined slightly over the period. This was dubbed *Greenspan's Conundrum* after a famous speech by the former chairperson in February 2005. This highlights the importance of understanding the efficacy with which the central bank may impact term premia through changes in the short-term rate. I find hikes in interest rates lead to reductions in rate spreads at first, before turning positive roughly about a year post shock. These findings are statistically significant for a variety of interest rate spreads over two different samples. Following a contractionary monetary policy action, the yield curve experiences a clockwise tilt at first and an eventual counterclockwise rotation after some delay. A counterfactual analysis suggests that augmenting the federal funds rate hike of 2004 with a similar action to the Fed's 2011 Operation Twist—but conducive to contraction rather than expansion—could have mitigated Greenspan's Conundrum of 2004–2005.

Keywords: Structural Vector Autoregressions (SVARs); sign restrictions; yield curve; Greenspan's Conundrum; Operation Twist; unexpected monetary policy shocks
JEL codes: E44, E50

1. Introduction

A large literature suggests a strong co-movement between short- and long-term rates. However, there have been episodes in the U.S. where sustained short rate hikes have not come hand-in-hand with comparable increases in long rates. One such episode occurred in 2004–2005 and was famously dubbed *Greenspan's Conundrum*. More recently, the Federal Reserve began its policy normalization efforts with an initial increase in the federal funds rate in December 2015 following over half a decade of this key short rate being stuck at its zero lower bound (ZLB). The top panel of Figure 1 shows various daily short-term rates over this period. The bottom panel shows treasury rates.

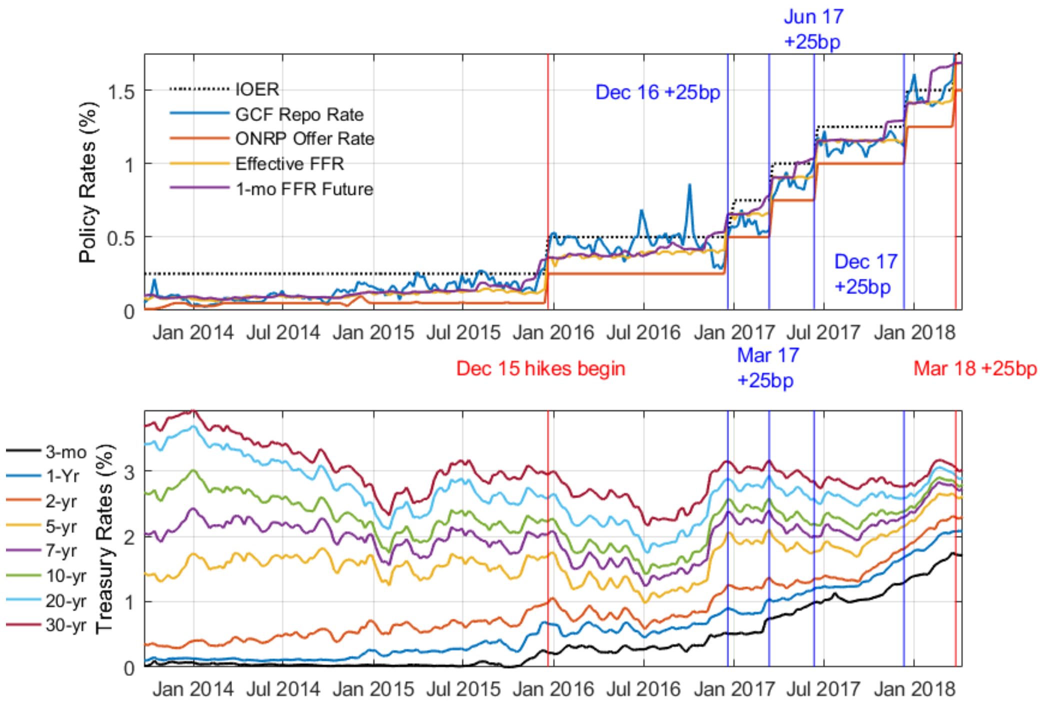


Figure 1. Daily interest rates during the policy normalization period.

Between December 2015 and April 2018, the Federal Reserve hiked the federal funds rate six times and, as the graph shows, short-term rates (from the three-month treasury bill to the two-year note) increased by an average of 100 basis points, while the long-term rate (the 10-year treasury bond) remained essentially flat during this period.

As a preview of results, the main findings suggest there is a dynamic impact of monetary policy shocks on the yield curve. I find an unexpected contractionary monetary policy action that increases the short-term rate leads to reductions in interest rate spreads at first, before turning positive roughly about a year after the shock. These findings are statistically significant for a variety of interest rate spreads over two different samples. The dynamic yield curve response to a term premium (TP) shock is inverted from the response to monetary policy where, at first, a counterclockwise tilt occurs on impact with a subsequent clockwise tilt.

A counterfactual analysis suggests that augmenting the federal funds rate hikes of 2004 and 2005 with similar actions undertaken during Operation Twist of 2011–2012—but conducive to contraction rather than expansion—could have mitigated Greenspan's Conundrum.

The rest of this paper is organized as follows. Section 2 outlines a brief literature review. Section 3 describes the sign restriction methodology I employ. Section 4 describes the identification strategy and the data. Section 5 collates results from the main model. Section 6 discusses robustness of the responses to monetary policy shocks. Section 7 describes a counterfactual analysis for the Greenspan's Conundrum period. Section 8 proposes an alternative sign restriction identification scheme and discusses the impact of shocks in term premia. Section 9 concludes.

2. Background on interest rate pass-through

Despite vigorous theoretical claims, evidence of substantial pass-through between short-term policy rates and longer-term rates has been mixed in a literature that considered various interest rates, sample periods, and monetary policy regimes [see, for example, Campbell and Shiller (1991), Bekaert et al. (1997), Cochrane and Piazzesi (2005) and Sarno et al. (2007).] This literature predates the Financial Crisis of 2007 and its aftermath. Thus, one may conclude this mixed evidence for pass-through might only bind to periods of relative normalcy and may not necessarily apply to periods of financial turmoil.*

In principle, the Federal Reserve's large-scale asset purchases during the zero-interest-rate-policy (ZIRP) period could have an impact on selected interest rates, which in turn could influence other rates through expectations and substitution effects. For example, Gagnon et al. (2010) show the Federal Reserve's large-scale asset purchases (LSAPs) led to reductions in interest rates of various securities, including those that were not part of the purchase program. They conclude these effects are indicative of lower risk premia. Conversely, Krishnamurthy and Vissing-Jorgensen (2011) advance the notion that focusing on treasury rates as a policy target is misplaced given that large-scale purchases only affected yields of those assets that were purchased. Thus, since 2008, evidence of policy transmission passing through to interest rates of other securities is, at best, mixed.

Whether during periods of financial turmoil or normalcy, the effect of monetary policy shocks on the term structure of interest rates is far from settled. For example, Cook and Hahn (1989) establish a positive empirical relationship between the short-term target rate and longer-term rates and interpret their findings as supportive of the rational expectations theory of the term structure. Romer and Romer (2000) disagree. They posit an increase in the short-term rate should lower inflation, thereby reducing the level of long-term interest rates. Ellingsen and Soderstrom (2001) distinguish between endogenous policy actions in response to new private knowledge about the economy from exogenous shifts in policy preferences. Their model extends the standard aggregate supply / aggregate demand (AS-AD) model of Svensson (1999) with a dynamic term structure equation.

In this paper, I eschew a mechanism for the effects of aggregate economic activity shocks on the yield curve. While it is likely these types of shocks have important effects on term spreads, I focus exclusively on an investigation of monetary policy shocks.

3. Modeling framework

Most of my analysis stems from a structural VAR where shocks are identified with the help of sign restrictions that are motivated by theoretical and empirical conclusions derived in the following sections while leaving the question of interest unrestricted. This section outlines the methodology employed for estimating the VAR with sign restrictions.

I begin with an $n \times l$ vector of variables Z_t that obeys the following:

$$Z_t = A(L)e_t \tag{1}$$

which contains an $n \times n$ matrix polynomial in the lag operator L where the A_i coefficients and the $n \times n$

*Keating et al. (2019) highlight the importance of models of monetary shocks that do not operate in a vacuum but remain relevant for periods of financial crises and normal conditions.

positive definite covariance matrix of the innovations Σ_e in this linear system are obtained from a p-th order reduced-form VAR. I assume a linear dynamic structural model as follows:

$$Z_t = B(L)\epsilon_t \tag{2}$$

with an $n \times n$ matrix $B(L) = (I - B_0 - B_1 L - ... - B_q L^q)^{-1}$ in the lag operator L —and with a $n \times n$ non-singular matrix B_0 —and a diagonal covariance matrix of structural shocks $E(\epsilon_t \epsilon_t') = I_n$. Finding a relationship between the innovation errors and the contemporaneously uncorrelated structural shocks to the economy requires restrictions of B_0 in

$$\epsilon_t = B_0^{-1} e_t \tag{3}$$

Alternatively, let $e_t = P\eta_t$ where e_t is the vector of reduced-form VAR innovations, η contains—by construction—mutually uncorrelated shocks with unit variance, and P is the lower-triangular Cholesky decomposition of Σ_e.[†] For some purposes, identification involving exclusion restrictions via Cholesky factorization may be useful, particularly at monthly frequencies. However, I want to rely on restrictions that are of a qualitative—rather than exclusionary—nature.[‡] Without exclusion restrictions, there is no guarantee the η_t shocks correspond to economically meaningful structural (ϵ_t) shocks. Thus, I search for candidate solutions for the unknown structural ϵ_t shocks by generating a large set of combinations of the η_t shocks

$$\epsilon_t^* = Q'\eta_t \tag{4}$$

where ϵ_t^* is a candidate solution as a function of contemporaneously uncorrelated η_t shocks rotated by a square orthogonal matrix Q' where $Q'Q = QQ' = I_n$. Thus, it follows that

$$e_t = PQQ'\eta_t = PQ\epsilon_t^* \tag{5}$$

Comparison of (3) and (5) suggests that only candidates that generate an impact matrix PQ that complies with the imposed sign restrictions on B_0^{-1} are admissible. Given that a Cholesky factorization (P) is unique for a given order of the n variables in the VAR, knowledge of Q allows the recovery of all implied structural responses from estimation of the reduced-form VAR.[§] However, unlike P, the orthogonal matrix Q is not necessarily unique for a single ordering of the variables in the VAR. Therefore, the construction of sign-identified impulse response functions requires drawing large numbers of candidate matrices (Q^*) where orthogonalization is accomplished via Givens rotation matrices or Householder transforms—both having been utilized in the literature. I opt for a Householder transform (which is an application of a QR decomposition) following ACR, which seems closest to the endeavor of eschewing overly informative prior information.

This approach requires imposing a prior distribution on the Q matrix (known as a Haar prior). Generating draws from either the Givens or Householder transform is equivalent to drawing from this Haar prior. As Kilian and Lutkepohl (2017) point out, however, this is an informative prior not based on economics. And information from the data cannot dominate this prior, even asymptotically, because the likelihood is independent of Q. For example, Baumeister and Hamilton (2015) specify the prior

[†] P could also be the unique differentiable and symmetric and positive-definite $\Sigma_e^{0.5}$ matrix.

[‡] With exclusion restrictions via Cholesky, ϵ_t and η_t are congruent.

[§] See Inoue and Kilian (2013).

directly on the elements of B_0. Kilian and Lutkepohl (2017) raise this as problematic because any prior on B_0 implies an informative prior on B_0^{-1} which has an ensuing "black box problem"—the prior is not made explicit and may not relate to any prior information on the structure of the economy. Baumeister and Hamilton (2015) advocate for the use of explicitly informative priors for elements in B_0 for sign identification.

Arias et al. (2016) (henceforth, ACR) show convincingly that if the prior is not agnostic, then the prior affects identification. Thus, when a researcher combines prior knowledge from theory to substantiate her sign restrictions and prior information on the parameters of B_0^{-1}, then there is no way to distinguish which information drives the results. Thus, I estimate a sign-restricted VAR by making use of the conditionally agnostic priors of ACR. To follow their nomenclature—established in Rubio-Ramirez et al. (2010) —let $A \equiv [c, A_1, ..., A_p]$ describe the set of reduced-form autoregressive matrices; $B_+ \equiv [c, B_1, ..., B_p]$ denote the equivalent matrices from the structural model. It is observationally equivalent to represent a VAR in terms of: the structural parameters $B_0^{-1}B_+$; the collection of reduced-form parameters with a rotation matrix (A, Σ_e, Q); or a structural parametrization (denoted by Θ).[¶]

The goal is for identification to emerge exclusively from the sign restrictions and not from the choice of priors. ACR show a way to ensure this by defining a conditionally agnostic prior (denoted by Π) as one that is equal across observationally equivalent parameters. This follows from Arias et al. (2018), who show that employing the same conjugate prior across observationally equivalent parametrizations is enough to guarantee agnosticism in the posterior as well as the likelihood.

An agnostic prior over parametrization Θ means that $\Pi(\Theta Q) = \Pi(\Theta)$ for every orthogonal rotation matrix $Q \in O(n)$. They show that a prior over the structural impulse responses is flat if and only if the equivalent prior over reduced-form representation (A, Σ_e, Q) equals $2^{(-n(n+1))/2}\,|det(\Sigma_e)|^{(np/2)-1}$ and it implies a flat prior for $Q \in O(n)$ and a Gaussian-inverse Wishart posterior for the reduced-form covariance matrix conditioned on the data as follows:

$$P\left(\Sigma_e|Z\right) \propto |\Sigma_e|^{\frac{-\nu+n+1}{2}} \exp\left\{-\frac{1}{2}tr\left(S\,\Sigma_e^{-1}\right)\right\} \tag{6}$$

It also implies a Gaussian marginal posterior for the reduced-form VAR parameters conditioned on the covariance matrix and the data with mean Â and variance $\Sigma_e \otimes (X'X)^{-1}$ as follows:

$$P\left(A|Z, \Sigma_e\right) \propto |\Sigma_e|^{\frac{-np+1}{2}} \exp\left\{-\frac{1}{2}vec\left(A - \hat{A}\right)'\left(\Sigma_e^{-1} \otimes X'X\right)vec\left(A - \hat{A}\right)\right\} \tag{7}$$

where $Z = Z_t$, $X = [Z_{t-1}, ...Z_{t-p}]'$ $\forall t = 1, ...T$ and $\hat{A} = (X'X)^{-1}X'Z$ along with $S = (Z - X\hat{A})'(Z - X\hat{A})$ with $\nu = T + n(2n + np + 1) - (np + 1) - n - 1$

Imposing these agnostic flat priors for the orthogonal reduced-form parametrization, I employ algorithm 2 in ACR.

[¶]ACR specify that Θ may refer to three different parametrizations: A parametrization of the structural parameters of the VAR; a parametrization of the structural impulse response functions; or the orthogonal reduced-form parametrization.

4. Identification strategy

Every specification considered in this paper involves a four-variable VAR with the following ordering: $Z_t = [x_t, \pi_t, i_t^{n_1}, i_t^{n_2} - i_t^{n_1}]'$ where x_t is real output, π_t is inflation, $i_t^{n_1}$ is the short-term interest rate, and $i_t^{n_2} - i_t^{n_1}$ (where $n_2 > n_1$) denotes the term spread between a longer-term interest rate and a shorter-term rate. I employ the Federal Reserve Bank of Chicago National Activity Index (CFNAI)—an index generated by the first principal component extracted from 85 separate economic series—as the measure of real aggregate economic activity.[‖] Inflation is constructed from log differences of the personal consumption expenditure (PCE) index. I consider various interest rates that include the federal funds rate; the three- and six-month treasury bill rates: secondary markets; and the one-, two-, three-, five-, seven- and 10-year constant maturity treasury rates.[**]

The period of investigation begins January of 1981. I follow Bernanke and Blinder (1992), Christiano et al. (1999) and many others by assuming that innovations in the federal funds rate represent monetary policy shocks. However, this assumption is more tenuous in the aftermath of the Financial Crisis and Great Recession in the U.S. Thus, I consider two samples. The first one ends in December 2008 as the federal funds rate reached its zero-lower-bound. In the second sample, I replace it with the shadow federal funds rate by Wu and Xia (2016) and extend analysis to April 2018 in order to include the ZIRP period and the subsequent beginning of the monetary normalization effort of the Federal Reserve.

Swanson and Williams (2014), highlight that the one- and two-year treasury rates remained substantially above zero during much of the post-2008 zero lower bound period. Thus, I also considered the one- and two-year treasuries as the short rate for the longer sample ending in 2018. Results were qualitatively similar to those where the shadow rate is used as the short rate and are available upon request.

The underlying structural shocks I am interested in are monetary policy (MP) shocks, and shocks to the term premium (TP). I remain agnostic as to the effects of MP shocks on $i_t^{n_2}$ - $i_t^{n_1}$ and we impose no restrictions on the responses of the remaining variables to TP shocks. I consider disturbances consistent with monetary policy tightening—through exogenous increases in the short-term rate—by imposing restrictions that monetary policy shocks that do not lead to a decrease in the short-term interest rate do not generate an increase in inflation or output on impact. Therefore, this may be interpreted as a contraction or tightening of monetary policy.

This examination focuses mainly on spreads between long-term and short-term interest rates in which the response of the interest rate spread to shocks in economic activity or monetary policy are not constrained in any way. These restrictions are summarized in Table 1 in what I designate the main specification.

If a contractionary monetary policy shock were anticipated by the market, we might expect both interest rates and interest rate spreads to respond in the same direction, leading to a positive response of the term spread to an increase in the short-term rate. Conversely, if an increase in the short-term rate led to a reduction in the term spread, this would be consistent with a (clockwise) rotation of the

[‖]Another common measure of real economic activity at monthly frequencies is industrial production. However, it is subject to data revisions and provides low coverage—representing about 20 percent of the aggregate economy. Benefits of the CFNAI are its broad coverage, strong contemporaneous correlation to real output, and relatively low sensitivity of the headline index to revisions in the underlying series.

[**]All data is obtained from the Federal Reserve Economic Database (FRED) website of the St. Louis Federal Reserve Bank.

Table 1. Main specification: sign restriction for *MP* shocks.

	MP Shock	***TP*** Shock
Output	≤ 0	?
Inflation	≤ 0	?
Interest Rate	> 0	?
Term Spread	?	> 0

Note: All sign restrictions (-/+) correspond to impact only (horizon=1). ? denotes no restriction.

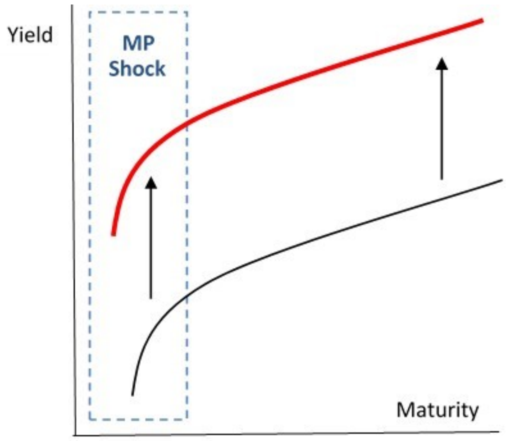
yield curve that could occur if the monetary policy action was unanticipated or caught markets by surprise. We leave all these dynamics to be explained by the data in the main model.

5. Term spread responses to monetary policy shocks

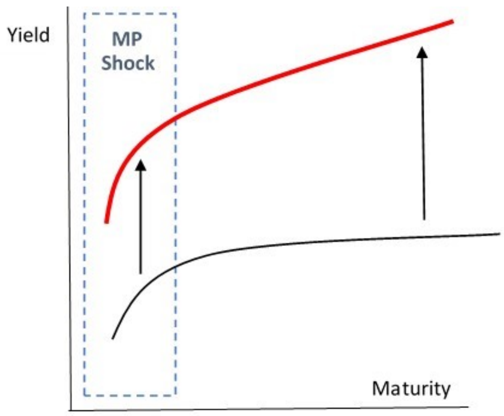
This section shows responses of the corresponding VARs to *MP* shocks. These are contractionary shocks that impose an interest rate hike and restrict output and inflation not to increase on impact. The confidence bounds associated with the 16–84% credible sets—particularly for the interest rate spread responses—are somewhat wider for the longer sample than the sample that ends in 2008. This is, perhaps, a function of a substantially higher degree of uncertainty that characterized much of the post-2008 U.S. economy; see e.g. Baker et al. (2016). Much of the literature agrees on the heightened level of uncertainty that occurs in the U.S. around the time of the Financial Crisis and its aftermath. There are, however, differing views as to its characterization (e.g. economic uncertainty, fiscal uncertainty, policy uncertainty, financial news). There is also some debate as to how protracted this uncertainty period was. Jurado et al. (2015a) and Jurado et al. (2015b) show very high levels of uncertainty during 2007 through 2009, with a drastic amelioration by 2010. By contrast, in Baker et al. (2016), estimates of higher uncertainty, associated with economic policy, are shown to be much more protracted, lasting through 2014.

If a monetary action is fully anticipated, markets for long-term securities might fully price the monetary disturbance, driving up long-term interest rates commensurately with the increases in shorter-term rates. Thus, a fully anticipated monetary action might serve to shift upward the whole yield curve. With such a wholesale shift of the yield curve, the difference between the long rate and the short rate would be roughly the same before and after the shock [this is illustrated in Figure 2(a)], which would yield a zero-response of the term spread in this specification.

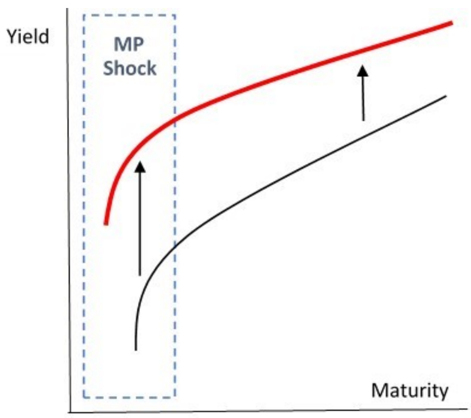
Conversely, if an overreaction of the long-term rate (i.e. it responded with a larger increase) ensued following the increase in the short-term rate, then this would be illustrative of a counterclockwise tilt of the yield curve [see Figure 2(b)]. An event that might be consistent with an intention to tilt the yield curve by policymakers is the September 21, 2011, Federal Open Market Committee announcement of the purchase of $400 billion of long-term treasuries with an equal sale of short-term treasuries. Recalling a similar Fed action in the 1960s, the term *Operation Twist* was resuscitated to characterize this event. Swanson (2011) shows the effect of Operation Twist on longer-term yields was statistically significant but economically small. In a press release, Ben Bernanke, the Fed chairman at the time, specified the $400 billion purchase would be of treasury securities with remaining maturities of six



(a) Zero Term-Spread Response



(b) Positive Term-Spread Response



(c) Negative Term-Spread Response

Figure 2. Static yield curve responses to exogenous contractionary monetary policy shocks.

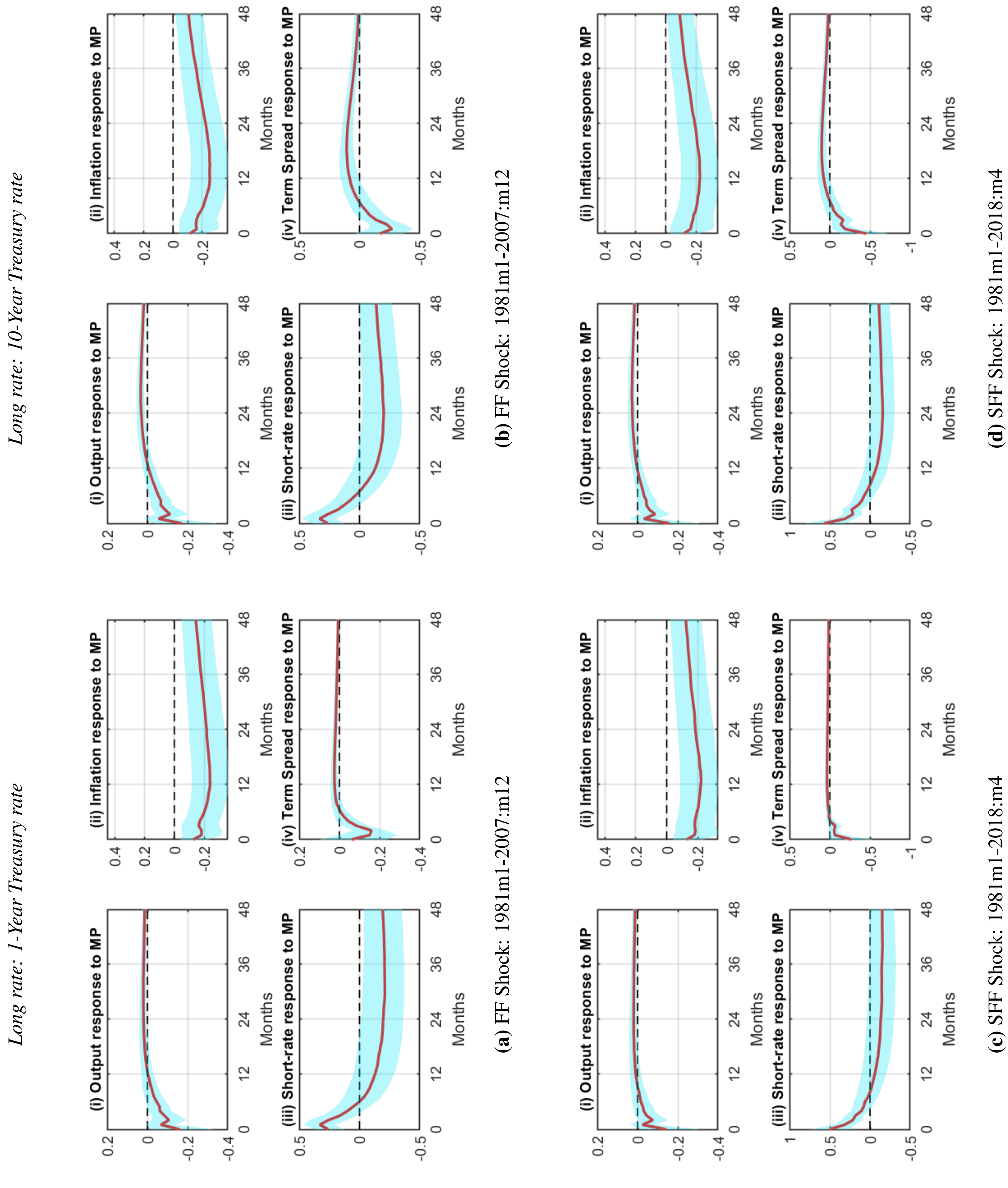


Figure 3. Responses to MP shock: One *s.d.* increase in the short-term rate.

years to 30 years with an equal amount of treasury securities sold with remaining maturities of three years or less.

Figure 2(c) illustrates a clockwise tilting of the yield curve to contractionary monetary policy disturbances. This occurs when long-term rates responses are more muted relative to shorter-term rates in response to *MP* shocks.

Figure 3 shows that, across all specifications, the interest rate spread moves in the opposite direction to the short-term interest rate. At shorter horizons, as the interest rate increases, the interest rate spread decreases significantly within the year. Subsequently, the spread response turns positive and often significantly so. In an investigation dealing with housing prices in the US, Jarocinski and Smets (2008) report a similar response in the federal funds—1-year treasury spread. Similarly, in a paper investigating housing and fiscal imbalances Eickmeier and Hofmann (2013) show responses that oscillate from positive to negative in the 5- 10- and 30-year spreads but offer no discussion of this result. Neither work centers analysis on interest rate spreads and advance no mechanism for the shape of these responses.

Immediately following a contractionary *MP* shock, the interest rate rises and the interest rate spread decreases. These results seem most consistent with the clockwise tilt of the yield curve, a dynamic illustrated by Figure 2(c). This could come about if the long-term interest rate either decreases or rises by less than the increase in the short-term interest rate. The latter explanation denotes an underreaction of long-term rates, which seems more likely given large evidence that interest rates of various maturities tend to co-move in SVAR models. This underreaction could be indicative that such monetary actions are not fully anticipated, thereby surprising markets of long-term securities on impact. Another possibility is that these actions generate an increase in term premia, so that markets of long-term securities either take time to fully price risk premia or they actively hedge with a "wait-and-see" attitude regarding whether the shock is temporary or indicative of a new stance. Ellingsen and Soderstrom (2001) propose theoretically that when the central bank's preferences (its degree of *allergic reaction* to inflation relative to output fluctuations) are unobservable by the public, an unexpected hike in the policy rate tilts the yield curve clockwise. Importantly, instead of imposing this prediction for the yield curve, I set out to empirically estimate its veracity.

Results support the hypothesis of the clockwise tilt of the yield curve to contractionary *MP* shocks. The implication of the theoretical proposition of Ellingsen and Soderstrom (2001), however, is that the tilt of the yield curve is made either statically or monotonically over time.

However, these responses imply a dynamic response regarding the tilt in the yield curve. For example, the interest rate spread response—to a hike in the short-term rate—turns positive and often significant beyond the first-year post shock. This is indicative of the notion that given sufficient time, markets for long-term securities eventually adjust to the monetary policy shock. Results suggest that the mechanism for the yield curve is that it shifts upward in response to a monetary contraction by tilting clockwise on impact and in the short run, with an eventual counterclockwise tilting at longer horizons post shock. This is graphically depicted by Figure 4.

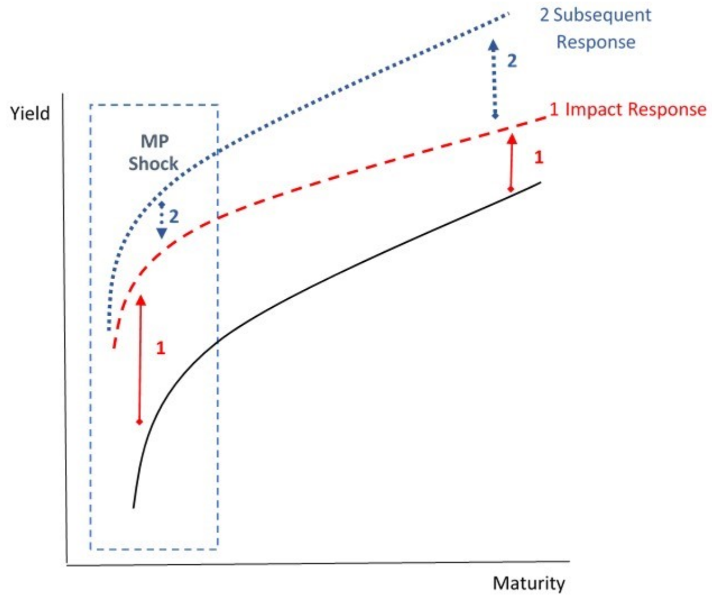


Figure 4. Dynamic yield curve responses to exogenous contractionary monetary policy shocks.

6. Robustness in the response to monetary policy shocks

This section extends my analysis and re-estimates the structural VAR by considering various constructions of the interest rate spread.

Figure 5 shows the combined responses of various term spreads to an exogenous increase in the short-term interest rate. The confidence bounds in these figures correspond to the largest interval (on average over 48 months post shock) associated with a given response across the various specifications of the interest rate spread considered. Thus, while most responses may fall mostly within the broadest confidence region among the set, any given response is under no obligation to fall within at all horizons. I do this in order to collate a relatively large amount of specifications within a few charts. I am interested in the general shape of responses across interest rate spreads. For example, panel (a) shows the response to an exogenous contractionary shock in the federal funds rate ($i_t^{n_1}$) for separate VAR specifications with a different interest rate spread ($i_t^{n_2}$ - $i_t^{n_1}$) where $i_t^{n_2}$ stands for the three- or six-month t-bill, or the one-, two-, three-, five-, seven-, or 10-year treasury note rate. The confidence bound corresponds to the largest 16%-84% credible set region across all these interest rate spreads, which for this sample is the interval for the response of the 10-year treasury rate minus the federal funds rate.

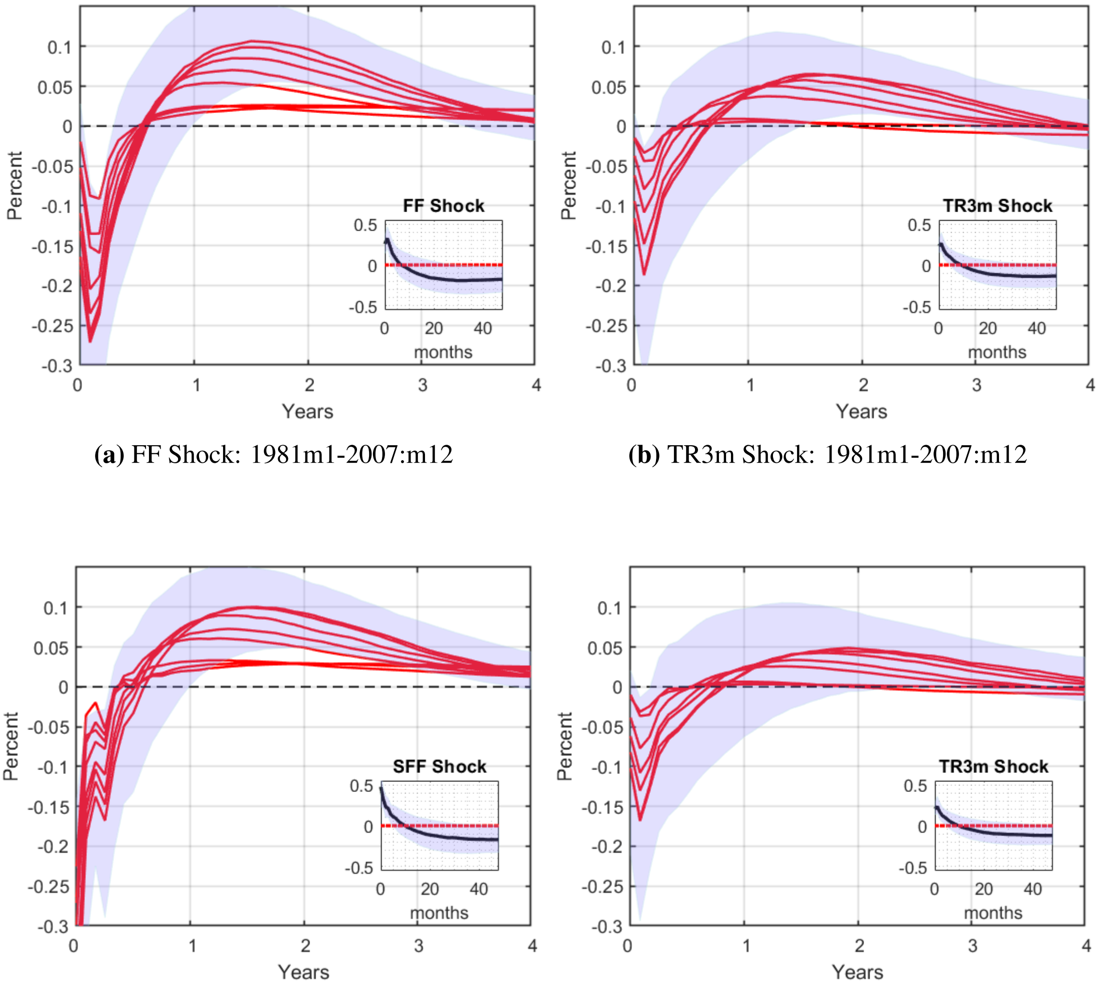
Panel (b) shows results from specifications that replace the federal funds rate with the three-month treasury bill rate as the third variable ($i_t^{n_1}$). There is one fewer impulse response here compared to panel (a) since the shortest-term premium considered in panel (b) is the one-year treasury note rate minus the three-month t-bill [instead of the three-month-t-bill minus the federal funds rate in panel (a)]. And the longest spread considered in panel (b) is the 10-year treasury rate minus the three-month-t-bill [instead of 10-year treasury rate minus the federal funds rate in panel (a)].

Finally, panels (c) and (d) of Figure 5 extend the sample to April 2018. Given the protracted period (roughly half a decade) when the federal funds rate was stuck at zero, I replace it with the shadow federal funds rate by Wu and Xia (2016). All responses show generally the same shape so that the term spread is negative in response to an increase in the interest rate within the year. Many of these positive responses in the short term are statistically significant. Subsequently, most of these responses turn positive and many significantly so beyond the first year post shock.

Overall, the results complement the notion of a positive correlation between short-term and long-term rates, but importantly, they suggest the pass-through is more dynamic than what a simple correlation study would suggest.

Long rates: 10-, 7-, 5-, 3-, 2-, 1-Year (and 3-mo) Treasury rates

Long rates: 10-, 7-, 5-, 3-, 2-, 1-Year Treasury rates



(a) FF Shock: 1981m1-2007:m12

(b) TR3m Shock: 1981m1-2007:m12

(c) SFF Shock: 1981m1-2018:m4

(d) TR3m Shock: 1981m1-2018:m4

Figure 5. Responses to MP shock: One *s.d.* increase in the short-term rate.

Rudebusch et al. (2006) report that a one percentage point increase in the monthly federal funds rate leads to a 30-basis point increase in the 10-year rate. However, between June 2004 and December 2005 this pattern changed. A hike in the federal funds rate—increased from one percent to 4.2 percent during that period—saw a minimal response in the 10-year US treasury rate. This took place amid a robust economic expansion and rising energy prices. Section 7 offers a counterfactual scenario on how the 10-year treasury rate would have responded between 2004 and 2006 had the Federal Reserve combined its contractionary action with similar unconventional measures to those it undertook after 2008.

7. A counterfactual experiment for Greenspan's Conundrum

In a press release on September 21, 2011, Ben Bernanke outlined the intent of the Federal Reserve behind its Operation Twist action:

"This program should put downward pressure on longer-term interest rates and help make broader financial conditions more accommodative."

While this statement cannot be taken as *prima facie* Federal Reserve control of long-term rates, it suggests an orientation toward managing the slope of the yield curve to some degree. The 10-year treasury rate stood at 2.15% in October 2011 and was down to 1.65% by November 2012—all while the federal funds rate remained near zero. This provides stark contrast to the period known as Greenspan's Conundrum where the 10-year treasury rate experienced a modest decline while the federal funds rate increased substantially. This would be consistent with a clockwise rotation of the yield curve absent a shift.

Could the 10-year treasury rate have been more responsive to the contractionary action during the Greenspan conundrum period had the Federal Reserve conducted, at that time, a similar action to Operation Twist but aimed at contraction rather than expansion? I derive the expected path of the 10-year treasury rate from a historical decomposition of a standard VAR that encompasses the full sample. I, then, take the expected path of the 10-year treasury rate for the portion of the sample associated with the Operation Twist event. Given that the period of 2011 and 2012 was consistent with expansionary monetary policy, I invert the expected path of the 10-year treasury rate estimated by the VAR, to evaluate a counterfactual consistent with policy contraction, and use it to replace the actual 10-year treasury rate between 2004 and 2006. Subsequently, I estimate a second VAR for a sample ending in July 2006—the last time the Federal Reserve hiked its federal funds rate before the long expansion following the 2007 Financial Crisis. Figure 6 shows historical decompositions of an MP shock describing the expected paths of PCE inflation, the 10-year treasury rate, and the term spread between the 10-year and the one-year treasuries, and compares them with the counterfactual. Discrepancies between the expected paths and the counterfactuals suggest modest impact on the inflation rate but more meaningful differences in the 10-year treasury rate and the term spread. The implication is that the clockwise rotation of the yield curve would have been less severe, and the 10-year treasury rate would have increased—rather than its actual decline during this contractionary period—had the Federal Reserve exerted a similar influence (in the same magnitude but in the opposite direction) on the long-term rate as was managed during Operation Twist. The counterfactual analysis suggests combining the federal funds rate hike in 2004 and 2005 with an Operation Twist action in reverse—conducive to contraction—could have mitigated, if not resolved, Greenspan's conundrum.

Conventional MP shocks are typically described as targeting, or operating on, short-term rates with subsequent effects on longer-term rates through some described, or assumed, transmission mechanism of monetary policy. However, there may be shocks that operate in an inverted fashion to this by perturbing the long end of the yield curve first, which may not necessarily stem from monetary policy action. Section 8 provides a description of such shocks.

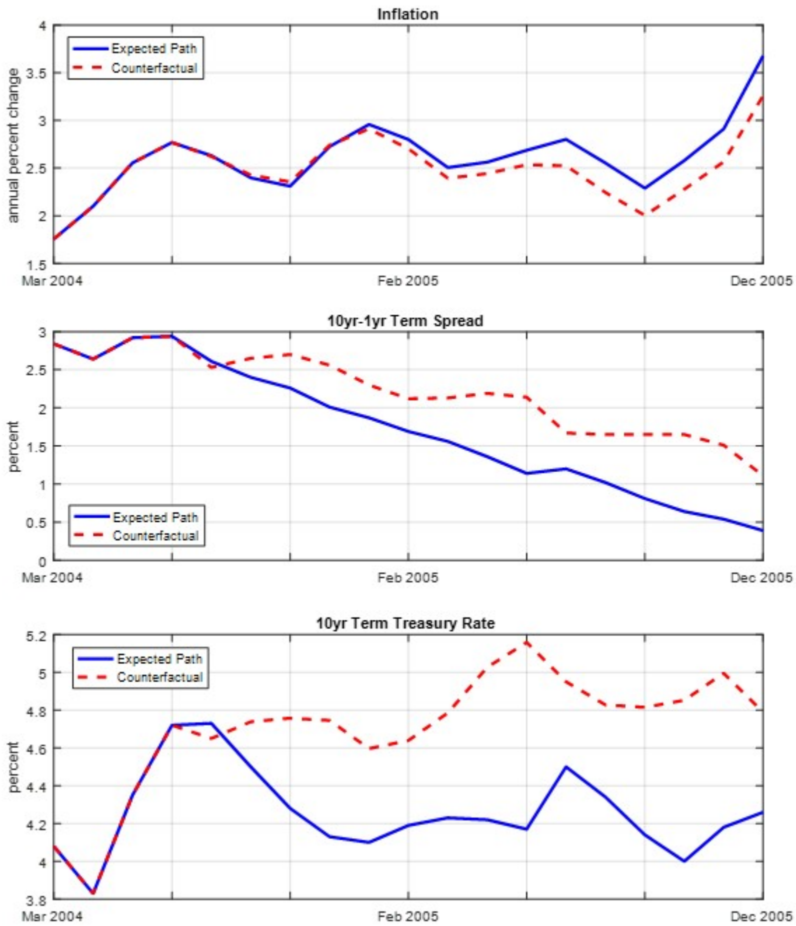


Figure 6. Cumulative effects of an exogenous TP shock during Greenspan Conundrum Period and Counterfactual TP Shocks.
The expected paths (solid lines) are obtained from the historical decomposition of the TP shock (ordered last in the VAR) constructed with the actual 10-year treasury rate 1-year treasury rates for this period. The counterfactuals (dash lines) are constructed by inverting the path of the 10-year treasury during Operation Twist period between 2011 and 2012 and using it to replace the 10-year treasury rate between June 2004 and December 2005—Greenspan Conundrum period.

8. The response of interest rates to shocks in term premia

The previous section shows evidence that contractionary MP shocks tend to be followed by a clockwise tilt of the yield curve, particularly for the period that excludes the aftermath of the Financial Crisis and the ensuing Great Recession. All these results came from specifications that let the data speak for itself on the unrestricted responses of various interest rates and interest rate spreads.

Thus far, the analysis keeps the effect of the fourth variable ($i_t^{n_2}$ - $i_t^{n_1}$) on interest rates ($i_t^{n_1}$) entirely unrestricted. In this section, I constrain the term spread not to respond negatively to a TP shock. As a means of contrasting the effect of the TP shock to the effect of the MP shock, I impose a clockwise tilt of the yield curve following an exogenous reduction in the term spread. Two possible dynamics could be consistent with such a reduction in the slope of the yield curve. A first scenario is that an unexpected increase in the term premium could come hand-in-hand with an *increase* in the short-term rate. This would constitute a clockwise tilt if the left tail of the yield curve shifted up while the right tail shifted down. Another possibility is if an unexpected hike in the term premium was followed by an increase in the short-term rate of a smaller magnitude than the long-term rate. In this case, an increase in the slope of the yield curve would result from the right tail of the yield curve shifting upward farther than the left tail. Figure 7 is an illustration of this latter case. I consider the latter dynamic for two reasons. First, I want to account for the TP shock as operating on the long horizon of the yield curve; this provides contrast with the MP shock, which I consider operates on the short end. Second, a Cholesky specification for every interest rate I consider led to both the interest rate and the term spread to move in the same direction following a disturbance in the fourth variable—which I identify as a TP shock. These results are not shown to save space but are available upon request.

Table 2. Alternative specification: sign restrictions for *TP* shocks.

	Output	Inflation	Interest Rate	Term Spread
TP Shock	?	?	≥ 0	> 0

Note: All the sign restrictions (-/+) correspond to impact only (horizon=1). ? denotes no restriction.

Along with the following restriction

$$\left|\frac{d(i_t^{n_2} - i_t^{n_1})}{d\epsilon_t^{TP}}\right|_h > \left|\frac{d(i_t^{n_1})}{d\epsilon_t^{TP}}\right|_h \quad \text{for } h\text{=1} \tag{8}$$

Table 2 summarizes the restriction structure for the TP shock. I restrict both the interest rate and the spread not to decrease (on impact) following a TP shock. This restriction motivates a wholesale upward shift of the yield curve. Additionally, I impose the interest rate response to be of a lower magnitude than the interest rate spread response to a shock in the term premium. This impact restriction ensures a counterclockwise tilt of the yield curve.

Figures 8 and 9 show rate responses to the TP shock for the short and long samples, respectively. For the short sample, both the response of the federal funds rate and the spread between itself and the

10-year treasury rate increase on impact after a TP shock with the spread response rising more. This is by construction. Both responses remain persistently positive four years post shock. Also, the gap in the responses is much larger immediately after the shock than for longer horizons. This gap closes considerably two years post shock for most rates. This suggests a mechanism for the impact of the TP shock on interest rates. The yield curve shifts up following an increase in the term premium. This wholesale upward shift, however, does not occur monotonically but in two stages. In the first stage, the yield curve shifts up with a counterclockwise tilt on impact and at near horizons. But eventually the left tail of the yield curve begins rotating in a clockwise rotation, ultimately settling on a wholesale shift of the yield curve. This is illustrated in Figure 7 and substantiated by the empirical results of Figure 8. Figure 9 shows the analogous response for the long sample extending beyond 2008. While the confidence bounds are wider (consistent with my other specifications) the closing of the gap in responses remains remarkably similar, suggesting the tilting dynamics of the yield curve generally follow the same mechanism during normal conditions or in a sample that includes Financial Crises.

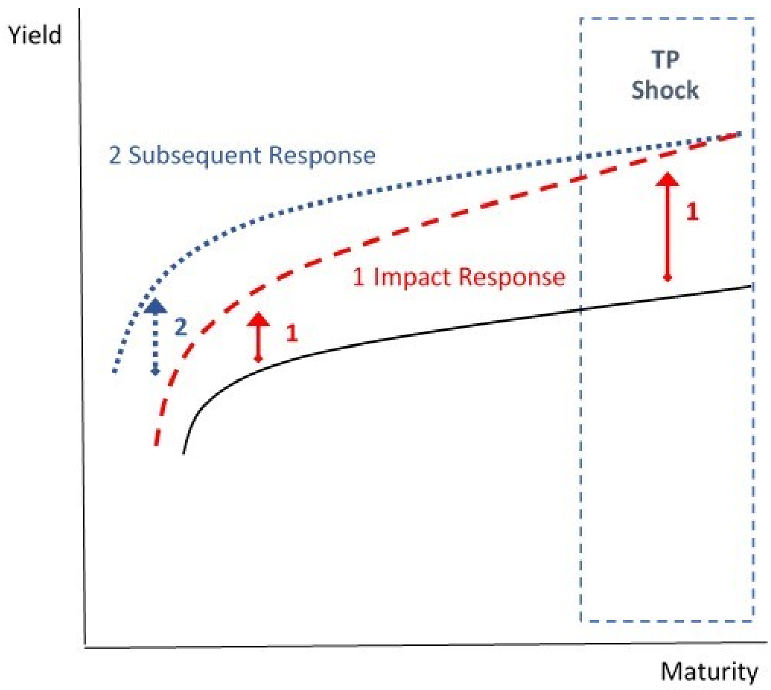


Figure 7. Dynamic yield curve responses to exogenous term premium shocks.

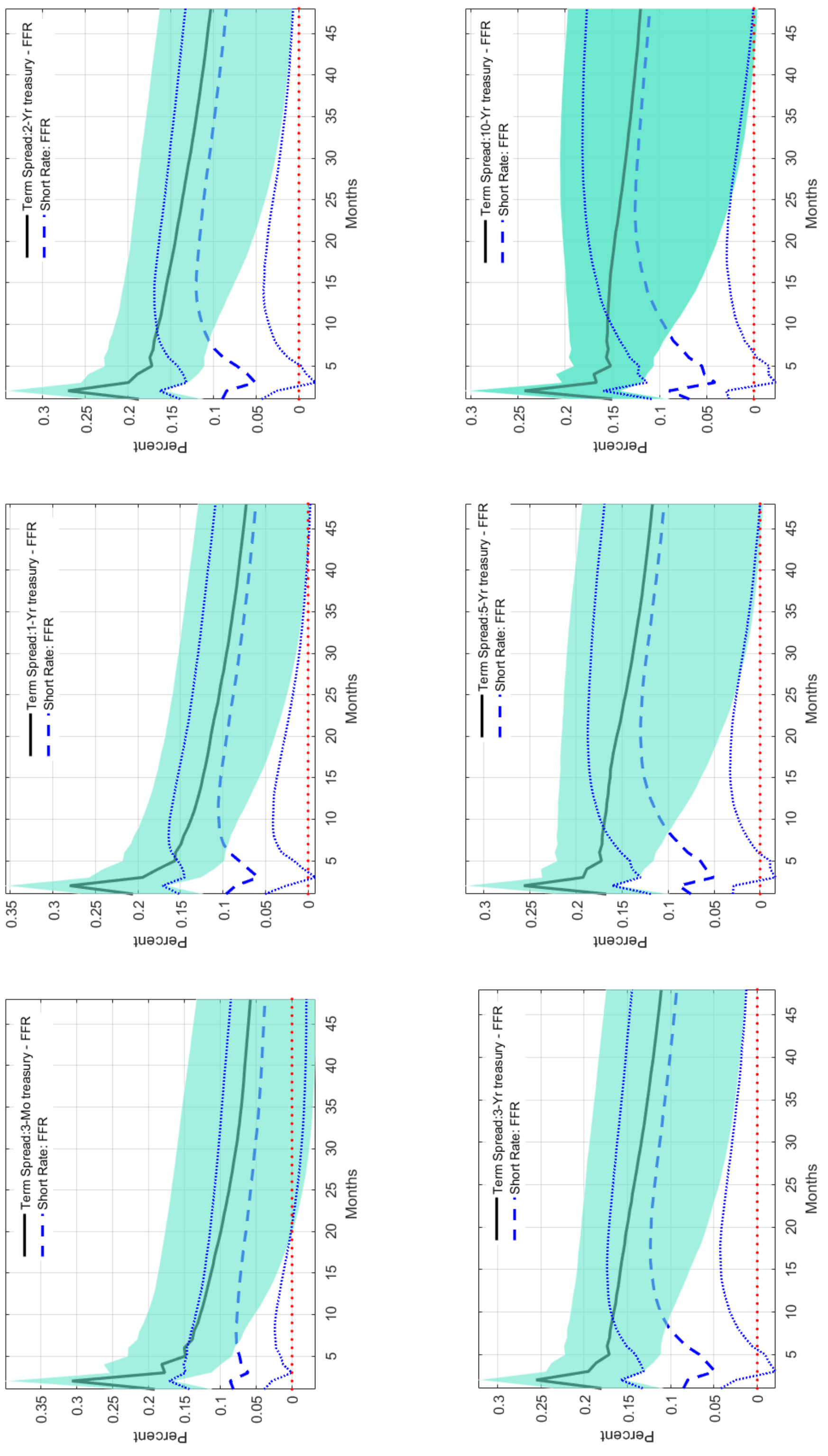


Figure 8. Short-term rate and term-spread responses to TP shock: (One *s.d.* increase in the term spread.) 1981:m1-2007:m12

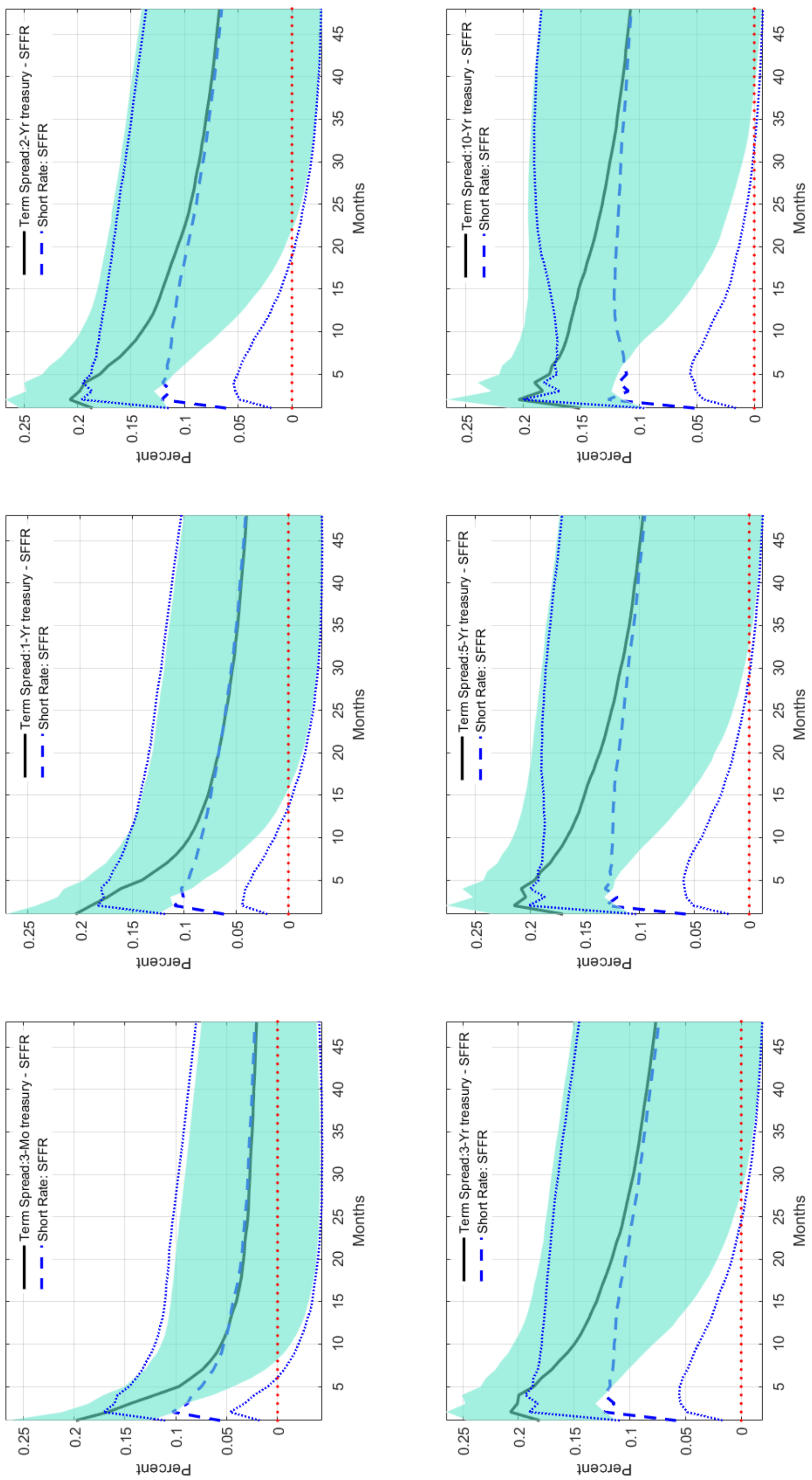


Figure 9. Short-term rate and term-spread responses to TP shock: (One *s.d.* increase in the term spread.) 1981:m1-2018:m4

9. Concluding remarks

If monetary transmission occurs through market interest rates, it follows that it should occur through interest rate spreads as well. Yet the question of quantifying the effect of monetary policy on the term structure of interest rates is far from settled. The rational expectations theory of the term structure maintains that there is a positive relationship between short-term and long-term rates. Another view is that, conditioned on MP shocks, short-term and long-term rates may be inversely related if increases in the short-term rate lead to lower inflation which puts downward pressures on long-term interest rates. Some of the theoretical predictions on the effects of monetary policy on the yield curve suggest the impact is monotonic, or static, over the length of the yield curve. An example would be the prediction that a contractionary monetary policy would lead to a parallel shift up the yield curve.

By contrast, the main findings suggest there is a dynamic impact of MP shocks on the yield curve, such that the shift may not be uniform over the length of the yield curve. Rather the upward shift may come about piecemeal from a series of rotations. This investigation shows that contractionary monetary action that raises interest rates leads to short-term reductions in term spreads in the short run. Subsequently, the spread response turns positive roughly about a year after the shock. This suggests that the yield curve ultimately experiences a wholesale upward shift with a clockwise tilt immediately following the policy action and an eventual counterclockwise tilt with some lag after the original policy shock. Thus, the yield curve seems to respond dynamically to monetary policy shocks.

I arrive at these conclusions while attempting to remain as agnostic as possible on the responsiveness of interest rate spreads to aggregate shocks. This seems an important line of inquiry to consider for further study given i) the Federal Reserve's recent efforts in actively affecting the slope of the yield curve and ii) interest rate spreads are more likely to remain informative in overly accommodative monetary periods than short-term policy rates.

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Conflict of interest

The author declares no conflict of interest.

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