POST-CRISIS REPO MARKET RESPONSES TO MONETARY POLICY

by

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Abstract

Repurchase agreement (repo) markets are a vital source of secured financing for depository institutions and the broader financial sector, making them a key channel for the transmission of monetary policy. Over the past decade, the repo market outweighs the federal funds market as the Federal Reserve's primary concern. Given the scale and significance of repos to financial institutions, fluctuations in the repo market can have important effects on the financial sector. Against this backdrop, the Fed might take measures to stabilize the repo market. Because the federal funds rate co-moves with the overnight repo rate, it is difficult to pin down the causal relationship between the repo rate and monetary policy. Using a two-variable and a three-variable vector autoregression (VAR) model, this paper characterizes the relationship between the Treasury General Collateral (GC) repo rate and the federal funds rate from January 2015 to March 2021. This paper investigates the initial transmission of monetary policy to closely related money markets. The results suggest that 1) even though monetary tools such as the funds target and open market operations are correlated, the Fed's response to a spiking repo rate might be an adjustment in the repo operation without changes in the effective federal funds rate; 2) post-crisis monetary policy is effective in maintaining financial stability; 3) monetary policy transmission only goes from the Federal funds market to money markets, with little evidence of systematic reaction of the funds rate to money markets. Several tests, including the alternative recursive orderings, the removal of the mid-September 2019 market event and the addition of Treasury yield spread into the VAR model, show that the results are robust.

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I. Introduction

Repurchase agreement (repo) markets are a vital source of secured financing for depository institutions and broader financial sector, and a key tool for the implementation of monetary policy. Repo markets have grown rapidly in the United States over the last twenty years. The gross amounts outstanding grew from roughly $4.5 trillion at year-end 2002 (Hördahl & King, 2012) to approximately $12 trillion as of 2009 (Gorton & Metrick, 2009).[2] The markets experienced a substantial collapse during the Great Recession but quickly picked up their growth momentum. As shown in the primary U.S. government securities dealers' financing data, the repo and reverse repo amount outstanding grew from roughly $3 trillion in 2013 to $4.2 trillion as of March 24, 2021.[3] These data are about 20% of total transactions in the repo market.

Repo and reverse repos have taken on new importance as monetary policy tools since the financial crisis. With the conclusion of large-scale asset purchases in 2014, the Federal Reserve laid out its plans to normalize monetary policy, also called the "exit strategy", by targeting the federal funds rate, as it did before the crisis. Massive asset purchases during and after the financial crisis have flooded the market with excess bank reserves, making it a challenge for the Fed to raise the federal funds rate above the near-zero market-clearing rate. Under this circumstance, the Federal Reserve raised the rate it pays banks on reserves held at the Fed

[2] In April 2005, Congress enacted the Bankruptcy Abuse Prevention and Consumer Protection Act of 2005 (BAPCPA), which expanded the definition of repurchase agreements to include mortgage loans, mortgage-related securities, and interest from mortgage loans or mortgage-related securities. The lack of official statistics precludes an accurate estimation of the size of the repo market. Gorton & Metrick (2009)'s estimation of the repo market likely includes some double counting.

[3] There is no official information on the evolution of the size of the repo market over the past quarter century. Therefore, the evolution of financing by primary dealers in the U.S. government securities market from 2013 through 2021 offers a feel for the exponential growth of the repo market post-crisis. https://www.newyorkfed.org/markets/counterparties/primary-dealers-statistics

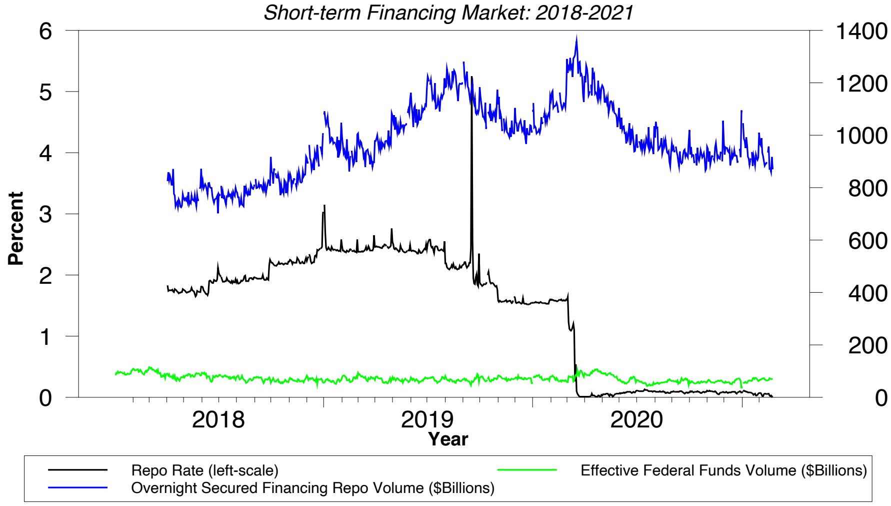
(IOER) and used large-scale reverse repo to alter repo rates. [4] Reverse repos have become a primary monetary tool for draining liquidity from the system and influencing short-term market rates, including the federal funds rate.

The repo market outweighs the federal funds market as the Federal Reserve's primary concern in recent years. The market volume of secured overnight repo transaction (blue line) is ten times higher than that of federal funds transaction (green line) from 2018 through 2021, as shown in **Figure 1**. More participants have become active in the repo market in the last few years. Federal Home Loan Banks (FHIBs), the main lenders in the fed funds market since the crisis, for example, expanded their lending in the repo rate in recent years. Depository institutions (DIs), who are primary borrowers in the fed funds market, transfer funds to its dealer affiliates over the last few years to lend in the repo market and take advantage of attractive rates. Financial institutions like hedge funds and money market mutual funds (MMMFs), which are not eligible to trade in the federal funds market, trade actively in the repo market. Because the federal funds market fails to capture a complete snapshot of what is going on in the broader financial sector to maintain financial stability, the Federal Reserve monitors both the repo market and the funds market vigilantly.

[4] See Federal Reserve Bank of New York, *FAQs: Overnight Fixed-Rate Reverse Repurchase Agreement Operational Exercise*, September 19, 2014, at http://www.newyorkfed.org/markets/rrp_faq.html. For a list of the Fed's current counterparties, see http://www.newyorkfed.org/markets/expanded_counterparties.html. See also Josh Frost et al., "Overnight RRP Operations as a Monetary Policy Tool," *Finance and Economics Discussion Series 2015-010*, February 19, 2015, at http://www.federalreserve.gov/econresdata/feds/2015/files/2015010pap.pdf.

Figure 1

Short-term Financing Market: 2018-2021



Sources: Federal Reserve Bank of New York

In this paper, I investigate two aspects of interactions between monetary policy and the repo market: 1) the repo market's response to shocks to the federal funds rate; 2) the degree to which spreads between the overnight repo rate and the federal funds rate induce the Fed to intervene in the repo market through setting a new target rate.

These research questions are of great interest for several reasons. First, they reveal the inter-connectedness between the federal funds market and repo market empirically which Afonso et al. (2020) fails to provide a model to explain the market spillovers. Inter-connectedness helps explain the mid-September 2019 cash crunch event, where both secured and unsecured interest rates spiked together unexpectedly. Second, repo rates are of importance for the transmission of monetary policy and the determination of the yield curve. Repo rates increase and banks' insurance against liquidity shocks becomes costlier if liquidity in repo markets dries up (Fuhrer, 2018). The question sheds light on the design of monetary tools and their effectiveness in controlling short-term interest rates and maintaining financial stability. Most importantly, given the scale and significance repos pose to financial institutions, fluctuations in the repo market can positively or negatively affect the broader financial sector. Against this backdrop, the Federal Reserve might take measures to stabilize the money markets, which could be reflected in its open market operations or asset purchases.

This paper characterizes the relationship between the Treasury General Collateral (GC) repo rate and the federal funds rate from January 2015 to March 2021. In particular, I estimate a bivariate vector autoregession (VAR) model to quantify the monetary policy transmission process. Estimates find that shocks to the federal funds rate lead to persistently higher-than-normal repo rate. Shocks to the repo rate in contrast, lead to only a transient increase in the federal funds rate. The model suggests that monetary policy transmission only goes from the Federal funds market to money markets, with little evidence of systematic reaction of the funds rate to money markets. Several tests, including alternative recursive orderings, the removal of the mid-September 2019 market event and the addition of Treasury yield spread into the VAR model, show that the results are robust.

The rest of the paper is organized as follows. Section II describes the key mechanics of the repo market and the mid-September cash crunch event. Section III reviews literature on the repo market's microstructure and the interaction between repos and monetary policy. Section IV gives an overview of the methodology, followed by a description of the dataset in Section V. Section VI uncovers the main findings and shows the robustness of these findings. Section VII discusses the policy implications and concludes.

II. Background

i. Key Mechanics of the Repo Market

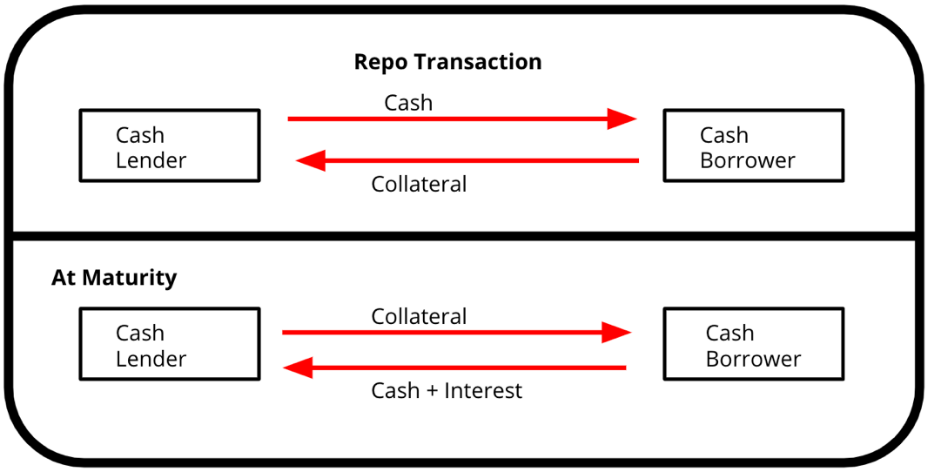
A repurchase agreement (repo) is a short-term secured loan. Cash borrowers sell securities to cash lenders and agree to repurchase those securities at a future date and specified price. The economic effect of a repo transaction is similar to that of a collateralized loan. The cash investor in a repo receives securities as collateral to protect her against the risk that the counterparty is unable to repurchase the securities at the agreed date (Baklanova, 2021). The collateral most commonly used in the repo market consists of U.S. Treasury securities, agency securities, and mortgaged-back securities (MBS).

The repo market can be split into two main segments: tri-party repo and bilateral repo. In tri-party repos, a central clearing bank stands between cash borrowers and lenders handling the administrative details between the two parties in the repo transaction. In the United States, JP Morgan and Bank of New York Mellon are the two major clearing banks facilitating settlement. Since clearing banks are obligated to disclose information to the regulated institutions, tri-party repo data is relatively complete, and the market is widely studied. In contrast, the bilateral repo market is composed of hedge funds, offshore institutions, and other unregulated cash pools, making it opaque to outsiders. [5]

[5] For more information on the US repo market: https://www.sifma.org/resources/research/us-repo-market-fact-sheet/.

The market can also be categorized based on the collateral type. General Collateral Financing (GCF) repos differ from “special collateral” repos in that for the former case, a certain designated class of securities are acceptable. For example, in terms of the Treasury GCF repos, the cash borrower has the option to deliver any Treasury securities as collateral. For special collateral repos, a specific security is designated as the only acceptable collateral. The market for GC repos has grown into one of the main channels for funding U.S. financial institutions in recent years because it allows for more flexibility in the securities being collateralized, thereby reducing costs and decreasing the complexity of handling securities for both borrowers and lenders.

In most cases, the market value of collateral exceeds the cash amount borrowed. The difference is known as over-collateralization, or simply, the repo haircut. Repo haircuts protect the cash lender from a fire sale of securities if the borrower defaults. The difference between cash borrowing and the repurchase price is the interest paid on the loan, known as the repo rate. Both the repo rate and the haircut are agreed upon at the outset of the deal, making repo financing unique because of its dual-pricing measure. A reverse repurchase agreement (reverse repo) is the mirror of a repo transaction: a short-term agreement to purchase securities in order to sell them back at a slightly higher price. A simple bilateral repo transaction is illustrated below.



Repos are important for the financial sectors and central banks for several reasons. First of all, they allow financial institutions like hedge funds or investment banks, which own a vast amount of short-term or long-term securities, to borrow cheaply. They also permit parties with spare cash, like money mutual funds, insurance companies and commercial banks, to earn a small return without bearing too much risk.

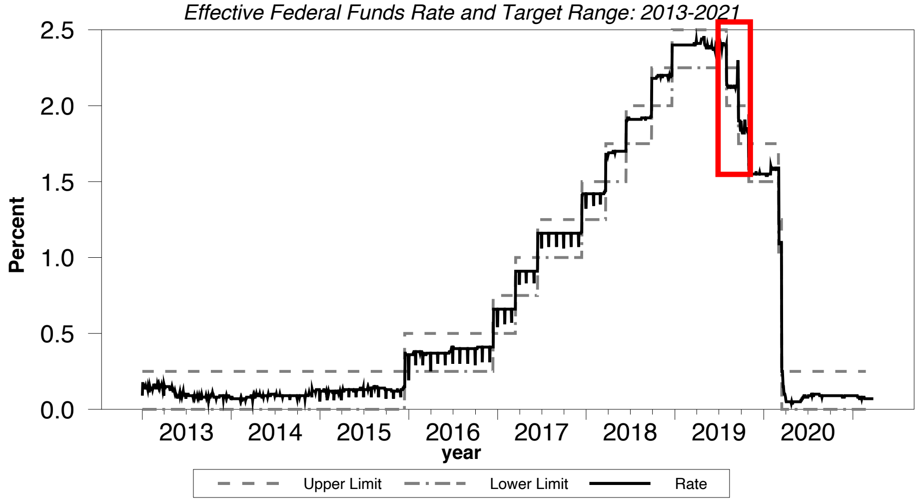
Secondly, central banks use repos and reverse repos to conduct monetary policy. In the textbook version of monetary policy implementation, central banks buy securities from dealers in the repo market, which gives the dealers cash that they deposit in their banks' accounts, and the bank then proceeds to sell the funds in the federal funds market (Bech et al., 2011).

ii. Mid-September 2019 Market Event

Repo rates suddenly spiked on September 17, 2019. **Figure 1** shows an increase of 3 percentage points in the secured overnight financing rate (SOFR), a measure of the cost of borrowing cash overnight collateralized by Treasury securities. Repo rates hit 10 percent at one point in the day, according to the media reports. [6] Strains in the repo market quickly spilled over to the federal funds market as banks shifted investments from federal funds to repo market in order to take advantage of higher repo rates. Outflows from the Federal funds market drove the effective federal funds rate (EFFR) exceeded the upper limit of the FOMC's target range of 2.5 percent, as **Figure 2** shows.

Figure 2

Effective Federal Funds Rate and Target Range: 2013-2021



Source: Federal Reserve of New York

What led to the unexpected temporary shortage of liquidity and secured rate spike? Anbil et al. (2020) point to two shocks that could have adversely affected money markets in September 2019: corporate tax payments and Treasury auction settlement. Both events entail cash transfers

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[6] "U.S. Repo Rate Falls After Fed Repo Operation," Reuters, September 20, 2019, at https://www.reuters.com/article/ us-usa-repo/u-s-repo-rate-falls-after-fed-repo-operation-idUSKBN1W51AW.

from commercial banks' accounts to the Treasury General Account at the Fed. Two events happening concurrently would cause a decline in the supply of reserves and an increase in the demand for cash in the market. Seasonal factors, like the two described above, are to some degree predictable. Therefore, even though these factors can help explain the upward pressure on the borrowing cost, they fail to provide a compelling explanation for the magnitudes of the increases in both the level and volatility of the repo rate.

Some observers have suggested that regulation played a role in September's repo market turmoil. Post-crisis financial stability reforms require large banks to hold more liquid assets and reduce financial leverage.[7] These requirements could raise the cost for large banks to borrow and lend in the repo markets, making participation in the repo markets less attractive.

Afonso et al. (2020) highlight two other factors that could have contributed to the mid-September stress in the money markets -- the reserves scarcity and a sharp increase in the intermediate costs for large domestic dealers. **Figure 3** shows a jagged but overall decline of total reserves of depository institutions from August 2014 to October 2019 followed by a drastic increase in reserves. Following a substantial improvement in the outlook for the labor market and inflation post-crisis, the Federal Reserve introduced policy normalization (**Table 1**). This policy ended the asset purchase program at the end of October 2014. The heavy use of overnight and term reverse repurchase agreement facilities since January 2014 significantly reduced the balance sheet. New sales of Treasury securities to finance deficits in recent years also lead to reserve scarcity as private investors shift from holding excess reserves to government bonds.

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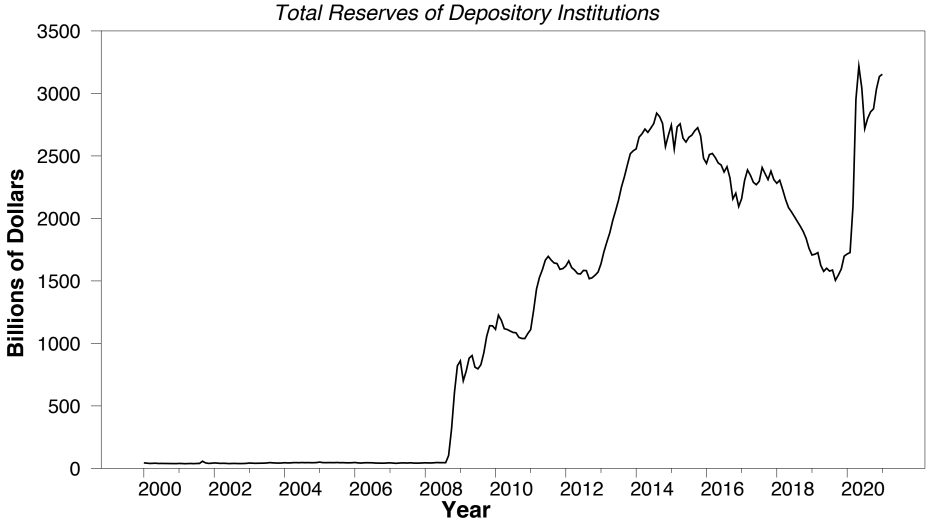
[7] More information on the large bank regulations, see CRS Report R45711, *Enhanced Prudential Regulation of Large Banks*, by Marc Labonte.

Figure 4 shows that the U.S. total public debt outstanding increased by around $7 trillion from 2016 to 2020. Among all, primary dealers' holdings of the amount of Treasury securities grew by $250 billion.

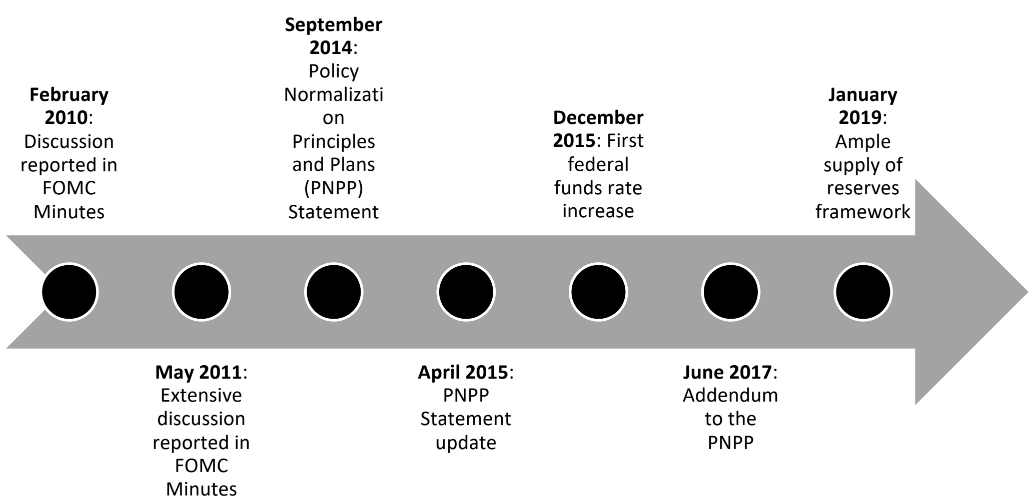
Figure 3

Total Reserves of Depository Institutions



Source: Board of Governors of the Federal Reserve System

Table 1: Timeline of Policy Normalization Principles and Plans

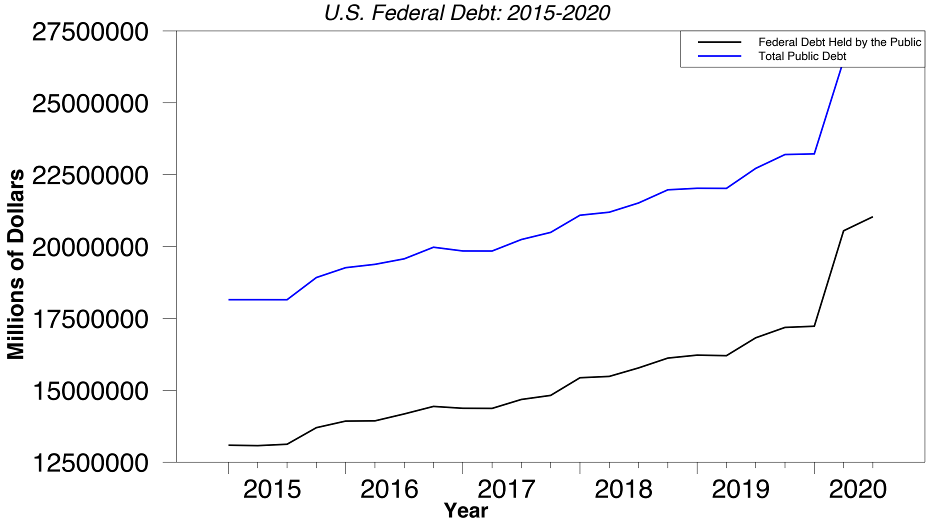


Source: Board of Governors of the Federal Reserve System[8]

[8] More information regarding the policy actions and communications: https://www.federalreserve.gov/monetarypolicy/timeline-policy-normalization-principles-and-plans.htm.

Figure 4

U.S. Federal Debt: 2015-2020



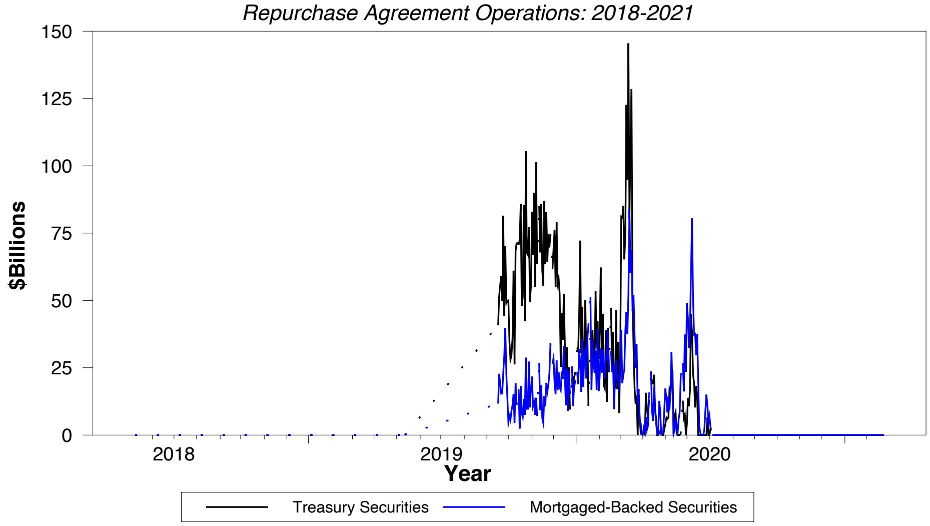
Source: U.S. Department of the Treasury. Fiscal Service

In addition, some large domestic dealers likely experienced a higher intermediation costs in mid-September 2019 due to the temporary withdrawal of money mutual funds from the Fixed Income Clearing Corporation's (FICC) repo program. The withdrawal expanded the bid-ask spread at which large dealers intermediate (Afonso et al., 2020).

In response to the elevated repo and federal funds rates, the New York Fed's Open Market Trading Desk (the Desk) announced an overnight repo operation to be conducted on September 17, 2019, which included $75 billion against Treasury, agency, and agency mortgaged-backed securities (MBS) collateral. The operation led to an immediate decline in rates, as shown in **Figure 1**. While the secured market was stabilized after several rounds of operations, **Figure 1** shows that trading volumes in the repo market stagnated. In the subsequent FOMC October 2019 meeting, the Desk extended both its overnight and term repo operations through at least 2020 in order to address potential liquidity strain in the market. The operations were extended again at the outset of the COVID-19 crisis in March 2020. Not only did repo operations extend longer than originally announced, they also vastly expanded to funnel additional cash to money markets to preserve financial stability (**Figure 5**).

Figure 5

Repurchase Agreement Operations: 2018-2021



Source: Federal Reserve Bank of New York

Note: The original announcement of repo operations following the mid-September market turmoil should end in 2020. However, the operations extended longer and vastly expanded during COVID-19.

III. Literature Review and Contribution

The literature on repos mainly focuses on asset pricing and market microstructure, not the connection of the repo market to monetary policy. For instance, Bartolini et al. (2011) investigate the relative valuation of different types of collateral that are used in repurchase agreements. Gorton & Holmström (2013) show repo haircuts arise from sequential trade in which parties may default and intermediate lenders face liquidity needs. Han & Nikolaou (2016) explore relationship lending among the tri-party repo trading parties to find that relationships affect both the likelihood and terms of a trade.

Regarding the market microstructure, Copeland et al. (2012) discuss weakness in the design of the U.S. tri-party repo market that could rapidly elevate and propagate systematic risk. Gorton & Metrick (2012) document a large increase in margins in the repo market and view the market as a potential source of financial instability since the financial crisis. Additionally, one of the most important reasons cited for the failure Lehman Brothers and the takeover of Bear Stearns was their inability to roll over the repo funding [Ball (2018), Fleming et al. (2010)].

My paper shares the common repo concepts mentioned above, however, it is more related to the few studies on interactions between repo market functioning and monetary policies. Relevant works include Gorton et al. (2018)'s study on changes in repo haircuts being traced to changes in the collateral brought to the Federal Reserve's emergency lending facilities in the financial crisis. They show that emerging borrowing, by category, co-moves with corresponding haircuts by category. The underlying mechanism is that once the haircut increases on a category of assets, the bank must fund the additional amount itself, which could be achieved by borrowing from an emergency lending facility. The authors combine haircut data from bilateral repo market with quantity data from emergency lending programs and find evidence of a strong relationship between the haircut value and the amount borrowed. The results are shown to be robust but have limitations because the metrics in the bilateral and tri-party repo markets are different (Krishnamurthy et al., 2014). Moreover, since the bilateral market is operated over the counter and since there is no centralized exchange with comprehensive coverage, their results based on the proprietary dataset collected from traders cannot be easily replicated. In contrast, my paper focuses on the interaction between repo pricing and monetary policy in a tri-party repo market setting, whose dataset is generally better covered and available to the public. My paper also fills the knowledge gap Gorton et al. (2018) fail to consider, thereby bringing better understanding of monetary policy impacts on the overall repo market function.

Fleming et al. (2010) examine how changes in collateral supply affect repo rates and spreads. They hypothesize that use of the Term Securities Lending Facilities (TSLF), which allows eligible financial institutions to swap less liquid collateral for Treasury collateral with the Federal Reserve following the Financial Crisis, should increase the supply of Treasury collateral available to the private market, thereby reducing the Treasury collateral's scarcity value and causing Treasury financing rates to rise. Besides that, use of this liquidity facility should also reduce the supply of less liquid collateral available to the dealers, thus increasing the collateral's scarcity value and causing financing rates on such collateral to decline. The authors use the TSLF operations data from the Federal Reserve Bank of New York and detailed repo rate data from the primary dealer survey. They consider changes in collateral supply from a particular TSLF to be exogeneous because of the highly insensitive repo rates and spreads to the expectations about future changes in supply. They find that the operations have precipitated a significant narrowing of repo spreads. Various additional tests, including a split-sample test, suggest that the findings are robust. Given the scale and significance of repos to the broader financial sector, the Federal Reserve might adjust the scale of TSLF operations here to there to promote market liquidity. For this reason, viewing the change in collateral supply as exogeneous could lead to bias. Instead of treating monetary policy as exogeneous, I model changes in monetary policy and repo rate as variables in a system of equations, allowing the possibility of central bank's intervention following changes in the repo market, like what the Federal Reserve did in response to the mid-September 2019 market event.

My paper specifically seeks to understand the link between the federal funds and the repo market. It also aims to quantify the transmission of monetary policy to the money markets. Related works include Afonso et al. (2020)'s discussion of the mid-September 2019 cash crunch event and the market spillovers as well as Bech et al. (2011)'s study on the connection between the federal funds and repo market before, during, and emerging from the financial crisis. In particular, Bech et al. (2011) use a vector error correction model (VECM) and empirically show that the repo rate and the federal funds rate are cointegrated during normal times and during the first stage of the financial crisis. After the introduction of the 0-25 basis point federal funds target range in December 2008, transmission of monetary policy to the repo market slowed and the link between two short-term financing markets weakened. By comparison, my paper treats the unit roots as random variables and does a parametric bootstrap to get the error bands for impulse response functions of a vector autoregression (VAR) model to elucidate the transmission of monetary policy from the federal funds market to the repo market post-crisis.

How market interest rates respond to Federal Reserve actions is a topic of great interest to financial market participants and policymakers alike. Considering the rising significance of repo market to the broader financial sector, it is essential to understand the transmission of Federal Reserve policy from the Fed funds target to repo rates. This paper contributes to the economic literature by empirically analyzing the inter-connectedness between the repo market and the Federal funds market. To my knowledge, this paper is the first study that traces the post-crisis transmission of monetary policy from one market to the other when the level of reserve exceeds banks' minimum reserve requirements.

IV. Methodology

In macroeconomics, when one analyzes the relationship among multiple time series, the natural framework is the vector autoregression (VAR), in which a vector of variables not only depends on their own lags but on the lags of every other variables in the vector. In this section, I use a two-variable VAR model with one lag to discuss the concept of orthogonalizing the shocks in a VAR. By doing so, I show what orthogonalization is, why I adopt it in the study, and what questions I hope to answer with it.

A structural VAR with one lag looks like

$$A_0 X_t = c_0 + A_1 X_{t-1} + \varepsilon_t \quad (1)$$

where c_0 is a n x 1 vector of constants, A_j is a n x n matrix (for j = 0,1) and ε_t is a n x 1 vector of error terms. The main diagonals of A_0 are normalized to 1. The error term ε_t satisfies $\varepsilon_t \sim N(0, I)$.

A two-variable structural VAR can be written in matrix form as

$$\begin{bmatrix} 1 & A_{0;1,2} \\ A_{0;2,1} & 1 \end{bmatrix} \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} = \begin{bmatrix} c_{0,1} \\ c_{0,2} \end{bmatrix} + \begin{bmatrix} A_{1;1,1} & A_{1;1,2} \\ A_{1;2,1} & A_{1;2,2} \end{bmatrix} \begin{bmatrix} x_{1,t-1} \\ x_{2,t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix} \tag{2}$$

By multiplying the structural VAR with the inverse of A_0

$$X_t = A_0^{-1}c_0 + A_0^{-1}A_1X_{t-1} + A_0^{-1}\varepsilon_t \tag{3}$$

and denoting $c = A_0^{-1}c_0$, $B = A_0^{-1}A_1$ and $u_t = A_0^{-1}\varepsilon_t$, one obtains the reduced VAR

$$X_t = c + BX_{t-1} + u_t \text{ (\textbf{Reduced Form})} \tag{4}$$

where the new error term u_t satisfies $u_t \sim N(0, \Sigma)$.

The best linear predictor, in terms of the minimum mean squared error (MSE), of X_{t+1}, or one-time forecast, based on information available at time t is

$$X_{t+1\,|\,t} = c + BX_t \tag{5}$$

Forecasts for longer horizon m (m-step forecasts) may be obtained using the chain-rule of forecasting as

$$X_{t+m\,|\,t} = c + BX_{t+m-1\,|\,t} \tag{6}$$

The m-step-ahead forecast error can then be expressed as

$$X_{t+m} - X_{t+m\,|\,t} = \sum_{s=0}^{m-1} B^s u_{t+m-s} \tag{7}$$

The problem with error term u_t is that it is not orthogonal, i.e., $\sigma_{u_{1t},u_{2t}} \neq 0$. Orthogonality is crucial in the estimation of VAR because without it, we could not answer the question of "what is the effect of a shock to one equation, holding other shocks constant?" In order to analyze the impulse response, it is important to keep other shocks fixed. The solution is to write the errors as a linear combination of "structural" shocks $\varepsilon_t = A_0 u_t$ which maps estimated forecast errors into exogeneous (structural) disturbances. The structural shocks that drive the dynamics of economic variables are assumed to be independent, which implies zero correlation between error terms. In addition, variables can have a contemporaneous impact on other variables in the structural form.

The goal here is to identify A_0. However, if $X \sim n \ \propto 1$, then Σ is n x n and has $n(n+1)$ distinct moments. The problem is that without further information, we cannot uniquely pin down A_0 from Σ. Therefore, to satisfy the necessary condition for the identification of A_0, we need $n(n-1)$ restrictions. One commonly used identification scheme is the Cholesky (recursive) orderings.

The mechanism for Cholesky identification is to require A_0 to be a lower-triangular or upper-triangular matrix, placing zeros on all entries above or below the diagonal.

For example, let $n = 2$, the model can be written as

$$x_{1,t} = c_{0,1} + A_{1;1,1} x_{t-1} + A_{1;1,2} x_{2,t-1} + \varepsilon_{1,t} \tag{8}$$

$$x_{2,t} = c_{0,2} + \beta_0 x_{1,t} + A_{1;2,1} x_{t-1} + A_{1;2,2} x_{2,t-1} + \varepsilon_{2,t} \tag{9}$$

In this case, $A_0 = \begin{bmatrix} 1 & 0 \\ -\beta_0 & 1 \end{bmatrix}$ is a lower triangular matrix that satisfies

$$A_0 A_0' = \Sigma \tag{10}$$

Cholesky ordering can be thought of as imposing a causal ordering on the variables in the VAR: shocks to one equation contemporaneously affect variables below that equation but only affect variables above that equation with a lag. In **Equations 8 & 9**, x_1 has a contemporaneous effect on x_2 , not vice versa. With Cholesky identification, order matters because switching the orders of variables in the VAR will permute the entries in Σ, thereby generating a different A_0 matrix. However, how much order matters depends on estimate of covariance between innovations.

In context of financial markets, "shocks" correspond to news that induces market participants to adjust their behavior. For instance, the mid-September 2019 market turmoil caused participants to shift investments from the Federal funds market to the repo market, driving up the federal funds rate. In response to the elevated short-term financing rates, the Federal Reserve implemented repo operations to bring rates down. It is evident that the federal funds rate and the repo rate appear in a system of equations as both endogenous and exogenous variables. Since the causal arrow relating repo spreads between the repo rate and the federal funds rate to monetary policy goes in both directions, isolating the repo market's response to monetary policy requires one to choose an appropriate identification scheme. Cholesky orderings serve the purpose due to the institutional features of the Federal Reserve. To illustrate, it takes time for the Fed to observe and understand repo market developments. Therefore, it is safe to assume that the Fed does not react within a day to news in the repo market, but it does respond with a one-day lag. Repo market, in contrast, does respond in same day to Fed's interest-rate actions. The identifying assumption is further explained in the empirical framework section.

V. Data

This section first describes the dataset used for the empirical analysis in this paper. It then presents some data analysis to provide justification for the econometrics techniques adopted throughout the paper.

i. Dataset

There are three sets of datasets used in this study. The first set of data are daily observations on the effective federal funds rate and the overnight Treasury GC repo rate from January 5, 2015 to March 26, 2021. The effective federal funds rate (EFFR) is calculated as a volume-weighted median of overnight federal funds transaction reported in the FR 2420 Report of Selected Money Market Rates. The Federal Reserve Bank of New York (FRBNY) publishes the rate for the prior business day at approximately 9:00 am. [9] The Treasury GC repo rate is a par-weighted averages of daily activity in the Treasury general collateral financing (GCF) repo market calculated and published by DTCC's Fixed Income Clearing Corporation. [10] Both rates measure market activity when the respective markets are most active.

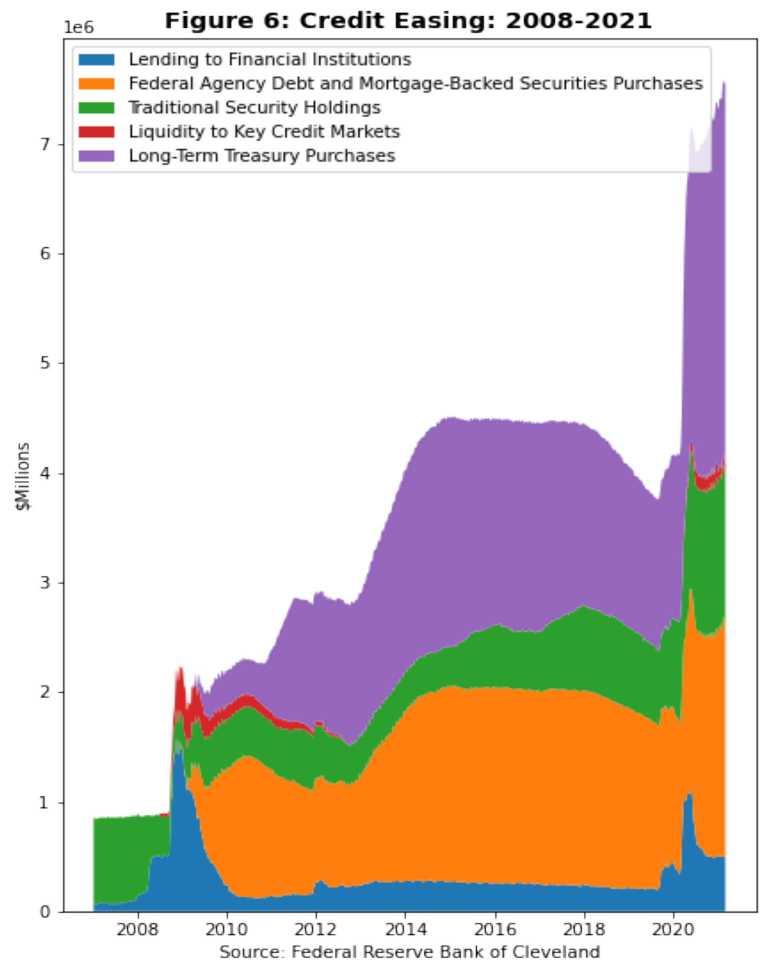
[9] Statement regarding the planned changes to the calculation of the federal funds effective rate: https://www.newyorkfed.org/markets/opolicy/operating_policy_150202.html
[10] The DTCC Treasury GCF Repo Index is composed of U. S. Treasury < 30-year maturity (371487AE9). More information on DTCC GCF repo index: https://www.dtcc.com/charts/dtcc-gcf-repo-index.

The second set of data are daily observations on the Federal Reserve's repurchase agreement and reverse repurchase agreement (RP/RRP) operations from January 5, 2015 to February 25, 2021. Both series are constructed as the aggregated daily amounts of RP/RRP transactions reported by FRBNY as part of the Temporary Open Market Operations which are designed to temporarily add or drain reserves available to the banking system and influence day-to-day trading in the federal funds market. The study also uses daily Treasury yield curve rates, commonly referred to as "Constant Maturity Treasury" (CMT) rates, from January 5, 2015 to March 24, 2021. These market yields are calculated from composites of indicative, bid-side market quotations (not actual transactions) obtained by the Federal Reserve Bank of New York at or near 3:30pm each trading day. [11]

The third set of datasets are weekly snapshots of the Federal Reserve balance sheet provided by the Federal Reserve Bank of Cleveland which captures the unconventional monetary policy tools usage following the beginning of the financial crisis in 2008, as shown in **Figure 6**. The tools are divided into three categories: lending to financial institutions, liquidity provided to key credit markets, and purchase of long-term securities. [12] The data keeps track of the increment in large-scale asset purchases, which could affect both repo and federal funds rates.

[11] The CMT yield values are read from the yield curve at fixed maturities, currently 1, 2, 3 and 6 months and 1, 2, 3, 5, 7, 10, 20, and 30 years. More information on the Treasury term structure: https://www.treasury.gov/resource-center/data-chart-center/interest-rates/pages/TextView.aspx?data=yieldYear&year=2013

[12] Former Federal Reserve Chairman Ben Bernanke called the use of balance sheet in this way "credit easing". More information on credit easing: https://www.clevelandfed.org/en/our-research/indicators-and-data/credit-easing/background-and-resources.aspx.



ii. Preliminary Data Analysis

This subsection reviews the preliminary data analysis results over two sample periods: the policy normalization period (Jan 2015 – Dec 2018) and the ample reserve balances period (Jan 2019 – Mar 2021).

The spreads between federal funds and overnight repos suggests that there could be a cointegrating relationship between these two series (**Figure 7.1**, **Figure 7.2**). After both effective federal funds and overnight GC repo rates are normalized, the funds rate has been persistently higher than repo rates between the end of 2016 and the onset of the COVID-19 pandemic. The relatively stable spreads between federal funds and overnight GC repo rates could be understood as the risk premium of the repo financing during peacetime.

Table 2 presents augmented Dickey-Fuller tests to determine whether these series have unit roots.[13] Surprisingly, the null of a unit root for the funds rate is accepted for both time periods. The analysis contrasts to the results Bech et al. (2011) get. They perform the tests over three subsamples: normal times (2002-2007), early financial crisis (2007-2008) and extended period (2008-2010) and discover that the null of a unit root is accepted for the first two periods but is rejected for the last period with ample reserve balances.

The reason that we obtain such different results might be threefold. First, as shown in **Figure 2**, even though reserve balances declined significantly from balance sheet normalization, total reserves of depository institutions in this time period still greatly exceed the amounts in Bech et al.'s "extended period" of the crisis. Comparing the results based on different "reserve balance" criteria could be misleading and will not generate useful insights. Second, the monetary regime is completely different post-crisis after the introduction of various unconventional tools, including large-scale asset purchases (LSAP) and interest paid on excess reserves (IOER). Third, the Fed kept close tabs on instability in the money markets to take actions if necessary, during and after

[13] The optimal lag length used is based on the Bayesian information criterion (BIC).

the financial crisis. [14] In this case, it is harder to pinpoint any longer-term relationship between federal funds and repo rates when the Federal Reserve monitors changes in both rates closely.

Table 2: Augmented Dickey-Fuller Tests

	Federal Funds	Treasury GC Repo	MBS GC Repo	# Observation
Jan 2015 – Dec 2018	-1.83	-1.97	-1.97	528
(lag length)	2	11	11	
Jan 2019 – Mar 2021	-1.97	-1.55	-1.69	345
(lag length)	8	9	9	

** Reject hypothesis of a unit root at the 5 percent confidence level

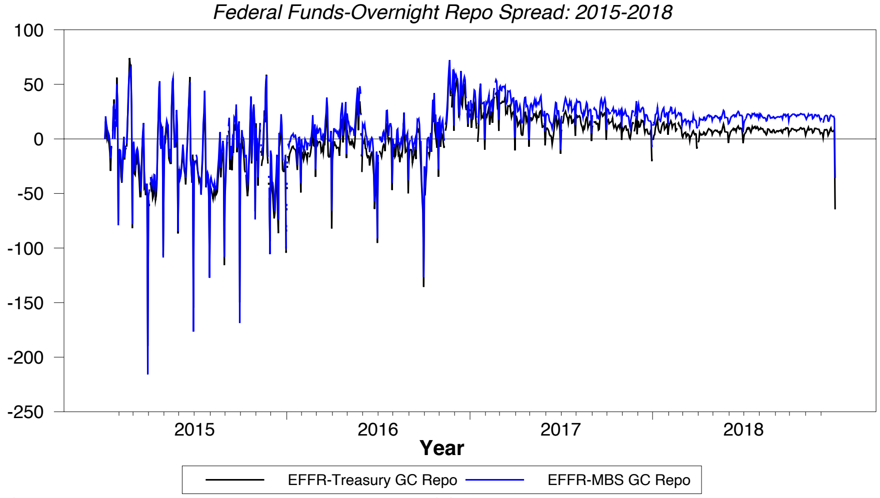
Figure 7.1 and **Figure 7.2** demonstrate that heteroskedasticity are present in both series. Differencing will not eliminate heteroskedasticity, nor render the federal funds rate and the repo rate stationary. More interestingly, there are calendar effects in the EFFR-repo spreads: both Treasury and MBS general collateral repo rates spiked on December 31, 2018, as a result of banks and dealers paring their lending activity to conserve cash to meet regulatory requirement. In fact, jumps in spreads happen frequently. Reasons for these patterns include elevated payment flows on beginning-, mid-, and end-month dates, as well as Treasury coupon securities issuance on the dates [(Happ, 1984), (Fleming et al., 2010)]. Moreover, repo rates tend to co-move with the federal funds rate during maintenance period when reserves are at its minimum requirement[(Griffiths & Winters, 1997), (Bech et al., 2011)].[15]

[14] Post-crisis FOMC minute: financial stability is a necessary condition for the achievement of the Committee's longer-run goals of maximum employment and price stability. Some participants offered suggestions for communicating more specifically on how financial stability, and perhaps other asymmetric risks to the outlook, are taken into account in the setting of monetary policy.

[15] A maintenance period consists of 14 consecutive days beginning on a Thursday and ending on the second Wednesday thereafter. More information on the mechanics of reserve maintenance: https://www.federalreserve.gov/monetarypolicy/files/reserve-maintenance-manual.pdf

Figure 7.1

Federal Funds-Overnight Repo Spread: 2015-2018

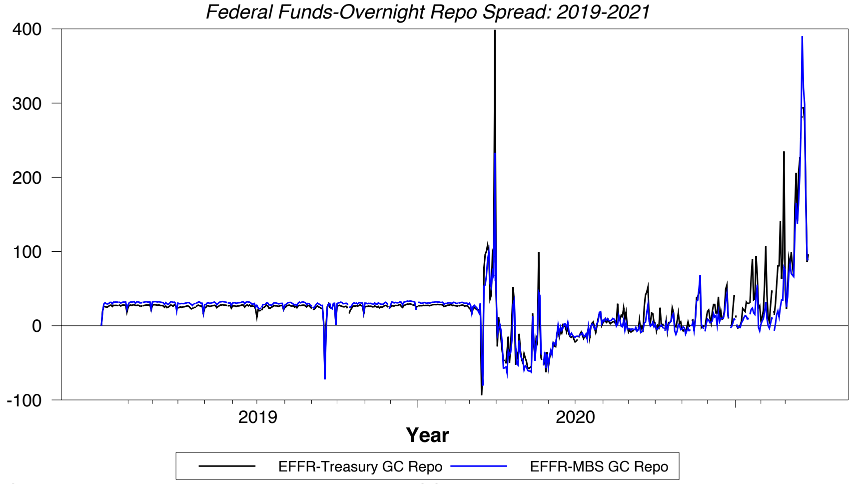


Source: Federal Reserve Bank of New York, DTCC

Note: EFFR-Treasury GC Repo (black line) is the difference between effective federal funds rate and overnight Treasury GC repo rate. Similarly, EFFR-MBS GC Repo (blue line) is the difference between federal funds rate and overnight MBS GC repo rate.

Figure 7.2

Federal Funds-Overnight Repo Spread: 2019-2021



Source: Federal Reserve Bank of New York, DTCC

Taken together, the preliminary data analysis suggests that it is not necessary to divide the sample period based on monetary regime. But calendar effects on repo rates should be taken into serious consideration when conducting the empirical analysis.

VI. Empirical Framework and Results

i. Simple Ordinary-Least-Squared Regression Model

This section uncovers the basic relationship between federal funds target rate changes and repo rates post-crisis. Before moving on to untangle the relationship between these two series, it first explores the relationship between target rate changes and Treasury yields using an OLS regression identical to that used in Cook & Hahn (1989) and Kuttner (2000)'s analysis, since the study focuses primarily on the repos against Treasury collateral. Their procedure regresses the change in Treasury GC repo, bill, note, and bond rates (denoted as R) on the change in the target Fed funds rate (denoted as r).

$$\Delta R_t = \alpha + \sum_{i=0}^{p} \beta_i \Delta r_{t-i} + \varepsilon_t \tag{11}$$

The response to target rate increases is positive and significant at all maturities, but smaller along the yield curve, as **Table 3** reports. A one percentage point increase in the Fed funds target leads to an increase of 0.6 percent in the overnight Treasury GC repo rate, but only a 10-basis point increase in the 30-year bond yield. A significant response of T-bill and bonds rate to lagged target rate changes also appears, suggesting some delay in market participants' recognition of certain actions. The overnight GC repo rate, in contrast, changes concurrently with the target rate, suggesting that participants in the repo market respond quickly to any changes in the Fed funds market.

Table 3. The 10-day response of interest rates to changes in the Federal Funds target

	Treasury GC		1 Month		3 Month		6 Month		1 Year	
Variable	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE
EFFR	0.590 (2.87**)	0.206	0.032 (0.90)	0.366	0.088 (1.87*)	0.047	0.085 (2.98**)	0.029	0.086 (2.97**)	0.029
EFFR{1}	0.371 (1.84*)	0.202	0.086 (3.02**)	0.003	0.058 (2.75**)	0.021	0.050 (1.58)	0.031	0.035 (1.15)	0.031
EFFR{2}	-0.017 (-0.07)	0.227	0.075 (2.42**)	0.015	0.131 (3.28**)	0.040	0.112 (3.37**)	0.032	0.053 (2.12**)	0.025
EFFR{3}	-0.067 (-1.05)	0.064	0.075 (1.48)	0.139	0.020 (0.61)	0.031	0.045 (1.50)	0.029	0.026 (1.22)	0.021
EFFR{4}	-0.029 (-1.34)	0.022	0.020 (0.84)	0.403	-0.005 (-0.19)	0.027	-0.004 (-0.10)	0.036	0.009 (0.26)	0.034
EFFR{5}	0.082 (1.68)	0.049	0.005 (0.13)	0.898	0.011 (0.82)	0.014	-0.013 (-0.76)	0.017	-0.012 (-0.75)	0.015
EFFR{6}	0.067 (1.49)	0.045	-0.005 (-0.39)	0.697	0.025 (1.16)	0.022	-0.001 (-0.05)	0.013	-0.029 (-1.03)	0.028
EFFR{7}	0.137 (0.45)	0.300	0.027 (1.04)	0.297	0.003 (0.13)	0.023	0.016 (1.23)	0.013	0.037 (2.35**)	0.016
EFFR{8}	0.043 (0.36)	0.122	0.052 (1.38)	0.168	-0.009 (-0.52)	0.019	0.018 (1.39)	0.013	0.025 (1.00)	0.025
EFFR{9}	0.052 (0.84)	0.062	-0.0004 (-0.02)	0.985	0.000 (0.00)	0.020	0.006 (0.35)	0.018	0.021 (1.22)	0.018
EFFR{10}	0.163 (1.33)	0.122	-0.050 (-2.4**)	0.019	-0.021 (-0.56)	0.038	-0.002 (-0.03)	0.046	0.015 (0.52)	0.029
Constant	0.001 (0.38)	0.004	-0.0005 (-0.63)	0.528	-0.0005 (-0.89)	0.001	-0.0004 (-0.75)	0.001	-0.00 (-0.18)	0.001

Note: The change in the target Fed funds rate and the interest rate changes are expressed in percent. Parentheses contain t-statistics.
** significant at the 5 percent confidence level
*significant at the 10 percent confidence level

ii. Bivariate Vector Autoregression Model and Robustness Check

In this subsection, I add dynamics to the model. I no longer treat changes in the target rate as exogeneous or impose unit roots. The procedure is to turn the simple ordinary-least-squared with a well-fitted number of lags into a vector autoregression with the goal of estimating the responses of repo rate to changes in the target rate in a dynamic setting. I consider a two-variable structural VAR of order p represented by the following system of linear equations:

$$A_0 X_t = c_0 + A_1 X_{t-1} + \cdots + A_p X_{t-p} + \varepsilon_t \tag{12}$$

where c_0 is a 2 x 1 vector of constants, $A_j = \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix}$ is a 2 x 2 matrix (for j = 0, 1,…, p) and ε_t is a 2 x 1 vector of error terms. The main diagonals of A_0 are normalized to 1. The error term ε_t satisfies $\varepsilon_t \sim N(0,\ I)$.

The reduced VAR is obtained as

$$X_t = c + B_1 X_{t-1} + \cdots + B_p X_{t-p} + u_t \ (\textbf{Reduced Form}) \tag{13}$$

where $c = A_0^{-1} c_0,\ B_i = A_0^{-1} A_i\ (i = 1, 2, \dots, p)$ and $u_t = A_0^{-1} \varepsilon_t$. The new error term u_t satisfies $u_t \sim N(0, \Sigma)$.

In context of the empirical analysis, $x_{1,t}$ is the target rate and $x_{2,t}$ is the Treasury GC repo rate. The 2x2 matrices B_1, B_2, …B_p are parameters to be estimated. Then the variance covariance matrix for the error vector

$$\Sigma = E u_t u_t' = \begin{pmatrix} \sigma_{u_1}^2 & \sigma_{u_1,u_2} \\ \sigma_{u_1,u_2} & \sigma_{u_2}^2 \end{pmatrix} \tag{14}$$

can be estimated by

$$\hat{\Sigma} = T^{-1} \begin{pmatrix} \sum \hat{u}^2{}_{1,t} & \sum \hat{u}_{1,t}\, \hat{u}_{2,t} \\ \sum \hat{u}_{1,t}\, \hat{u}_{2,t} & \sum \hat{u}^2{}_{2,t} \end{pmatrix} \tag{15}$$

where $\hat{u}_{1,t}$ and $\hat{u}_{2,t}$ are residuals.

Since $u_{1,t}$ and $u_{2,t}$ are contemporaneously correlated (not-orthogonal), I use Cholesky (recursive) orderings described in the methodology section. Without loss of generality, we assume $A_0 = \begin{pmatrix} 1 & 0 \\ -\beta_0 & 1 \end{pmatrix}$ to be a lower triangular matrix that satisfies

$$\Sigma = A_0 A_0' \ \ (\textbf{Cholesky Decomposition}) \tag{16}$$

By construction the error vector ε_t is orthogonal because its variance-covariance matrix is diagonal. Note A_0 is lower triangular, therefore

$$A_0 X_t = \begin{pmatrix} 1 & 0 \\ -\beta_0 & 1 \end{pmatrix} \begin{pmatrix} x_{1,t} \\ x_{2,t} \end{pmatrix} = \begin{pmatrix} x_{1,t} \\ -\beta_0 x_{1,t} + x_{2,t} \end{pmatrix} \tag{17}$$

Equation (17) shows that $x_{2,t}$ will not appear in the regression for $x_{1,t}$, whereas $x_{1,t}$ will appear in the regression for $x_{2,t}$.

It is valid to use Cholesky orderings in this study because of the institutional features of the Federal Reserve: it takes time for the Fed to observe and understand the development in the repo market. Therefore, the Federal Reserve does not react to the repo rate within a day, but it responds with a one-day lag. When the Fed adjusts the federal funds rate, its information set only includes past values of repo and federal funds rates. Contemporaneous repo rate thus has no effect on the federal funds rate. The repo market, in contrast, responds immediately to any changes in the monetary policy because the private sector has a larger information set.

The results are displayed in **Table 4**. The variance decomposition for both series indicates that the federal funds market is more likely to lead to changes in the repo funds market than the other way around. The results are consistent with what Bech et al. (2011) get for the early financial crisis when the Federal Reserve cut the target federal funds rate and provided sufficient reserve balances to preserve ample liquidity. The variance decomposition indicates that the federal funds rate gradually picks up the explanation power of the repo rate, suggesting that repo markets react systematically to news about monetary policy (**Table 4**).

Table 4. The Decomposition of variance (2-variable VAR)

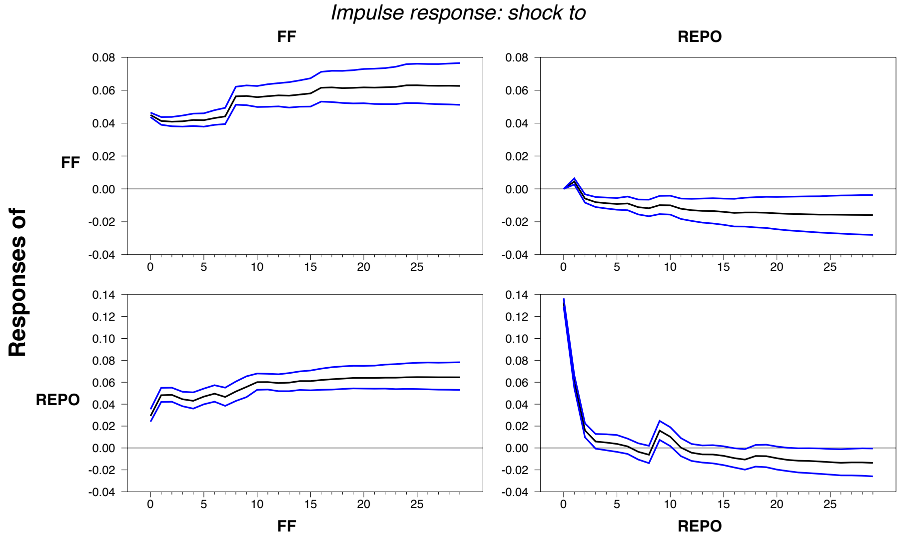
	Fed funds			Repo		
Step	SE	EFFR	Repo	SE	EFFR	Repo
1	0.044	100.00	0.00	0.134	4.51	95.49
2	0.061	99.48	0.52	0.152	12.11	87.89
3	0.073	99.01	0.99	0.160	19.74	80.26
5	0.092	97.20	2.80	0.169	28.25	71.75
10	0.139	94.86	5.14	0.191	42.44	57.56
20	0.226	92.62	7.38	0.251	65.41	34.59
30	0.299	90.83	9.17	0.311	74.96	25.04

Note: The third and fourth column should add up to 100, same as the sixth and seventh column. To calculate the variance decomposition for both series, I use Bayesian bootstrap and handle the antithetic draws differently than the original Monte Carlo Integration of VAR.

The impulse response functions, as shown in **Figure 8.1**, present the reactions of fed funds rate and repo rate in response to an external shock to either series. A one standard deviation shock to target rate generates significant increases in both repo and fed funds rate (determined by which the length of periods for which the SE bands are above 0). In addition, **Figure 8.1.1** indicates that shocks to federal target rate do not permanently narrow or widen repo spread between the federal funds rate and the repo rate: the spread is increased by less than 0.02 percentage point when the shock hits, but it gradually declines back to zero.

Figure 8.1

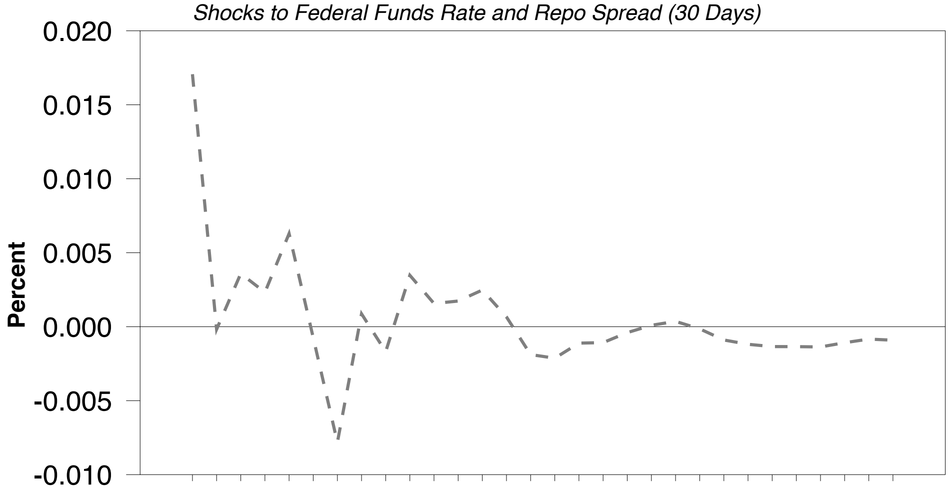
Impulse response: shock to



Note: the impulse response graph places one impulse in each row and one response variable in each column. The horizontal axis for each graph is in the units of time that the VAR is estimated in, in this case, days. Hence, the impulse response graph shows the effect of a shock over a 30-day period. The vertical axis is in the units of the variables in the VAR, in this case, everything is measured in percentage points. The black line plots the impulse response and the blue error bands represent the 95% confidence interval.

Figure 8.1.1

Shocks to Federal Funds Rate and Repo Spread (30 Days)

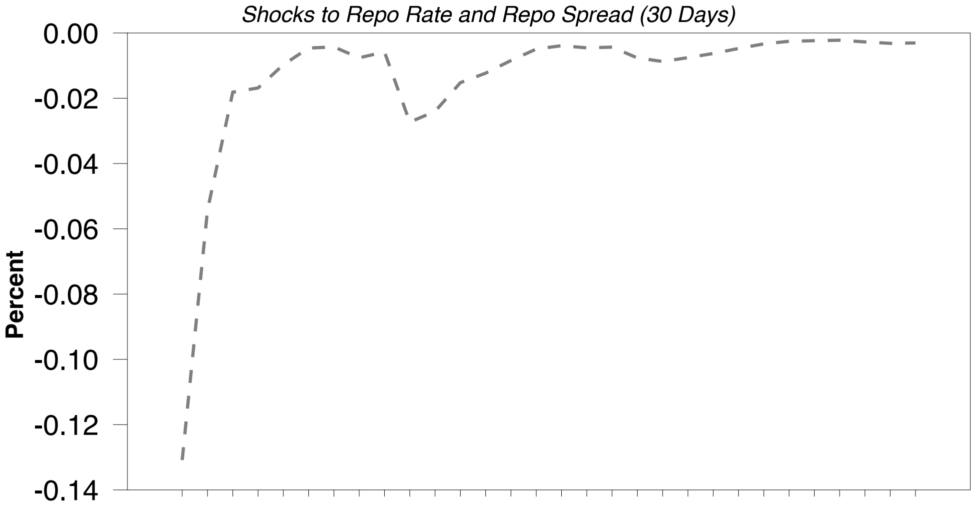


Note: the repo spread is calculated as the subtraction of the overnight repo rate from the federal funds rate.

A one standard deviation shock to repo rate, in contrast, only leads to a transient increase in the fed funds rate. The funds rate declines after one period and stays persistently below zero. Similarly, a positive shock to the repo rate dies out quickly. The impulse responses together suggest that shocks to repo rate significantly widen the repo spread, as **Figure 8.1.2** shows. For the repo rate, the jump in the impulse response after 10 periods indicates some seasonality in the original data series, which reflects the calendar effects mentioned in the preliminary data subsection.

The impulse response graphs in **Figure 8.1** suggest that monetary policy transmission mechanism runs primarily from the Federal funds market to money markets, not vice versa. When the Federal Reserve targets a new federal funds rate, that interest rate becomes a new market-clearing price for the short-term secured financing market as market participants shift reserves from markets to markets to take advantages of the interest rate arbitrage. Cook & Hahn (1989) provides another explanation of the monetary shock persistence: The Federal Reserve makes discrete changes in its federal funds rate target in reaction to new information affecting its policy decisions, such as money growth rates, inflation rates, unemployment, and foreign exchange rates. This makes target changes highly persistent and rarely quickly reversed. When there is an unexpected spike in the repo rates, by contrast, the Fed implements repo operation with a lag to bring rates down to the target range.

Figure 8.1.2

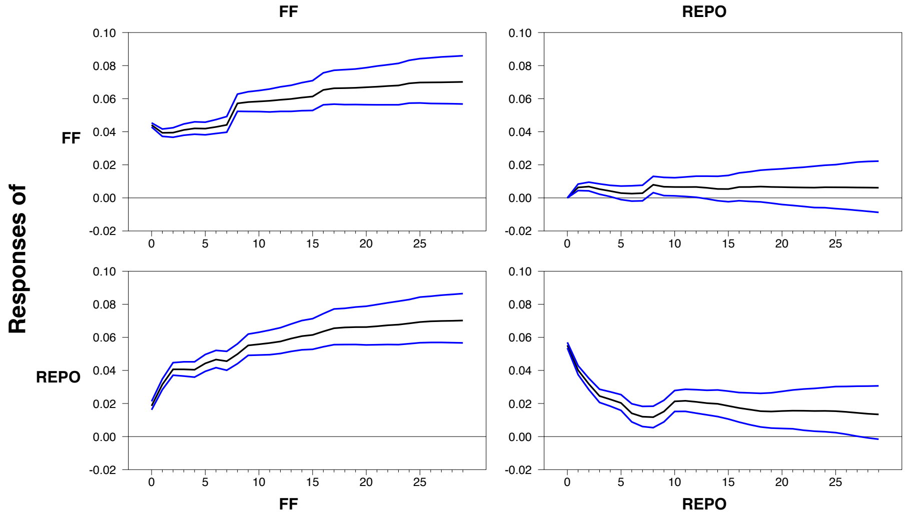


Note: the repo spread is calculated as the subtraction of the overnight repo rate from the federal funds rate. Since there is a positive shock to the repo rate, the spread is negative initially.

To avoid the possibility that the mid-September 2019 market event could potentially bias the results, I redo the entire analysis excluding this short period of time. The results suggest that the cash crunch event does not have a significant impact on the original impulse responses. But it is worth noting that when the event is absent, a positive repo shock dies out for a while but has a persistent effect on its own series and the federal funds rate (**Figure 8.2**). The reasons are straightforward. As described in Section II, the main difference since September 2019 was the greater magnitude of the Fed's intervention in the repo market to bring the costs of overnight financing down. Without Fed's intervention in the money market, a repo shock could have a more long-lasting impact on both the federal funds rate and the repo rate.

Figure 8.2

Impulse response (Mid-Sep 2019 Excluded): shock to



Since the impulse responses one draws from the model are conditional on the ordering of the variables. As a robustness check, I reverse the ordering of the vector of variables to see whether the impulse responses will vary significantly. In this case, I place the repo rate first, and then the federal funds rate. The new Cholesky ordering means that contemporaneous federal funds rate has no effect on the repo rate. The impulse responses with order reversal are displayed in **Figure 8.3**.

The order reversal does not have a significant impact on the impulse responses. A one standard deviation shock to repo rate only generates a transient increase of both repo and federal funds rates. Both series decline to zero over time. The impulses responses together show that repo shocks widen the repo spread (in absolute term) in the short-term, but have a less significant impact on the spread over time (**Figure 8.3.1**). On the contrary, a one standard deviation shock to federal funds rate leads to above-zero rates for both series. What differs **Figure 8.3** from **Figure 8.1** is that when the vector of variables is reversed, a shock to repo rate increases federal funds rate by a larger magnitude. Therefore, when the funds rate subsequently declines, it takes a longer time for the rate to return to baseline (**Figure 8.3.2**).

Figure 8.3

Impulse response (order reversal): shock to

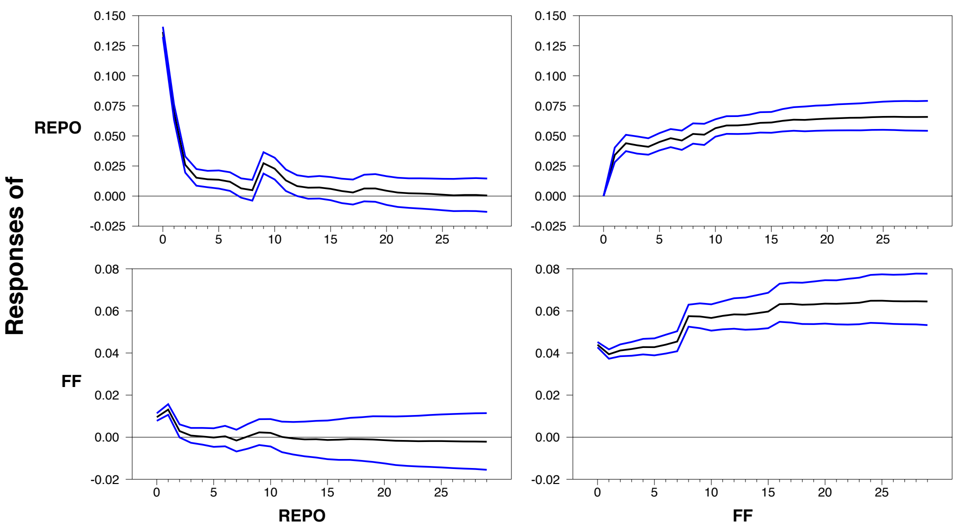


Figure 8.3.1

Shocks to Repo Rate and Repo Spread (30 Days)

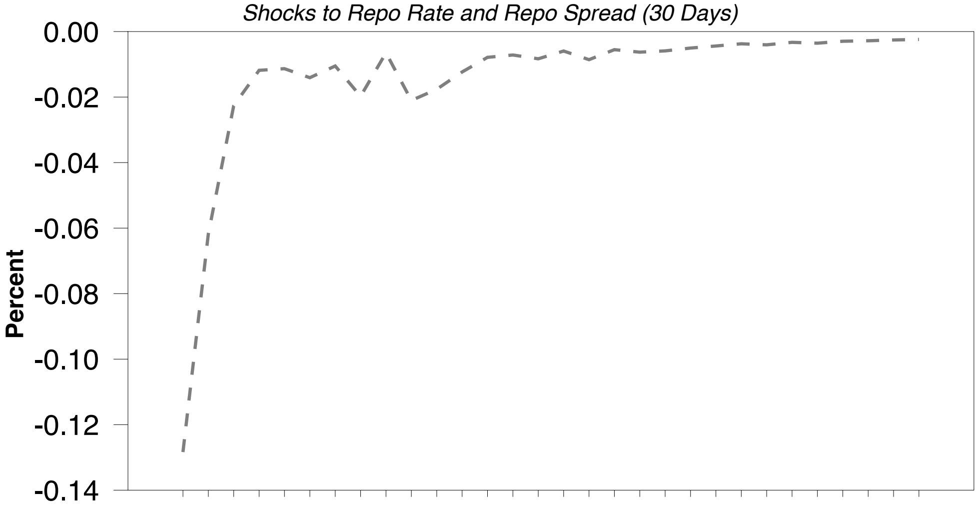
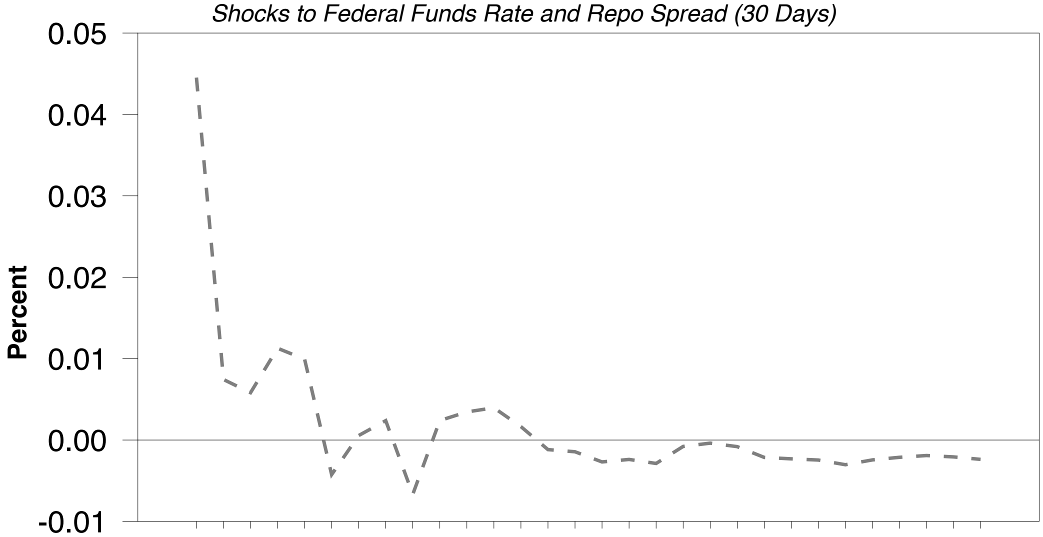


Figure 8.3.2

Shocks to Federal Funds Rate and Repo Spread (30 Days)



Note: A one standard deviation shock increases the repo spread by 0.45 percentage point at the beginning but the increase in spread dies out over time. The increase is significantly lower when the federal funds rate is ordered first, then the repo rate.

iii. Three-Variable Vector Autoregression Model and Robustness Check

In the remaining part of this section, I add another important variable into the VAR model as a different kind of robustness check.

The slope of the yield curve, i.e., the difference between 10-year Treasury bond rate and the 3-month Treasury bond rate, is the leading predictors of future economic growth, inflation, and recessions. Estrella & Hardouvelis (1991, 1997) show that yield curve has predicted essentially every recession in the United States since 1950 with only one false signal, which preceded the credit crunch and slowdown in production in 1967. Not only does the spread contain a great deal of information about the future evolution of the economy, it is also a measure of monetary policy as Bernanke (1990) discovers that interest rate spreads respond to changes in monetary policy. Since an innovation in the slope of the yield curve reflects investor confidence, I envision slope bring in distinct information that might have a bearing on the inferences about monetary policy and repo interactions.

In order to control for shocks in the federal funds rate stemming from contemporaneous or past changes in the investor confidence, I turn the two-variable VAR into a three-variable VAR model by adding the yield spread data. The new model looks like

$$A_0 \begin{bmatrix} x_{1,t} \\ x_{2,t} \\ x_{3,t} \end{bmatrix} = A_1 \begin{bmatrix} x_{1,t-1} \\ x_{2,t-1} \\ x_{3,t-1} \end{bmatrix} + \cdots A_p \begin{bmatrix} x_{1,t-p} \\ x_{2,t-p} \\ x_{3,t-p} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \end{bmatrix} \tag{18}$$

where A_0 is a 3 x 3 matrix with main diagonals normalized to 1. Each A_j $(j = 1,2, \dots p)$ is a 3x3 matrix of coefficients. $x_{1,t}$, $x_{2,t}$, and $x_{3,t}$ are federal funds rate, Treasury yield spread and repo rate, respectively. I adopt Cholesky orderings for identification. The identifying restrictions stem from the institutional features that when the Federal Reserve sets a new target for the federal funds rate, it takes time for the Fed to observe the development in the repo market and the bond market. Therefore, the Fed fails to react to changes in these markets within a day, but it responds with only a one-day lag. Both the Treasury yield spread and the repo rate are sensitive to the contemporaneous changes in federal funds target because market participants in the bond and repo market keep close tabs on monetary policy. The variance decomposition results are displayed in **Table 5**.

Table 5. The Decomposition of variance (3-variable VAR)

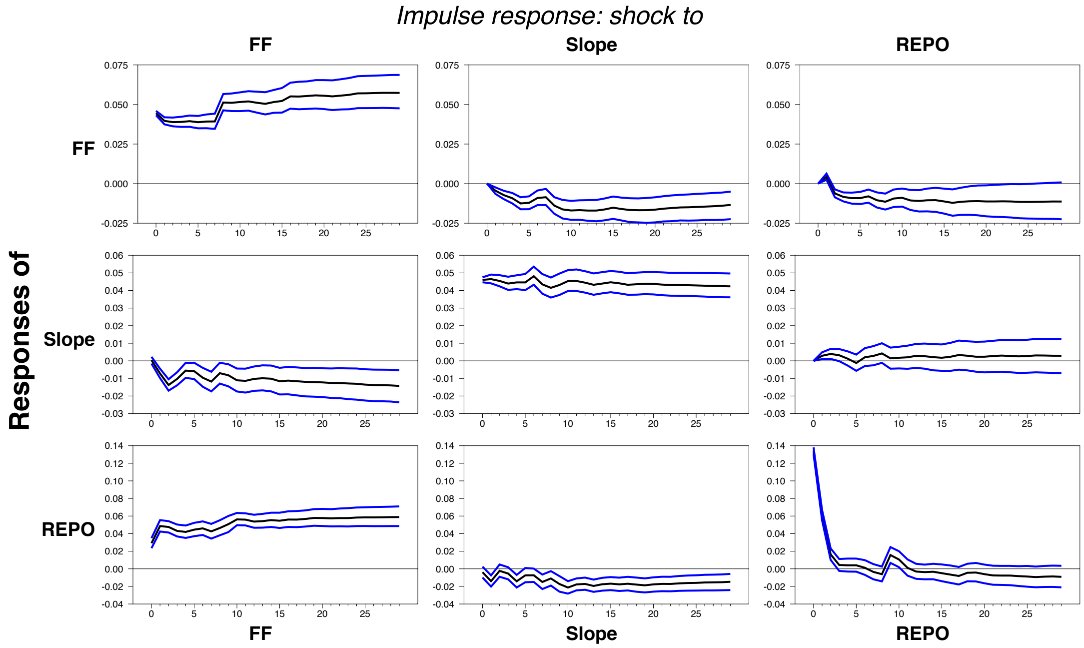
	Fed funds				Slope				Repo rate			
Step	SE	EFFR	Slope	Repo	SE	EFFR	Slope	Repo	SE	EFFR	Slope	Repo
1	0.04	100.00	0.00	0.00	0.04	0.01	99.99	0.00	0.13	4.50	0.07	95.41
2	0.06	98.38	0.69	0.93	0.06	1.54	98.38	0.08	0.16	12.27	0.76	86.97
3	0.07	97.62	1.26	1.12	0.08	4.98	94.61	0.41	0.16	21.21	0.90	77.89
5	0.09	94.71	3.14	2.15	0.10	6.39	93.24	0.37	0.18	32.16	2.36	65.48
10	0.14	91.13	6.92	1.95	0.15	9.40	90.15	0.45	0.21	47.52	5.36	47.12
20	0.22	88.16	10.14	1.70	0.21	11.40	88.37	0.23	0.28	62.70	9.61	27.69
30	0.28	88.35	10.17	1.49	0.26	12.99	86.84	0.17	0.33	69.51	10.41	20.07

The variance decomposition indicates that almost 90 percent of the variability in the federal funds rate or the Treasury yield spread could be explained by its own lags. Exogeneous shocks to repo rate cannot account for the forecast error variance of the federal funds rate or the Treasury yield spread. In contrast, **Table 5** shows that more than half of the variability in the repo rate is explained by the federal funds rate, suggesting that the funds rate is "stronger" in explaining the variability in the repo rate over time. The results are consistent with the results in **Table 4**.

Figure 9.1 shows the impulse response graphs of the 3-variable VAR model. Similar to **Figure 8.1**, a one standard deviation shock to federal funds target rate generates significant increases in both the repo and the fed funds rates even after we have controlled for the contemporaneous changes in the Treasury yield spread. The slope of the yield curve is negatively associated with the federal funds rate when there is a shock to the target rate. In contrast, a one standard deviation shock to repo rate dies out quickly. A shock to repo rate also only leads to a transient increase in the fed funds rate, followed by a persistently lower than zero interest rate. The slope of the yield curve is not significantly affected by a shock to the repo rate, either. Unsurprisingly, a one standard deviation shock to Treasury yield spread leads to a negative federal funds rate.

The result is consistent with Bech et al.'s study as they show that the change in the slope of the yield curve is associated with a negative change in federal funds rates at the 10 percent confidence level.

Figure 9.1

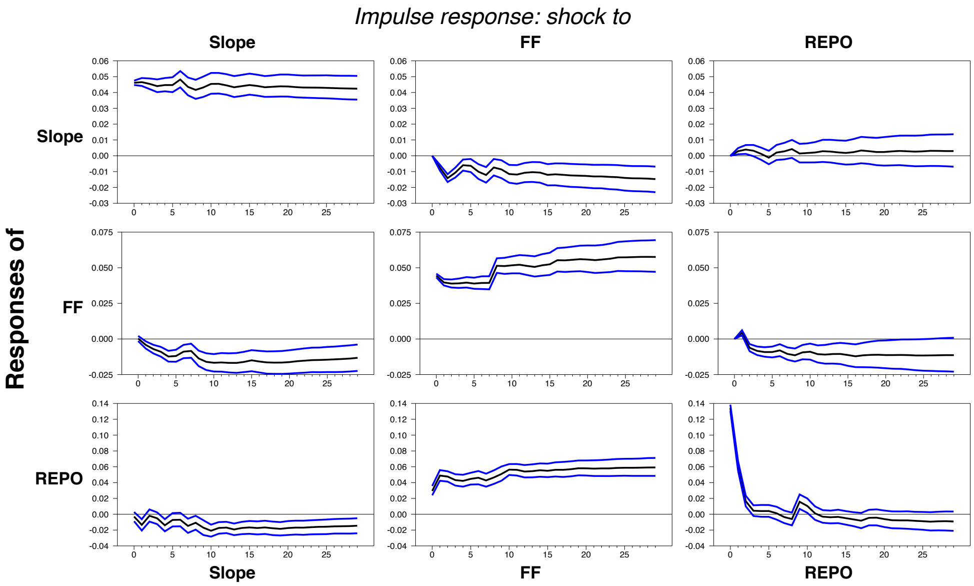


Note: slope data is the subtraction of the 3-month Treasury bill rate from the 10-year Treasury bond rate.

In short, **Figure 8.1** and **Figure 9.1** both show that repo market responses to shocks to the federal funds rate are long-lived, regardless of the contemporaneous change in the slope of the yield curve. On the contrary, the Federal Reserve does not react systematically to shocks to the repo rate. Taken together, it suggests that slope of the yield curve fails to bring in some new information that might have altered the inferences on monetary policy and repo interactions. In addition, **Figure 9.1** further supports the argument that monetary policy transmission only goes from the Federal funds market to money markets, with little evidence of systematic reaction of the funds rate to money markets.

Since the results are conditional on the Cholesky identification, I try another ordering to see whether impulse responses varied much. In this case, I will place the slope of the yield curve first, then federal funds rate, then repo rate. Comparing **Figure 9.2** with **Figure 9.1**, I demonstrate that there is almost no difference with the Cholesky ordering switched.

Figure 9.2



VII. Discussion and Conclusion

In the paper, I describe the post-crisis market activities in the repo market with special emphasis on the mid-September 2019 cash crunch event. In particular, I first use a simple OLS regression and discover that a one percentage point increase in the federal funds rate leads to a 0.6 percent increase in the contemporaneous repo rate, suggesting that the repo market and the Federal funds market are closely connected. I then use a two-variable vector autoregression model to investigate the initial transmission of monetary policy to closely related money markets in a dynamical setting. The results suggest that shocks to the federal funds rate have a significant effect on the path of the repo rate, but shocks to the repo rate have almost no impact on the funds target rate. Several tests, including the reversal of Cholesky ordering, the removal of the mid-September 2019 market event and the addition of Treasury yield spread, indicate that the results are robust. The results suggest that 1) even though monetary tools are closely related, a spiking repo rate may lead to the Federal Reserve's intervention in the repo market via discretionary repo operations. A repo spike does not necessarily precipitate a permanent change in the federal funds rate because an enduring increase or decrease in the funds rate indicates fundamental changes in the economy beyond the temporary turmoil in the financial market. 2) Post-crisis monetary policy is effective in maintaining financial stability as the impulse responses show that shocks to the repo rate fail to generate a persistently wider repo spread between the repo and the federal funds rate. 3) Monetary policy transmission only goes from the Federal funds market to money markets, with little evidence of systematic reaction of the funds rate to money markets. This implies that the funds target could be an effective monetary tool to influence the market clearing price in the repo market.

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