Unconventional Monetary Policy Spillovers and the (In)convenience of Treasuries

Karlye Dilts Stedman *
Federal Reserve Bank of Kansas City

Andrew Hanson †
University of Tennessee, Knoxville

November 8, 2024

Preliminary draft; please do not circulate

ABSTRACT

We examine the changing impact of unconventional monetary policy (UMP) spillovers to the United States term structure of interest rates. Using high frequency data, we find that spillovers to the U.S. yield curve from the European Central Bank (ECB) increased following the Global Financial Crisis, and strengthened when the U.S. normalized policy out of sync with other advanced economies. A shadow rate term structure model suggests that spillovers to the U.S. gained salience during the crisis through growing sensitivity of the term premium to spillovers. In particular, spillovers from the ECB were amplified by a contemporaneous waning in the "convenience" of Treasuries, which heightened their substitutability with Bunds. Among drivers of the convenience yield, higher Treasury issuance, lower intermediation capacity, and deviations of expected inflation from target are all associated with larger spillovers. These findings provide evidence a the portfolio balance channel of transmission that is time-varying based not on the fact or intensity of unconventional monetary policy, but on the non-pecuniary characteristics of Treasuries.

*E-mail: Karlye.Stedman@kc.frb.org.
†E-mail: ahanson8@utk.edu.

1 Introduction

While an abundant body of research documents spillovers from the Federal Reserve to foreign economies, the effects of other central banks' policies on the United States have received limited study.[1] [2] This historical inattention to the U.S. experience of spillovers has stemmed, reasonably, from the confluence of two critical factors. First, the global centrality of the U.S. economy and its financial markets have historically shielded it from the comparatively smaller real and financial ripples generated by other economies' individual monetary policy actions. Lessons from 2008 to the present, however, suggest a second factor interacts with the first. Specifically, the international transmission of monetary policy conducted through conventional (i.e., short-rate-based) channels, like changes in trade, exchange rate dynamics, bank lending and bank balance sheets, are dwarfed by the centrality of the United States in international trade and finance (see e.g., Ehrmann and Fratzscher (2005)).

However, the suite of tools necessitated by the effective lower bound of interest rates (ELB) have coupled with an evolving economic and policy landscape in ways that carry important consequences for the openness of U.S. financial markets to global shocks. In particular, both domestic and international transmission of unconventional monetary policy (UMP) depends crucially on the degree of substitutability between assets, and their relative scarcity. In order for U.S. markets to be shielded from *unconventional* monetary policy spillovers, then, Treasuries must be truly unique. However, seismic shifts in the market for Treasuries has engendered explosive growth in the literature on the changing uniqueness or "convenience" thereof. Although demand for Treasuries has come to be treated as relatively inelastic due of their nonpecuniary properties (see e.g. Krishnamurthy and Vissing-Jorgensen (2012)), recent developments strongly suggests time variation in the elasticity of Treasury demand. This paper explores the extent to which these special properties underlying the convenience of

[1] Although the term "spillovers" could be used to denote the impact of foreign policy on any number of variables, throughout the text we use "spillovers" to refer to the effect of one central bank's monetary policy surprises on another country's sovereign yield curve.

[2] For spillovers from the Federal Reserve, see for example Krishnamurthy and Vissing-Jorgensen (2011), Bauer and Rudebusch (2014), Neely (2015), Fratzscher, Lo Duca, and Straub (2018), Christensen and Rudebusch (2012), Gagnon, Raskin, Remache, and Sack (2011), Hamilton and Wu (2012), D'Amico and King (2013), and Wright (2012). A small but growing body of literature treats spillover effects from the ECB. Fratzscher et al. (2016), Falagiarda, McQuade, and Tirpák (2015), Bluwstein and Canova (2016) explore the effects of the ECB's asset purchase programs on emerging and non-euro European markets, while Georgiadis and Gräb (2016), and Curcuru, De Pooter, and Eckerd (2018) examine spillovers from ECB monetary policy on advanced economy assets.

Treasuries interact with the nature of unconventional monetary policy to govern the degree to which U.S. markets are subject to international spillovers.

In short, this paper documents the magnitude of cross-border spillovers to the United States from the European Central Bank (ECB), with a focus on time-varying channels of transmission. we focus on three key questions. First, how does the sensitivity of Treasuries to foreign monetary policy change over time? Second, what role do term premia play in international transmission compared to more conventional channels? Finally, does mere fact of large scale asset purchases (LSAPs) drive spillovers, or can these dynamics change with the international financial landscape?

To answer these questions, this paper uses high frequency identification to extract intradaily monetary policy surprises from futures contracts and bond yields on the dates of monetary policy announcements in the manner of Kuttner (2001), Gürkaynak, Sack, and Swanson (2005) and others. While a growing literature documents spillovers to the U.S. from unconventional monetary policy (i.e., monetary policy conducted at the effective lower bound), this paper shows not only that the appearance of such spillovers post-GFC can be explained by the portfolio balance channel of transmission, but that spillovers to the United States depend critically on the degree to which Treasuries are considered "special". That is, large spillovers from the ECB resulted not only from the unique features of unconventional monetary policy (UMP), but also because Treasuries became more sensitive to portfolio rebalancing forces. By directly demonstrating the impact of substitutability on the strength of the portfolio balance channel, this paper represents a novel contribution both to the literature on monetary policy spillovers, and to that on the convenience of Treasuries. Importantly, the results herein imply that the United States' historical insulation from monetary policy spillovers is a direct result of exorbitant privilege. As recent work on the determinants of the convenience premium have shown, these benefits of exorbitant privilege are not guaranteed (Du, Hébert, and Li (2023), Acharya and Laarits (2023)).

Focusing first on the slope of the yield curve, we find that spillovers to the United States not only shift from short maturities to long ones at the effective lower bound, but that they also increase in overall magnitude, continuing to expand in the period during which the Federal Reserve pursued its first round of quantitative tightening (QT). Contravening a focus in the spillover literature on the Federal Reserve, we find that the ECB generates substantial spillovers to the long end of the U.S. yield curve (e.g., Ehrmann and Fratzscher (2005); Fratzscher, Duca, and Straub (2016); Brusa, Savor, and Wilson (2020); Mueller, Tahbaz-Salehi, and Vedolin (2017); Rogers, Scotti, and Wright (2014)).[3] Notably, the ECB's measured spillovers in the post-Lehman era actually derive in large part from increases following the start of monetary policy normalization.

Second, to pinpoint the importance of the term premium in driving international transmission, we decompose the zero coupon bond yield into an expected path of short rates and a term premium using the shadow rate term structure model (SRTSM) of Wu and Xia (2016).[4] Results from this yield decomposition suggest that, in almost every case and time period, the term premium drives the bulk of spillovers where they appear. we find that these term premium spillovers are strongest in the period of asynchronous monetary policy normalization, in which the Fed alone engaged in quantitative tightening and moved away from the effective lower bound. Underlying this heretofore under-explored stylized fact is the relationship between spillovers and the "specialness" of Treasuries. In particular, we find that the effect of foreign monetary policy shocks on the U.S. term premium rises when Treasuries become more like other safe sovereign assets (i.e., when the convenience yield on Treasuries falls).

This relationship highlights the unique nature of monetary policy conducted at the effective lower bound. Both domestic and international transmission of UMP via portfolio rebalancing depends crucially on the degree of substitutability between assets. When Treasuries command a substantial convenience premium, the marginal investor impacted by ECB asset purchases may be unwilling to pay the premium needed to substitute European sovereign

[3]Throughout this paper, we follow Bernanke (2009) and others and define quantitative easing as a central bank balance sheet expansion focused on the mix of loans and securities that the central bank holds, with explicit consideration on the effect this composition of assets affects credit conditions. This definition distinguishes the experience of the ECB from the Fed, the Bank of England, and the Bank of Japan. In contrast to these other central banks, the ECB's balance sheet expansion during its early crisis response mainly reflects its increased intermediation role and the growth of its lending to banks, which play a crucial part in financing the Euro area's private sector. While the other central banks orchestrated the growth of their balance sheets as part of their policies of quantitative easing, in the case of the ECB, the discretion of commercial banks and their need for refinancing drove balance sheet expansion. The contraction of the ECB's balance sheet that began in 2012 reflected the banks' declining need for liquidity following the reduction in financial fragmentation in the Euro area (de Sola Perea and Van Nieuwenhuyze (2014)).

[4]The choice of a shadow rate term structure model with daily data further distinguishes this paper from the existing literature by taking into account the influence of the effective lower bound on the expected path of short rates (Kearns, Schrimpf, and Xia (2023); Rogers et al. (2014); Shah (2022)).

bonds for Treasuries, which dampens spillovers to the U.S. term premium. Empirically, we show that this connection between the term premium, spillovers, and the convenience yield is reflected in rising spillovers when Treasuries are plentiful, when inflation expectations lay outside of historical ranges, and when intermediation costs are elevated—all of which are associated with diminished convenience yields. We rationalize these facts using a model of preferred habitat investors in the vein of Gourinchas, Ray, and Vayanos (2022).

This paper contributes to a small but growing literature showing that other advanced economy central banks generate larger spillovers to the U.S. yield curve at the ELB (see e.g. Kearns et al. (2023); Miranda-Agrippino and Nenova (2022); Georgiadis and Gräb (2016); and Curcuru, De Pooter, and Eckerd (2018)). However, this work goes a step further in providing evidence that these large spillovers emanate from the portfolio balance channel insofar as they 1.) largely affect term premia rather than expected short rates, and 2.) relax when the uniqueness of Treasuries is elevated. Thus, spillovers to the U.S. grew during normalization in part because quantitative tightening increases effective net Treasury supply. To our knowledge, this paper is the first to document the importance of Treasuries' special status in determining time-varying spillovers.

Time varying elasticity of demand for Treasuries carries important implications for both fiscal and monetary policy. Pointedly, the results obtained here suggest that ongoing low long-term interest rates (and the resulting inversion of the yield curve) between the GFC and the Covid-19 pandemic can be traced in no small measure to international spillovers from other advanced economies, and that these spillovers were fueled in part by quantitative tightening. The absence of expectations for the Federal Reserve to absorb Treasury issuance effectively increases Treasury supply, which erodes their special status. In addition, monetary policy tightening (whether conventional or unconventional) dampens expected returns on long term Treasuries, and with them private demand. Together, increased supply and weak client demand detracts from the convenience of Treasuries, as dealers and levered investors struggle to accommodate intermediate Treasuries on their balance sheets (Du, Hébert, & Li, 2023).

The remainder of the paper is organized as follows. Section 2 explores the relationship between the channels of monetary policy spillovers at the ELB and the convenience yield, laying out a pattern of time varying spillovers from the ECB to Treasury yields. Section 3 lays out the mechanisms relating the elasticity of demand for Treasuries to the size of spillovers formally in a preferred habitat framework based on Gourinchas et al. (2022). Section 4 presents empirical evidence linking the growth of spillovers to the (in)convenience of Treasuries. Section 5 explores additional potential channels of transmission, and Section 6 concludes.

2 Motivation and Background: Spillovers at the Effective Lower Bound

Over long stretches of history, central banks have largely conducted monetary policy by buying and selling short-term debt and, in most instances, target short-term interest rates. However, at the effective lower bound, the availability of cash as an asset prevents stimulus from decreasing the short-term policy rate indefinitely below zero. Beyond the effective lower bound of interest rates, central banks have enacted a suite of policies such as direct lending, liquidity provision to key credit markets, and large-scale asset purchases in pursuit of their mandates. These large-scale asset purchases, coupled with forward guidance regarding the path of policy, aim specifically to lower long-term interest rates through heavier management of expectations and adjustments to term premia.[5]

To distinguish between conventional and unconventional monetary policy channels, it is convenient and common to consider the yield on an n-period risk-free bond as the average level of short-term interest rates over the maturity of the bond and a term premium:

$$Y_t^{(n)} = \mathbf{E}[\bar{Y}_{t,t+n}|I_t] + YTP_t^{(n)} \tag{1}$$

where $\mathbf{E}[\bar{Y}_{t,t+n}|I_t]$ is the average short-term rate expected to prevail over the period t to $t+n$ (that is, the component of the yield that would drive yield variation if the expectations hypothesis were to hold exactly), and $YTP_t^{(n)}$ is a maturity-specific term premium. The term premium captures the additional required compensation for holding a long-term bond (duration risk), subsuming the price and amount of interest rate risk, inflation risk, and macroeconomic growth risk. Monetary policy enacted through policy rates operates chiefly via the expected

[5] Bernanke, Ben S. (19 November 2013) *Communication and Monetary Policy*. Retrieved from https://www.federalreserve.gov/newsevents/speech/bernanke20131119a.htm

path of short-term interest rates, as compensation for maturity risk shrinks to zero with the maturity of the bond (Hamilton (2009); Sims and Wu (2020)). However, unconventional monetary policy influences both terms of (1), either by signaling the central bank's intention to keep interest rates low over longer horizons, thereby reducing $\mathbf{E}[\bar{Y}_{t,t+n}|I_t]$, or by removing duration risk from the market (decreasing $YTP_t^{(n)}$).

Homing in on the first term of equation 1, expansionary forward guidance lowers the expected path of interest rates by communicating the central bank's intention to keep interest rates low (or to pursue ongoing asset purchases), committing often to a specific time horizon or state of fundamentals. This "signaling" channel carries the potential to generate international spillovers through conventional means like international bank balance sheets, exchange rates, or the current account.

However, as the maturity of an asset increases, the expected path of short interest rates explains less of the yield, in part because uncertainty increases with the time horizon. For this reason, monetary policy at the effective lower bound also aims at decreasing longer term rates by decreasing term premia. While expansionary forward guidance can support the reduction of term premia by reducing interest rate risk, central banks can also directly target longer term interest rates by purchasing long duration assets, thereby reducing the effective supply of such assets raising their prices, lowering their yields, and decreasing the duration risk associated with holding them. As investors rebalance their portfolios in response to large scale asset purchases, the prices of the assets they acquire rise as well, decreasing their respective yields through the term premium and potentially prompting further rebalancing. "Restricted" or preferred habitat investors at home and abroad can amplify this portfolio balancing channel by purchasing additional long-dated assets, even as their prices rise in order to balance long-dated obligations on their balance sheets or to search for yield.[6] In this way, an expansionary monetary policy shock with strong portfolio balance effects has the potential to decrease *international* term premia, specifically at the long end of the yield curve in safe sovereign markets.

In practice, central bank policy rates and sovereign bond yields can be correlated interna-

[6] Shin (2017) provides an illuminating example of long-term bond yield amplification through the duration balancing activities of German insurance firms.

tionally for various reasons, especially among countries with close economic ties. These can emerge through trade flows, or they can comprise information flows that manifest through business cycle comovement (see, for example, Kose, Otrok, and Whiteman (2003)). In this way, foreign monetary policy reveals information on the state of the global economy to which the marginal investor expects the domestic central bank to react. For example, while an episode like the "Taper Tantrum" of 2013 may increase yields by signaling an increase in the path of U.S. interest rates, it also suggests optimism on the part of the FOMC regarding the state of the U.S. economy. This might, in turn, be expected to benefit the global economic outlook, raising yields via projected future growth and, in turn, expected real interest rates. Such informational spillovers can manifest through the expected path of short rates (average path) as well as term premia (volatility) through a "confidence" channel.[7]

2.1 Time varying spillovers

Altogether we should expect, and previous research has shown, that spillovers rise with the global adoption of unconventional monetary policy. However, the literature on unconventional monetary policy transmission suggests that the strength of the portfolio balance channel hinges on a number of economic conditions, and these vary over time. For example, Droste, Ray, and Gorodnichenko (2023) show that local supply effects of Treasury demand shocks are most obvious during periods of elevated risk. That is, LSAPs are less likely to be "spot" effective when the risk bearing capacity of arbitrageurs is high. Given that preferred habitat investors become less willing to substitute to other maturities of the same broad asset when risk bearing capacity is low, we might surmise that willingness to substitute between international markets might be suppressed under these conditions. Similarly, the strength of signaling and confidence channels may vary over time. For example, signals from other central banks leading up to an FOMC decision may become more influential with respect to the expected path of U.S. interest rates in an environment marked by elevated policy uncertainty.

A rolling regression of changes in U.S. interest rates on ECB monetary policy shocks crys-

[7]Conversely, central banks in countries facing expansionary financial spillovers may therefore be expected by the marginal investor to *withdraw* stimulus in the face of increased liquidity from abroad. We would expect the same reaction by central banks if expansionary monetary conditions abroad generally engender expansionary domestic demand conditions through a trade channel.

talizes this point. In the baseline regressions, we use zero coupon bond yield parameters published by the Fed from Gürkaynak, Sack, and Wright (2007).[8]. we use same parameters that produce these zero coupon yields to estimate the term premium and expected path of short rates at various maturities. The sample spans March 2001, to December 2022. Figure 1 depicts estimates from a 700 business day rolling regression of changes in 1-, 5-, and 10-year U.S. zero coupon bond yields on intraday ECB monetary policy shocks. These shocks comprise the first principal component of intraday changes in the yields on a number of assets, measured from 10-20 minutes pre-decision release to 10 - 20 minutes post-press conference, from Altavilla, Brugnolini, Gürkaynak, Motto, and Ragusa (2019). These include 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year German, Italian, French, and Spanish bond yields. Monetary policy surprises derived from the cross-section of yields have the advantage of subsuming policies aimed at different maturities in the yield curve. Such compound measures summarize shocks to the overall stance of monetary policy both at and away from the effective lower bound. For ease of interpretation, we normalize monetary policy surprises to a one standard deviation loosening in all estimates. Appendix Figure 1 displays monetary policy shocks in standard deviations, before loosening normalization.

Several patterns stand out from Figure 1. First, as previous work has shown, spillovers within the period of conventional monetary policy are not statistically different from zero, while the period of unconventional monetary policy is marked by growing spillovers at the longer end of the yield curve. Second, the time period in which spillovers become significant (i.e., when the rolling regressions integrate observations that pull the window's estimate away from zero) varies substantially from the time when the ECB began to engage in LSAPs. In particular, spillovers from the ECB become statistically significant when rolling regressions integrate observations starting in 2010, well before the start of the Expanded Asset Purchase Program (EAPP) in 2015 (and even before the "whatever it takes" speech in the summer of 2012). Moreover, while spillovers from the ECB last through most of the policy response to Covid, they began to dissipate not when the Pandemic Emergency Purchase Program (PEPP) ended in March of 2022, but when the Fed announced a start to LSAP tapering in November 2021. It seems, therefore, that the prevalence of spillovers to the U.S. emanates from more

[8]https://www.federalreserve.gov/pubs/feds/2006/200628/200628abs.html

Figure 1: Time-varying ECB spillovers to the U.S. yield curve

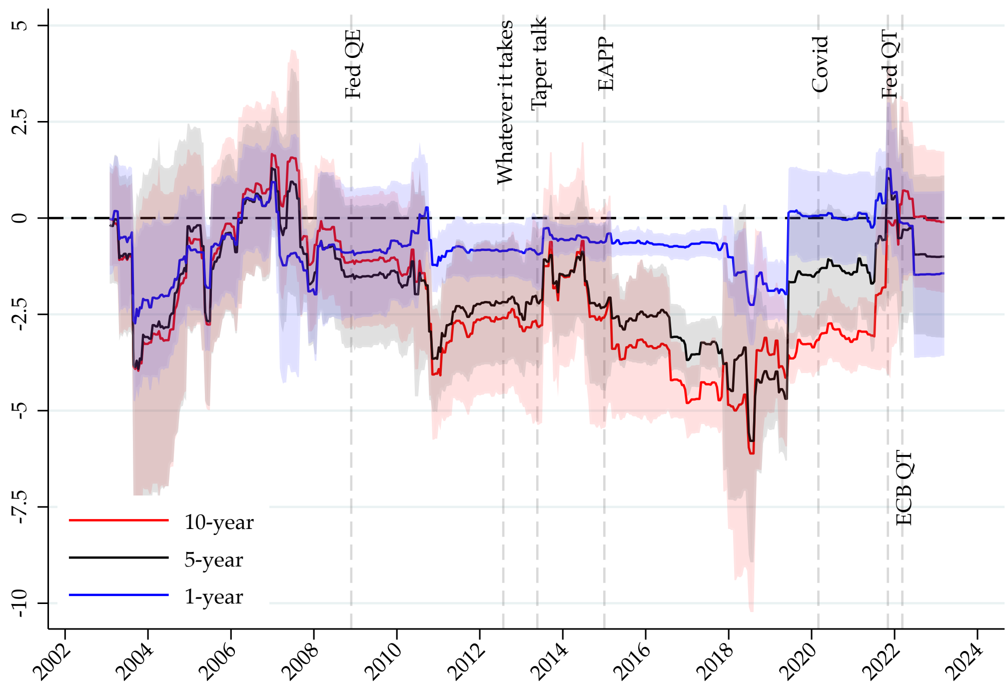


Figure 1 depicts estimates from a 700 business day rolling regression of changes in 1-, 5-, and 10-year U.S. zero coupon bond yields on the z-scores of ECB monetary policy shocks. Shocks comprise the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Shaded areas denote 90% robust confidence intervals.

than the mere fact of ECB LSAPs.

To begin to see why, we return to the decomposition from Equation 1 and repeat rolling regressions with elements of the 10-year yield decomposition as the dependent variable. Figure 2 plots the estimated impact of ECB monetary policy shocks on the 10-year term premium and expected path of short rates. Two features emerge that both validate the importance of the portfolio balance channel and suggest its explanatory power varies. First, during intervals marked by the largest spillovers, term premium effects surpass the expected path of short rates. Second, however, spillovers to the expected path of short rates also increase at various points. In particular, early spillovers from unconventional monetary policy comprise a more even mix of expected path and term premium spillovers, while later spillovers (roughly post-2014) feature larger term premium spillovers. This latter result stands out because the timing overlaps with the announced cessation of U.S. LSAPs; that is, term premium spillovers to the United States feature most prominently when the Federal Reserve is out of sync with other advanced economy central banks, trying to withdraw stimulus while other central banks were stepping on the gas.

Figure 2: Time varying ECB spillovers to the U.S. term premium and expected path of short rates

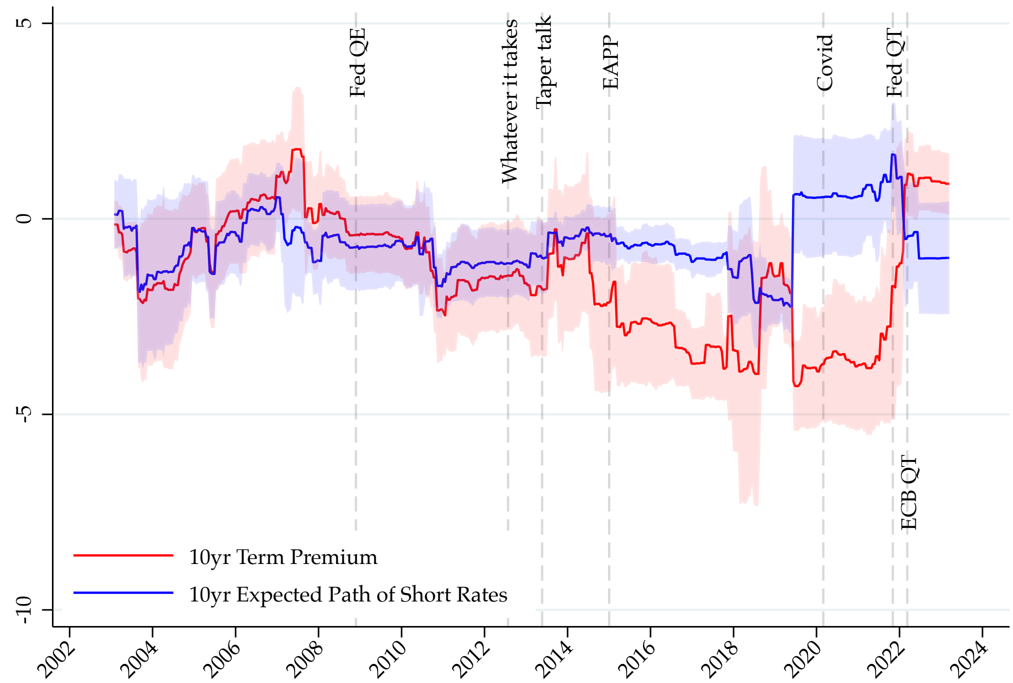


Figure 2 depicts estimates from a 700 business day (24 - 25 announcement) rolling regression of changes in the 10-year U.S. term premium and expected path of short rates on the z-scores of ECB monetary policy shocks. Shocks comprise first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Shaded areas denote 90% robust confidence intervals.

Taken together, these results suggest that taking into account the cross-country nature of unconventional monetary policy through the lens of time varying regimes provides a more nuanced image of international spillovers. While spillovers increase during periods of heavy multilateral large scale asset purchases, the size of spillovers is clearly changing over time. To wit, a Bai Perron unknown breakpoint test suggests *five* structural breaks in the relationship between ECB monetary policy shocks and 10-year Treasury yields.

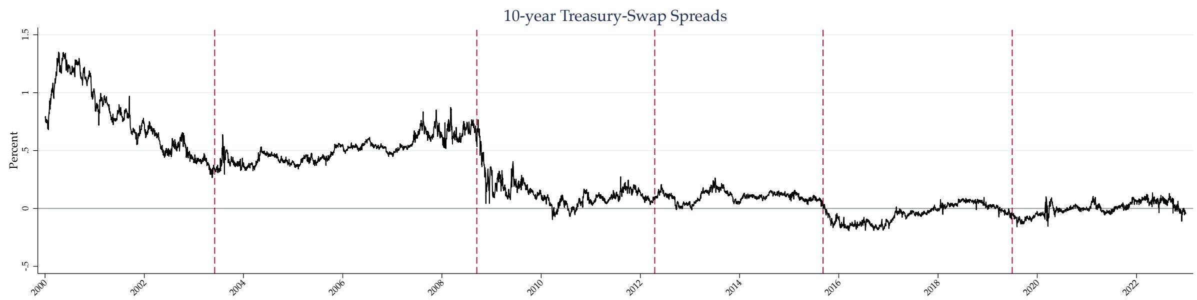
2.2 The changing convenience of Treasuries

The natural question arising from this collection of estimates is: why? The U.S. Treasury market is the world's deepest, most liquid asset market, standing at the center of the U.S. and global financial systems. As a consequence of the dollar's ubiquity in trade and finance, safe dollar-based fixed income assets (and Treasuries in particular) command a premium in their pricing due to structural demand from both domestic and international actors. Brunnermeier, Merkel, and Sannikov (2024) likens safe assets like Treasuries to a "good friend"—always around (i.e., ever valuable and ever tradable, even in the face of an adverse shock). These nonpecuniary properties are reflected in the spread between sovereign bond yields and other risk-free assets of the same maturity and domicile, most commonly represented by the spread between sovereign bond yields and maturity matched overnight index swaps (OIS) or the swap spread.

Prior to the Global Financial Crisis, yields on Treasuries ran below the fixed interest rates on swaps of the same maturity. However, the years following the GFC brought about seismic shifts in the global financial and regulatory landscape, and contemporaneous to those changes emerged a diminution and even reversal of this relationship, shown in black in Figure 3. This attenuation in the convenience yield on Treasuries reflects a degradation in their special status. In the context of international spillovers from monetary policy, the less special are long term Treasuries, the more directly substitutable they are for other risk-free long-duration assets, including other safe sovereign bonds. It is not unreasonable to postulate, therefore, that time variation in the sensitivity of the U.S. yield curve to unconventional monetary policy spillovers may emanate in part from the increased substitutability associated with diminishing non-pecuniary benefits. Put differently, when Treasuries command a large premium in their price, individuals nudged away from their pre-announcement allocation by the yield compression wrought by LSAPs (or the expectation of LSAPs) are unwilling to pay the premium because it prices characteristics not shared by the assets they seek to replace. The more price-sensitive the marginal investor, the lower would be their willingness accept the premium associated with the nonpecuniary benefits of Treasuries, and therefore the lower would be spillovers from foreign monetary policy.

Figure 3: Convenience Yields

(a) US swap spreads



(b) Breakpoints in the convenience yield

Breaks	Mean	Chg. from previous period	LL	UL
Nov 4, 2002	0.50	-0.35	Oct 24, 2002	Nov 15, 2002
Oct 10, 2008	0.12	-0.38	Oct 2, 2008	Oct 18, 2008
May 1, 2012	0.09	-0.03	May 29, 1399	Apr 4, 2625
Nov 19, 2015	-0.04	-0.14	Sep 8, 2014	Jan 29, 2017
Jun 12, 2019	0.00	0.04	Oct 25, 1904	Jan 28, 2134

Figure 3a shows the yield on the 10-year overnight index swap less that of 10-year Treasuries for the convenience yield. Table 3b displays estimated break points from a Bai Perron unknown breakpoint test, the mean of the ten year swap spread between break dates, the change in mean relative to the previous period, and 95% confidence intervals.

3 Model

This section explores the "specialness" of Treasuries as a key buffer of international spillovers to the United States through the lens of the portfolio rebalancing channel. Pointedly, when the ECB announced the public sector purchase program (PSPP) in March of 2015, policy makers explicitly referenced the accompanying fall in yields in terms not only of a reduction of duration risk, but also the "creation of scarcity" (Cœuré (2015)). In the face of increased scarcity, the preferences of habitat investors for the relative safety and liquidity of advanced economy sovereign bonds causes these assets' prices (and those of their closest substitutes) to rise because they cannot easily be replaced (Vayanos and Vila (2021)). Empirical evidence on this front validates the notion that the net supply of debt can explain domestic yields (e.g., Krishnamurthy and Vissing-Jorgensen (2011); Hamilton and Wu (2012); Greenwood and Vayanos (2014); Wolcott (2020); Blattner and Joyce (2020)).

The existence of a portfolio balance channel relies on the notion of partially segmented asset markets. If investors care only about risk-adjusted returns and view assets as otherwise perfect substitutes, then LSAPs would not affect yields at all, including those of domestic sovereign bonds (Curdia and Woodford (2011). On the other extreme, if markets are completely segmented, then LSAPs might pass through to other domestic assets, but would not generate international spillovers. In practice, investors fall between these two extremes. In partially segmented markets, investors view assets in different markets as imperfect substitutes, in which case asset purchases affect yields in both the domestic sovereign bond market and other markets (home and foreign). Taking for granted that markets are partially segmented, we would expect to observe spillovers between safe sovereign bonds of similar maturities. Within this setting, portfolio rebalancing should move funds toward the most similar assets, and away from less similar assets. The substitutability among assets depends, in turn, on the degree to which they confer similar benefits, and on the degree to which investors who do not value the dissimilar benefits are price sensitive. We use the framework laid out in Gourinchas et al. (2022) to formalize these ideas in a two-country model with preferred habitat investors operating in partially segmented markets.

3.1 Comparative Statics in General Equilibrium

Consider the modeling environment of Gourinchas et al. (2022) in which investors maintain preferred investment habitats along yield curves of both foreign- and domestic-issued bonds. We assume the global arbitrage specification of their model and assume the demand curve for j country bonds of τ maturity in period t follows

$$Z_{jt}^{(\tau)} = -\alpha_j(\tau) \log P_{tj}^{(\tau)} - \beta_{jt}^{(\tau)}$$

where the slope term $\alpha_j(\tau)$ is a country-specific, deterministic function of maturity length, but the intercept is time-dependent

$$\beta_{jt}^{(\tau)} = \zeta_j(\tau) + \theta_j(\tau)\,\beta_{jt}$$

The authors solve a general equilibrium model and consider unconventional monetary policy to be shocks to $\beta_{jt}^{(\tau)}$ via the β_{jt} term conditional on $\alpha_j(\tau)$. For full details of the model and solution method we refer the reader to Gourinchas et al. (2022).

Our question extends beyond those of Gourinchas et al. (2022) to examine the implications of a change in country- and maturity-specific demand slopes $\alpha_j(\tau)$. We hypothesize that as preferred habitat marginal investors in a country j's bond of maturity τ become more price-elastic, spillovers (in terms of price) from foreign policy—both conventional and unconventional—should decline. We can think of this as a partial equilibrium effect. However, if demand has become more price-elastic, the equilibrium price should be more appealing to investors displaced from other assets by monetary policy. In this case, the shift in the demand curve will be larger than before for a similar-sized monetary policy shock. This is a general equilibrium effect. Which effect dominates determines whether price-sensitivity exacerbates or insulates the home country's yield curve to foreign policy. A demand function at a given $\{j, t, \tau\}$ becoming more elastic would imply a growing $\alpha_j(\tau) \geq 0$. Specifically, we are concerned with the quantities $\left(\partial^2_{\alpha_k,b} \log P_{jt}^{(\tau)}\right)[\phi_k, h]$ such that $b_t \equiv (i_{Ht}, i_{Ft}, \gamma_t, \beta_{Ht}, \beta_{Ft})^\top$ where for each $j,k \in \{H,F\}$ the quantity should be thought of as a second-order mixed Gateaux differential. We begin by examining the simpler case of $\left(\partial_{\alpha_k} \log P_{jt}^{(\tau)}\right)[\phi_k]$ which describes how the yield curve for each country $j \in \{H,F\}$ changes given a generic change in demand slopes for investors in country $k \in \{H,F\}$. Given a log-affine function of the yield curve conjectured and confirmed by Gourinchas et al. (2022) taking the following form

$$\log P_{tj}^{(\tau)} = -a_j(\tau)^\top q_t - c_j(\tau)$$

such that $a_j(\tau) \in \mathbb{R}^5$ and $c_j(\tau) \in \mathbb{R}$ are functions of model primitives, the following applies:

Definition 3.1. The Gateaux differential of the yield curve with respect to demand slopes is

$$\sum_{k\in\{H,F\}} \left(\partial_{\alpha_k} \log P_{jt}^{(\tau)}\right)[\phi_k] = -\sum_{k\in\{H,F\}} \left(\partial_M a_j(\tau)\right)\left[\left(\partial_{\alpha_k}\mu\right)[\phi_k]\right]^\top \times \left(\partial_{\alpha_k}\mu\right)[\phi_k] \times q_t$$
$$+ \left(\partial_M c_j\right)\left[\left(\partial_{\alpha_k}\mu\right)[\phi_k]\right] \times \left(\partial_{\alpha_k}\mu\right)[\phi_k] + \left(\partial_{\alpha_k} c_j\right)[\phi_k]$$

where $(\partial_M)\left[\left(\partial_{\alpha_k}\mu\right)[\phi_k]\right]$ represents the Gateaux differential operator with respect to M in the direction of $\left(\partial_{\alpha_k}\mu\right)[\phi_k]$, which is itself a matrix-valued Gateaux differential. The matrix M is defined in Gourinchas et al. (2022).

Proof 1. Follows directly from the properties of the Gateaux differential.

As a necessary step, we show in the following lemma that the matrix M defined in Gourinchas et al. (2022) may be locally defined as a function of the demand curve slopes.

Proposition 3.1. The matrix M may be described locally as a functional of $\{\alpha_H(\tau), \alpha_F(\tau)\} \in C^b(\mathbb{R}) \times C^b(\mathbb{R})$, the union of Banach spaces of bounded functions:

$$M = \mu(\alpha_H(\tau), \alpha_F(\tau))$$

in a neighborhood U_1 of some $\alpha_1^0(\tau)$ and U_2 of some $\alpha_2^0(\tau)$ such that the mapping

$$\mu : U_1 \times U_2 \to \mathbb{M}_{5\times 5}$$

is continuous C^1.

Proof 2. See A.1

We now solve for each of the functional derivatives in turn.

Proposition 3.2. The exposure of the log price to shocks varies with the matrix M according to:

$$\left(\partial_M a_j(M,\tau)\right)[H] = -\left(I - e^{-M\tau}\right)^{-1} a_j(M,\tau) \times H \times \left[M^{-1} - \tau \frac{e^{-\frac{\tau}{2}M}}{e^{\frac{\tau}{2}M} - e^{-\frac{\tau}{2}M}}\right]\left(I - e^{-M\tau}\right) \quad (2)$$

Proof 3. See A.2

In order to complete this particular differential, we need to calculate the direction in which the differential should be taken $H = \sum_{k=1}^{2}\left(\partial_{\alpha_k}\mu\right)[\phi_k]$. Because $\mu(\alpha_H, \alpha_F)$ is solved implicitly in equilibrium according to 3.1, this derivative is less straightforward:

Proposition 3.3. The matrix $M = \mu(\alpha_H, \alpha_F)$ varies according to

$$\sum_{k=1}^{2}\left(\partial_{\alpha_k}\mu\right)[\phi_k] = \left\{H + \left\{(\partial_M Y)[H] + (\partial_M Z)[H]\right\}Q\right\}^{-1}\left\{\sum_{k=1}^{2}\int_0^T \phi_k(\tau)\, a_k(\tau) \otimes a_k(\tau)\, d\tau\right\} Q\Bigg|_{H=\sum_{k=1}^{2}\left(\partial_{\alpha_k}\mu\right)[\phi_k], M=\mu(\alpha_1,\alpha_2)}$$

where

$$\left(\partial_{M}Y\right)[H]=\sum_{j=1}^{2}\int_{0}^{T}\left\{\left[\theta_{j}\left(\tau\right)e_{3+j}-\alpha_{j}\left(\tau\right)a_{j}\left(\tau\right)\right]\otimes\left(\partial_{M}a_{j}\right)[H]-\alpha_{j}\left(\tau\right)\left(\partial_{M}a_{j}\right)[H]\otimes a_{j}\left(\tau\right)\right\}d\tau$$

$$\left(\partial_{M}Z\right)[H]=\alpha_{e}M^{-1}\left[HM^{-1}\left(e_{1}-e_{2}\right)\otimes\left(e_{1}-e_{2}\right)+\left(e_{1}-e_{2}-\frac{\theta_{e}}{\alpha_{e}}Me_{3}\right)\otimes\left(e_{1}-e_{2}\right)M^{-\top}H^{\top}\right]M^{-\top}$$

such that e_k represents the kth standard basis of $\mathbb{R}^5$; $Q \equiv a\Sigma \otimes \Sigma \in Sym_5$, $\Gamma \in \mathbb{M}_{5\times 5}$, $\theta_e \in \mathbb{R}$, $\alpha_e \in \mathbb{R}_+$, and $\theta_j(\tau) \in C^b(\mathbb{R})$ are given; and $\otimes$ is the tensor product.

Proof 4. See A.3

Propositions 3.2 and 3.3 describe how changes in the price elasticities at various maturities of the yield curve impact the sensitivity of the yield curve to exogenous shocks $b_t \in \mathbb{R}^5$, both foreign and domestic. In Gourinchas et al. (2022) these shocks represent traditional monetary policy actions, changes in currency demand for the foreign currency, and demand shocks for domestic and foreign bonds irrespective of maturity. These final shocks are used to instrument–along with a well-specified propagation function $\theta_j(\tau)$–for unconventional monetary policy such as quantitative easing. This is more clearly seen using the Vasicek process for q_t specified by Gourinchas et al. (2022):

$$dq_t = \Gamma\left(\bar{q}-q_t\right)dt + \Sigma db_t$$

Consider the impact of a $h_t \in \mathbb{R}^5$ during a period in which the price elasticities are changing according to some $\phi_k(\tau)$ for $k \in \{H, F\}$.

Theorem 3.1. The sensitivity of the yield curve in period $s \geq t$ to monetary policy actions h_t; conventional and unconventional, foreign and domestic; in country $j \in \{H, F\}$ given a change in the price elasticities of demand for domestic bonds $\phi_H(\tau)$ is given by the following mixed functional derivative:

$$\left(\partial^{2}_{\alpha_H,b}\log P^{(\tau)}_{js}\right)[\phi_H,h]=h_t\cdot\left\{\Phi\left(\tau\right)^{\top}\left[I+\exp\left\{-\left(s-t\right)\Gamma\right\}\right]\Sigma\right\}$$

where

$$\Phi\left(\tau\right)=\left(\partial_{M}a_{j}\left(\tau\right)\right)\left[\left(\partial_{\alpha_H}\mu\right)[\phi_H]\right]^{\top}\times\left(\partial_{\alpha_H}\mu\right)[\phi_H]$$

Proof 5. See A.4

Whereas Theorem 3.1 accounts for the change in slope of the yield curve with respect to the shocks, the changing demand elasticities will also impact the level. The final elements needed to characterize the functional derivative are given in the following proposition:

Proposition 3.4. Changing price elasticities impact the level of the yield curve according to

$$\left(\partial_M c_j\right)\left[\left(\partial_{\alpha_k}\mu\right)[\phi_k]\right] \times \left(\partial_{\alpha_k}\mu\right)[\phi_k] + \left(\partial_{\alpha_k} c_j\right)[\phi_k]$$

where individual terms $\left(\partial_M c_j\right)\left[\left(\partial_{\alpha_k}\mu\right)[\phi_k]\right]$ and $\left(\partial_{\alpha_k} c_j\right)[\phi_k]$ are derived in A.5.

3.2 Calibration and Implications

We proceed broadly with the parameter calibrations by Gourinchas et al. (2022).

4 The Portfolio Balance Channel of Spillovers

As a first step to explore the size of spillovers to the U.S. term structure conditional on the (in)convenience of Treasuries, we condition the response of Treasury yields to ECB spillovers on the estimated breakpoints in the ten year swap spread. Columns 1 and 2 use the break dates suggested by a Bai Perron test without additional processing. We see that the breakpoints bookended by Nov. 10, 2008 - Apr. 19, 2012 and by Sep. 28, 2015 - Jul. 8, 2019 are associated with larger yield and term premium spillovers. In contrast, those starting Apr. 19 - 2012 and Jul. 8, 2019 are not. Note, however, that the confidence bounds corresponding to these particular dates in Table 3b are remarkably wide, suggesting that the associated break is small (visual inspection of Figure 3a corroborates such a conclusion). Therefore, columns 3 - 4 repeat the exercise with three break points. This exercise thus offers preliminary evidence that changes in the convenience of Treasuries shifted contemporaneously with the size of spillovers, particularly after momentous changes.

Taking the analysis in a more explicit direction, we regress various segments of the term structure on intradaily ECB monetary policy shocks, interacting the shocks with the level of

Table 1: Spillovers to the 10 year Treasury conditional on regimes of the convenience yield

	Baseline breakdates		**Alternative breakdates**	
	Y_{10}	TP_{10}	Y_{10}	TP_{10}
ECB	0.18	0.01	0.18	0.01
	(0.78)	(0.52)	(0.78)	(0.53)
FFR_{t-1}	-0.02	-0.10	-0.05	-0.12
	(0.36)	(0.24)	(0.35)	(0.24)
Jun 12, 2003=1 × ECB	-1.39	-0.11	-1.38	-0.10
	(1.18)	(0.78)	(1.18)	(0.80)
Nov 10, 2008=1 × ECB	-2.23**	-1.34*		
	(1.10)	(0.72)		
Apr 19, 2012=1 × ECB	-1.64	-0.73		
	(1.68)	(1.11)		
Sep 28, 2015=1 × ECB	-4.89***	-3.66***		
	(1.82)	(1.20)		
Jul 8, 2019=1 × ECB	-2.02	0.53		
	(1.33)	(0.88)		
Nov 10, 2008=1 × ECB			-2.08**	-1.25*
			(1.03)	(0.70)
Sep 28, 2015=1 × ECB			-2.94**	-1.04
			(1.18)	(0.80)
Constant	2.06	2.44**	2.15	2.49**
	(1.61)	(1.06)	(1.60)	(1.08)
Observations	234	234	234	234

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 1 displays estimates regressing changes in 10-year U.S. zero coupon bond yields and term premiaon the z-scores of ECB monetary policy shocks, conditional on a series of date indicators bookended by estimated breakpoints in the convenience yield (see Figure 3b). Shocks comprise first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

the convenience yield in the U.S. and in Germany. In these regressions, we follow the standard practice of controlling for the policy rate in each respective market, as convenience yields and policy rates tend to be highly correlated (Nagel (2016)). In addition, in some specifications we include the spread between maturity-matched Treasury and Bund yields to account for the raw return differential. This allays the valid concern that investors could be dissuaded from substituting into Treasuries from European bonds due solely to a divergence in their returns.

$$\Delta y^{(n)}_{US,t} = \alpha + \beta_1 MP^{ecb}_t + \beta_2 SS^{(n)}_{US,t-1} + \beta_3 SS^{(n)}_{EU,t-1} + \beta_4 MP^{ecb}_t \times SS^{(n)}_{US,t-1} + \beta_5 MP^{ecb}_t \times SS^{(n)}_{i,t-1} + \\ ... + \gamma_1 PR_{t-1} + \gamma_2 (y^{n}_{US,t-1} - y^{(n)}_{EU,t-1}) + \epsilon_{it} \quad (3)$$

As in Figure 3, convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap. $SS^{(n)}_{EU,t-1}$ and $SS^{(n)}_{US,t-1}$ are the n-year swap spreads for Germany and the U.S. ($y^{ois,n}_{i,t-1} - y^{n}_{i,t-1}$), expressed in z-scores, and $y^{(n)}_{US,t}$ is either the yield on the n-year Treasury bond, the n-year term premium, or the expected path of short rates over an n-year horizon. Convenience yields and policy rates enter as the previous day's value, given that convenience yields, Treasury yields, and policy rates are simultaneously determined on announcement days. So, while t indexes ECB announcement days, $t-1$ refers to the day before an announcement. In regressions conditioning on Treasury convenience, PR_{t-1} is the fed funds rate, but when conditioning on the convenience yield of Germany, the ECB's policy rate stands in. To avoid excessive influence of outliers, we estimate parameters by robust regression, using an M-estimator as in (Rogers et al., 2014).

Tables 2 and 3 display the results. Because spillovers are concentrated, both theoretically and empirically, at the longer end of the yield curve, we focus first on estimates for the decomposition of the 10-year yield. Table 2 shows the impact on 10 year yields of a one standard deviation monetary policy shock from the ECB, conditional on the convenience yields on Treasuries and Bunds. Columns 2 - 5 show spillovers to the yield conditioning on the level of the term premium including and excluding various controls, while column 6 shows the preferred specification conditioning on the Treasury-Bund spread instead of convenience yields. We see in columns 2 - 5 that the degree to which a loosening shock from the ECB pulls down longer-term Treasury yields ebbs when the convenience yield on Treasuries rises ($\beta_1 < 0$ and $\beta_4 > 0$), and that the magnitude is remarkably consistent between specifications. Focusing on column 5, when convenience yields are at average levels (i.e., the z-score is equal to zero), a one standard deviation monetary policy shock from the ECB reduces 10 year yields by 2 basis points. When the convenience yield is one standard deviation above the mean, the size of spillovers from the ECB reduces by half.

Table 2: Spillovers to the 10 year Treasury yield, conditional on convenience yields

	(1) Y_{10}	(2) Y_{10}	(3) Y_{10}	(4) Y_{10}	(5) Y_{10}	(6) Y_{10}	(7) TP_{10}	(8) SR_{10}
ECB	-1.46***	-1.76***	-1.74***	-1.97***	-2.01***	-1.37***	-1.09***	-1.01***
	(0.39)	(0.41)	(0.41)	(0.46)	(0.46)	(0.44)	(0.32)	(0.21)
Y_{10}^{us} - Y_{10}^{eu}					-1.91	-1.95	-0.59	-1.29**
					(1.21)	(1.21)	(0.83)	(0.53)
FFR_{t-1}			-0.17		0.60	0.62	-0.08	0.74***
			(0.33)		(0.57)	(0.57)	(0.39)	(0.25)
MRO_{t-1}			-0.49		-1.83	-2.00*	-0.29	-1.51***
			(0.74)		(1.21)	(1.21)	(0.84)	(0.54)
Swap spread_{10}^{US}		0.03	1.13	-0.10	0.96	1.12	0.60	0.15
		(0.45)	(1.40)	(0.46)	(1.48)	(1.48)	(1.02)	(0.66)
Swap spread_{10}^{EU}				-0.66	-0.14	-0.14	0.05	-0.24
				(0.42)	(0.50)	(0.50)	(0.34)	(0.22)
ECB × Swap spread_{10}^{US}		1.11***	1.08***	1.14***	1.09***		0.67**	-0.14
		(0.39)	(0.40)	(0.40)	(0.40)		(0.28)	(0.18)
ECB × Swap spread_{10}^{EU}				0.25	0.29		0.42	-0.15
				(0.37)	(0.38)		(0.26)	(0.17)
ECB × Y_{10}^{us} - Y_{10}^{eu}						-0.54		
						(0.49)		
Constant	0.90**	0.91**	2.00	0.78**	4.38*	4.58**	1.90	2.17**
	(0.38)	(0.38)	(1.39)	(0.39)	(2.28)	(2.28)	(1.58)	(1.01)
Observations	234	230	230	230	230	230	230	230

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 2 displays estimates regressing changes in 10-year U.S. zero coupon bond yields, term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of Treasury and Bund convenience yields. Shocks comprise first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap and are normalized to have zero mean and unit variance. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

To give a sense of the economic significance of this difference, a 2 basis point drop in 10 year yields (which corresponds to the size of the spillover when convenience yields are at their historical average) would fall in the bottom 35% of the unconditional distribution of treasury yield changes. A 3.2 basis point drop, which corresponds to the effect of a one standard deviation loosening estimated when the convenience premium is one standard deviation *below* historical average, would fall in the bottom 26% of the unconditional distribution. Notably, the convenience yield on Bunds does not appear to impact the size of spillovers to the U.S. yield curve. In some sense, this is unsurprising. ECB LSAPs included bonds according to their weight in the capital key, such that Bunds themselves are an incomplete representation of the portfolio characteristics requiring substitution in the event of LSAPs. In contrast to the results obtained from convenience yields, conditioning the impact of ECB shocks on the simple yield spread does not appear to alter the size of the effect (column 6).

Turning to the yield decomposition in columns 7 and 8 shows that the change in the 10 year Treasury yield arises primarily through the term premium, given that the parameter estimate on β_4 is positive and statistically significant for the term premium and not statistically different from zero for the expected path of short rates. A diminution of convenience yields, by increasing the substitutability between Bunds and Treasuries, contributes to an increase in spillovers to the U.S. 10 year term premium because displaced Bund investors increase their demand for Treasuries at a higher rate. This mechanism, both in theory and in the evidence presented in column 8, bears no relation to the expected path of short rates over a ten year horizon.

Table 3 shows regression results across the yield curve, supporting the notion that these mechanisms are unique not only to periods of diminished Treasury convenience, but to the long end of the yield curve in particular. Row 2, columns 3, 6, and 9 match Table 2, row 7, columns 5, 7 and 8; however, adjacent columns 1 - 2 and 4 - 5 show that the yield and term premium effects appear only for longer-duration Treasuries. These patterns lend credence to the notion that conditioning on the convenience yield sheds light on portfolio rebalancing, rather than signaling or confidence, and helps to explain why spillovers from *unconventional* monetary policy grow when the convenience yield ebbs, but dissipated once the ECB resumed the use of *conventional* (i.e., short rate-based) monetary policy tools.

4.1 Policy Decomposition

The baseline analysis uses a measure of monetary policy designed to reflect the changing exercise of monetary policy over time, summarized by one variable. However, given the present

Table 3: Spillovers to the Treasury yield curve, conditional on convenience yields

	Yield			**Term Premium**			**Expected Path of Short Rates**		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Y_1	Y_5	Y_{10}	TP_1	TP_5	TP_{10}	SR_1	SR_5	SR_{10}
ECB	-0.63***	-1.94***	-2.01***	-0.38***	-1.06***	-1.09***	-0.10	-1.17***	-1.01***
	(0.20)	(0.45)	(0.46)	(0.11)	(0.29)	(0.32)	(0.21)	(0.24)	(0.21)
ECB $\times SwapSpread_n^{(US)}$	0.51**	0.38	1.09***	0.02	0.31	0.67**	0.00	0.00	-0.14
	(0.22)	(0.30)	(0.40)	(0.12)	(0.19)	(0.28)	(0.23)	(0.16)	(0.18)
ECB $\times SwapSpread_n^{(i)}$	-0.30*	-0.03	0.29	0.04	0.11	0.42	-0.45***	-0.03	-0.15
	(0.16)	(0.33)	(0.38)	(0.08)	(0.20)	(0.26)	(0.16)	(0.17)	(0.17)
Constant	0.40	2.18	4.38*	0.45	0.96	1.90	-1.61***	1.54**	2.17**
	(0.54)	(1.45)	(2.28)	(0.29)	(0.91)	(1.58)	(0.56)	(0.78)	(1.01)
Observations	230	230	230	230	230	230	230	230	230

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3 displays estimates regressing changes in 1- 5, and 10-year U.S. zero coupon bond yields, term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of Treasury and Bund convenience yields. Shocks comprise first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap and are normalized to have zero mean and unit variance. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses. All regressions include the controls listed in Table 2, column 6.

focus on the differing mechanisms brought to bear by conventional versus unconventional monetary policy tools, it makes good sense to decompose the baseline results into long-rate-based and short-rate based tools as best we can. To that end, we follow Swanson (2021) in generating a three-part monetary policy shocks in the following manner.

First, we extract the surprise component of the decision about the target rate based on the change in yield on the one-month ahead OIS futures contracts on the dates of monetary policy announcements, which we label the "target surprise". Next, we take the residual from a regression of the announcement day change in the implied yield on the 24 month ahead futures contracts on the three-month Euro Interbank Offered Rate onto the target surprise and label this the "forward guidance surprise". Finally, we take the residual from a regression of the announcement day change in the 10 year bond futures onto the target and forward guidance surprises. This "LSAP surprise" is intended to capture changes in long-term interest rates that are associated with announcements related to large-scale asset purchases. As large scale purchases begin strictly after November 2008 for each case except for Japan, we restrict this monetary policy surprise measure to equal zero before then as in Swanson (2021) and Rogers, Scotti, and Wright (2018).

With these measures in hand, we regress 1-, 5-, and 10-year yields, term premia and expected path of short rates on the three-part shock in the full sample, shown in Table 4. This exercise underlines the notion that spillovers from unconventional monetary policy operate chiefly through the term premium.

Table 4: Spillovers to the U.S. yield curve, by shock duration

	Yield			**Term Premium**			**Expected Path of Short Rates**		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Y_1	Y_5	Y_{10}	TP_1	TP_5	TP_{10}	SR_1	SR_5	SR_{10}
Target EU	0.04	-0.33	-0.32	-0.32***	-0.49**	-0.29	0.78***	0.33	0.17
	(0.18)	(0.36)	(0.38)	(0.10)	(0.23)	(0.27)	(0.21)	(0.20)	(0.17)
Path EU	-1.18***	-2.38***	-2.05***	-0.10	-0.68***	-0.68**	-1.27***	-1.40***	-1.25***
	(0.19)	(0.37)	(0.40)	(0.11)	(0.24)	(0.28)	(0.22)	(0.21)	(0.18)
LSAP EU	-0.05	-0.27	-0.61*	-0.42***	-0.44**	-0.51**	0.21	0.08	0.03
	(0.16)	(0.32)	(0.35)	(0.09)	(0.21)	(0.24)	(0.19)	(0.19)	(0.15)
Constant	0.09	0.52	0.83**	0.37***	0.71***	0.81***	-0.27	0.03	0.12
	(0.17)	(0.35)	(0.38)	(0.10)	(0.23)	(0.26)	(0.20)	(0.20)	(0.17)
Observations	237	237	237	237	237	237	237	237	237

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

(a) Conditional on negative convenience premium

	Yield			**Term Premium**			**Expected Path of Short Rates**		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Y_1	Y_5	Y_{10}	TP_1	TP_5	TP_{10}	SR_1	SR_5	SR_{10}
Target EU	0.17	-0.37	-0.31	-0.30***	-0.38	-0.25	0.77***	0.31	0.13
	(0.19)	(0.36)	(0.38)	(0.11)	(0.24)	(0.26)	(0.21)	(0.21)	(0.17)
Path EU	-1.30***	-2.51***	-2.29***	-0.10	-0.83***	-0.85***	-1.15***	-1.23***	-1.15***
	(0.21)	(0.40)	(0.42)	(0.12)	(0.26)	(0.29)	(0.24)	(0.23)	(0.19)
LSAP EU	-0.21	-0.10	0.18	-0.22*	0.08	0.26	-0.09	-0.08	0.02
	(0.22)	(0.43)	(0.45)	(0.13)	(0.28)	(0.31)	(0.25)	(0.24)	(0.21)
$\mathbb{1}[Y_n > OIS_n]$=1	0.13	1.09	2.50**	0.75**	1.63**	2.44***	-0.71	-0.29	0.19
	(0.56)	(1.11)	(1.19)	(0.32)	(0.72)	(0.82)	(0.64)	(0.63)	(0.54)
$\mathbb{1}[Y_n > OIS_n]$=1 × Path EU	0.49	-0.12	0.38	0.78**	0.37	0.61	-0.44	-0.95	-0.51
	(0.55)	(1.06)	(1.11)	(0.31)	(0.68)	(0.77)	(0.62)	(0.60)	(0.50)
$\mathbb{1}[Y_n > OIS_n]$=1 × LSAP EU	0.20	-0.26	-1.41**	-0.54***	-1.10**	-1.75***	0.65	0.61	0.10
	(0.35)	(0.67)	(0.70)	(0.20)	(0.43)	(0.49)	(0.39)	(0.38)	(0.32)
Constant	0.60	2.25**	3.46**	0.46*	0.82	1.32	-0.17	0.70	1.23*
	(0.46)	(1.10)	(1.39)	(0.26)	(0.71)	(0.96)	(0.52)	(0.62)	(0.63)
Observations	233	233	233	233	233	233	233	233	233

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4 Table 4a

4.2 Drivers of the Convenience Yield

Exploring the changing factors underlying the specialness of Treasuries offers additional insights about the changing nature of spillovers from unconventional monetary policy and helps to validate the properties of Treasuries as a key driver of the strength of spillovers. The literature on the Treasury's convenience yield offers competing (and complementary) views as to what it prices. This subsection explores some of the most commonly cited drivers underlying the changing convenience of Treasuries: net Treasury issuance, balance sheet constraints, and inflation risk.

A number of key contributions in this literature emphasize the net supply of Treasuries, showing that a relative increase in the supply of Treasury bonds makes them less special (Krishnamurthy and Vissing-Jorgensen (2012); Du, Im, and Schreger (2018)). Additional issuance, or the cessation of central bank purchases, eases the scarcity of sovereign bonds, thereby lowing convenience yields. Figure 4 bears this relationship out in striking fashion.

Figure 4: Debt Supply and the Convenience Yield

United States | Euro Area

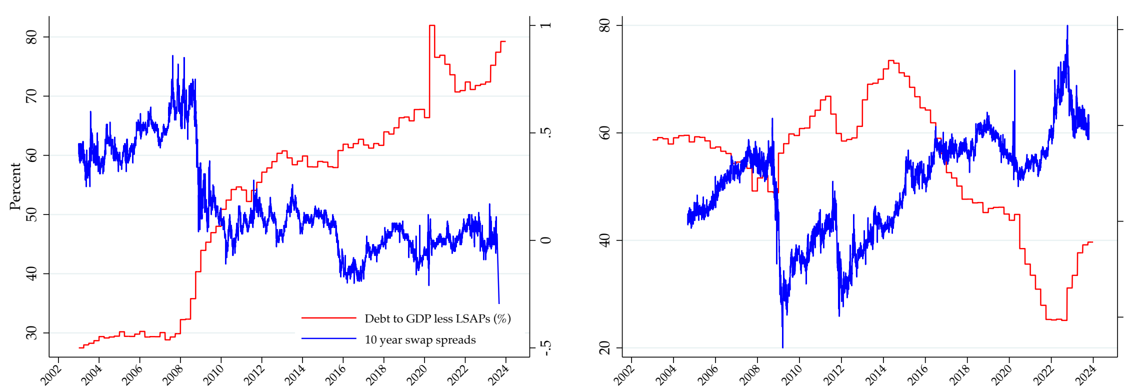


Figure 4 depicts government debt outstanding in the United States and in the Euro area as a percent of GDP, less holdings by the Fed and the ECB respectively, in red. Blue lines depict the 10 year swap spread on Treasuries and Bunds.

Linking debt supply to time variation in spillovers, Table 5 shows the impact of ECB monetary policy shocks conditioning on the previous quarter's outstanding sovereign debt (net of central bank purchases) as a percent of GDP, again controlling for the lagged level of the policy rate and the Treasury-Bund spread. Here again, we limit the results to 10-year yields to economize on space, although additional results appear in the appendix.

Table 5: Spillovers to the 10 year Treasury yield, conditional on net bond supply

	(1) Y_{10}	(2) Y_{10}	(3) Y_{10}	(4) Y_{10}	(5) Y_{10}	(6) TP_{10}	(7) SR_{10}
ECB	-1.46***	-1.66***	-1.65***	-1.65***	-1.75***	-0.72**	-1.08***
	(0.39)	(0.40)	(0.40)	(0.41)	(0.41)	(0.28)	(0.18)
Float/GDP (US)		-0.19	-0.43	-0.22	-0.23	0.07	-0.36
		(0.38)	(0.49)	(0.86)	(0.99)	(0.68)	(0.43)
FFR_{t-1}			-0.21	-0.18	0.54	-0.17	0.73***
			(0.29)	(0.37)	(0.57)	(0.39)	(0.25)
Y_{10}^{us} - Y_{10}^{eu}				-0.27	-1.56	-0.28	-1.31**
				(0.80)	(1.17)	(0.80)	(0.51)
Float/GDP (EU)					0.25	0.18	-0.07
					(0.54)	(0.37)	(0.23)
MRO_{t-1}					-1.25	0.23	-1.56***
					(0.88)	(0.60)	(0.38)
ECB $\times$ Float/GDP (US)		-0.94**	-0.94**	-0.94**	-0.87**	-0.39	-0.01
		(0.40)	(0.40)	(0.40)	(0.41)	(0.28)	(0.18)
Constant	0.90**	0.90**	1.24**	1.41**	3.16*	0.85	2.35***
	(0.38)	(0.38)	(0.56)	(0.64)	(1.61)	(1.10)	(0.70)
Observations	234	234	234	230	228	228	228

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5 displays estimates regressing changes in 10-year U.S. zero coupon bond yields, term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of U.S. and Euro area debt outstanding (less central bank purchases) as a percent of GDP, expressed in z-scores and lagged one quarter. "Float/GDP" in the table refers to debt outstanding that is available to the public (e.g., net of central bank holdings). Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year sovereign bond yields. Estimates are obtained using Huber biweights, robust standard errors appear in parentheses.

We see in each specification of Table 5 that spillovers to U.S. yields grow when the net supply of Treasuries rises. Column 5 suggests that a one standard deviation ECB monetary policy shock when debt outstanding (less Fed holdings) is at historical averages decreased the 10 year Treasury yield by 1.75 basis points. When the publicly available debt stock increases one standard deviation over historical average (about 7.6 percentage points), the impact of an ECB monetary policy shock rises by 50 percent (from 1.75 basis points to 2.62 basis points).

Columns 6 - 7 suggest that this impact likely arises from term premia, although the point estimates are statistically insignificant. The full set of specifications can be found in Appendix Table 6.

A complementary strand of literature highlights the importance of balance sheet constraints among primary dealers and arbitrageurs in causing Treasuries to become "inconvenient" after the GFC (Klingler and Sundaresan (2023); Jermann (2020); Duffie (2023)). In particular, Du, Hébert, and Li (2023) and Klingler and Sundaresan (2023) draw a tight link between falling convenience yields and the breakdown in covered interest parity (CIP) observed post-crisis. we follow Du, Hébert, and Huber (2023) in measuring the shadow cost of intermediary constraints using violations of CIP, conditioning the impact of monetary policy shocks on the first principal component of the lagged CIP deviations (in absolute value) of the U.S. dollar against G10 currencies. Table 6 displays parameter estimates for the 10-year Treasury yield.

Keeping in mind that G10 CIP deviations are measured as absolute deviations from zero, these results suggest that spillovers from the ECB become larger when intermediary constraints assert themselves (i.e., when CIP deviations move away from zero). The parameter values suggest that a change in CIP deviations from average to one standard deviation below historical average is associated with the spillovers from a one standard deviation monetary policy shock increasing in magnitude from 1.87 basis points to 2.81 basis points. Consulting columns 5 - 6, the impact of balance sheet constraints is weighted heavily toward the term premium. Appendix table 8 corroborates the impact of institutional constraints, showing that term premium spillovers are also larger in the last three weeks of the quarter.

Alternatively, a number of authors name inflation risk as a key driver of the convenience yield. We should expected to see larger spillovers through term premia when inflation expectations are less well anchored because the stability of Treasuries' real value is a critical element supporting their special status, and thus the convenience premium. To test the relationship between inflation anchoring and spillovers, we condition the impact of ECB monetary policy shocks on a simple measure of anchored inflation expectations. Following Gürkaynak, Levin, and Swanson (2006), we measure inflation expectations using the 9-year 1-year forward rate on nominal Treasuries less the 9-year 1-year forward rate on TIPS. we first test the

Table 6: Spillovers to the 10 year Treasury yield, conditional on intermediary constraints

	(1) Y_{10}	(2) Y_{10}	(3) Y_{10}	(4) Y_{10}	(5) TP_{10}	(6) SR_{10}
ECB	-1.46***	-1.84***	-1.84***	-1.87***	-0.81***	-0.88***
	(0.39)	(0.41)	(0.42)	(0.41)	(0.28)	(0.19)
10yr G10 CIP deviations		0.23	0.27	0.76	0.58	0.04
		(0.37)	(0.50)	(0.60)	(0.41)	(0.28)
FFR_{t-1}			0.03	0.14	0.16	-0.02
			(0.30)	(0.32)	(0.22)	(0.15)
Y_{10}^{us} - Y_{10}^{eu}				-0.78	-0.90**	0.08
				(0.54)	(0.37)	(0.25)
ECB × 10yr G10 CIP deviations		-0.86**	-0.87**	-0.94**	-0.60*	-0.12
		(0.44)	(0.44)	(0.44)	(0.31)	(0.21)
Constant	0.90**	0.91**	0.86	1.39**	1.33***	0.10
	(0.38)	(0.38)	(0.57)	(0.62)	(0.43)	(0.29)
Observations	234	233	233	229	229	229

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6 displays estimates regressing changes in 10-year Treasury yields on ECB monetary policy shocks, conditional the first principal component of G10 cross currency bases against the USD, expressed in z-scores and lagged by one calendar day. Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year sovereign bond yields. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

impact of spillovers conditioning on an indicator equal to one if inflation expectations lie outside the historical interquartile range:

$$\Delta y_{US,t}^{(n)} = \alpha + \beta_1 \mathbb{1}[\pi_t^e \notin \{Q25, Q75\}] + \beta_2 MP_t^{ecb} + \beta_3 \mathbb{1}[\pi_t^e \notin \{Q25, Q75\}] \times MP_t^{ecb}$$
$$... + \gamma_1 PR_{t-1} + \gamma_2 (y_{US,t-1}^{n} - y_{EU,t-1}^{(n)}) + \epsilon_{it} \quad (4)$$

Where $y_{it}^{(n)}$ is either the yield on the n-year Treasury bond, the n-year term premium, or the expected path of short rates over an n-year horizon. we use the out-of-range indicator for two reasons. First, dummy interactions are easier to interpret. Second, and more importantly, the direction of inflation expectations' movement only signifies un-anchoring if 1.) expectations are moving away from the target and 2.) the magnitude of the deviation is outside some acceptable band.

Table 7 displays the results. Column 4 reflects the full specification (equation 4), suggesting that spillovers to the 10-year Treasury yield grow larger when inflation expectations are outside the interquartile range. Figure 5 plots the measure of inflation expectations, along with the 25^{th} and 75^{th} percentiles of those expectations. From this figure it becomes clear that inflation expectations deviated most from the interquartile range (IQR) from 2015 to the spring of 2021, when the rolling regressions suggest spillovers were largest. However, the literature on stock-bond correlations and inflation expectations tend to emphasize increases in inflation expectations as a driving factor eroding the convenience yield. We see in the figure that inflation expectations breached the 75^{th} percentile frequently before 2012, when spillovers were smaller in magnitude.

Figure 5: Inflation expectations from 9y 1y forward rates

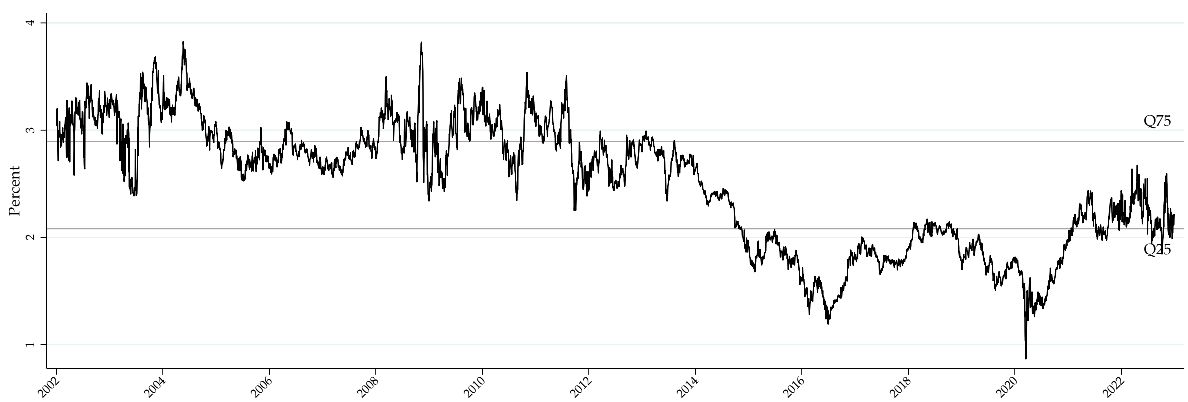


Figure 5 shows inflation expectations as proxied by the spread between nominal and TIPS 9-year 1-year foward rates.

To test whether being above or below that band drives the effect, we split the estimate into above-IQR and below-IQR indicators. Table 7, column 5 suggests that periods with inflation expectations either above the 75^{th} percentile or below the 25^{th} are associated with enlarged spillovers. Although the point estimate associated with below-25^{th} percentile readings is larger, a Wald test cannot reject the null hypothesis that the impact of spillovers is equally large above and below the interquartile band.

$$\Delta y^{(n)}_{US,t} = \alpha + \beta_1 \mathbb{1}[\pi^e_t \geq Q75] + \beta_2 \mathbb{1}[\pi^e_t \leq Q25] + \beta_3 MP^{ecb}_t + \beta_4 \mathbb{1}[\pi^e_t \geq Q75] \times MP^{ecb}_t$$
$$... + \beta_5 \mathbb{1}[\pi^e_t \leq Q25] \times MP^{ecb}_t + \gamma_1 PR_{t-1} + \gamma_2 (y^n_{US,t-1} - y^{(n)}_{EU,t-1}) + \epsilon_{it} \quad (5)$$

The above- and below-IQR indicators flattens variation in a key sense: the only period of below-band inflation expectations corresponds almost exclusively to the period of largest spillovers following the adoption of the EAPP. To return some variation to the analysis, we add the level of lagged inflation expectations in columns 6 - 8, expressed in z-scores. This exercise estimates the impact of spillovers conditional on the level of inflation expectations when expectations are running high (higher risk of upward unanchoring), versus when expectations are low (higher risk of downward unanchoring). The last row of table 7 shows that an increase in inflation expectations contributes to spillovers from the ECB only when expectations are above the 75^{th} percentile, while a change in inflation expectations when they lie below the 25^{th} does not add to (or subtract from) spillovers. Columns 7 and 8 show that the impact is divided evenly between the term premium and the expected path of short rates.

Taken together, this evidence adds support to the notion that the convenience of Treasuries alters the impact of spillovers through the portfolio balance channel—developments that erode the "specialness" of Treasuries are associated with larger spillovers from the ECB. At the same time, the occasional presence of an effect through the expected path of short rates points to the existence of an international signaling channel between the ECB and the Fed. For example, it appears as though high upside unanchoring risk causes market participants to more forcefully update their expectations of Fed actions in response to "news" generated by the ECB. The danger of unanchored inflation expectations is well known, and a credible Fed might be perceived as having a stronger incentive to act on the revelation of global news. we turn to the possibility that spillovers derive from the release of market news in the next section.

Table 7: Spillovers to the 10 year Treasury yield, conditional on inflation anchoring

	(1) Y_{10}	(2) Y_{10}	(3) Y_{10}	(4) Y_{10}	(5) Y_{10}	(6) Y_{10}	(7) TP_{10}	(8) SR_{10}
ECB	-1.46***	-0.34	-0.35	-0.30	-0.33	-0.60	0.17	-0.53**
	(0.39)	(0.50)	(0.50)	(0.50)	(0.51)	(0.59)	(0.40)	(0.27)
$\pi^e \notin \{Q25, Q75\}$=1		-1.31*	-1.51*	-1.51*				
		(0.75)	(0.78)	(0.78)				
FFR_{t-1}			-0.19	-0.26	-0.21	-0.24	-0.03	-0.13
			(0.23)	(0.23)	(0.24)	(0.25)	(0.17)	(0.11)
Y_{10}^{us} - Y_{10}^{eu}				-0.19	-0.95	-0.94	-1.45***	0.38
				(0.44)	(0.65)	(0.81)	(0.56)	(0.37)
$\pi^e > Q75$=1					-2.50**	1.37	-0.65	1.36
					(0.97)	(2.68)	(1.84)	(1.22)
$\pi^e < Q25$=1					-0.04	-2.24	-0.85	-1.56
					(1.27)	(3.29)	(2.26)	(1.50)
$\pi^e \notin \{Q25, Q75\}$=1 × ECB		-2.90***	-2.90***	-2.97***				
		(0.79)	(0.79)	(0.78)				
$\pi^e > Q75$=1 × ECB					-2.66***	3.32	2.85	1.41
					(0.88)	(3.85)	(2.64)	(1.76)
$\pi^e < Q25$=1 × ECB					-3.26***	-5.61	-6.41	0.66
					(1.23)	(3.67)	(5.99)	(3.98)
π^e_{t-1}						-0.32	-1.21	0.38
						(1.67)	(1.15)	(0.76)
ECB × π^e_{t-1}						1.03	-0.22	1.13**
						(1.23)	(0.85)	(0.56)
$\pi^e < Q25$=1 × π^e_{t-1}						-1.32	-0.10	-0.87
						(2.83)	(1.94)	(1.29)
$\pi^e < Q25$=1 × ECB × π^e_{t-1}						-2.58	-2.34	-0.18
						(2.30)	(4.31)	(2.86)
$\pi^e > Q75$=1 × π^e_{t-1}						-2.75	0.15	-1.83
						(2.63)	(1.81)	(1.20)
$\pi^e > Q75$=1 × ECB × π^e_{t-1}						-6.45*	-3.82*	-3.26**
						(3.36)	(2.30)	(1.53)
Constant	0.90**	1.46***	1.87***	2.14***	2.60***	2.64***	2.39***	0.30
	(0.38)	(0.53)	(0.71)	(0.78)	(0.84)	(0.98)	(0.68)	(0.45)
Observations	234	234	234	230	230	229	228	228

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

7

5 Confidence and Signaling: News, Uncertainty and Risk Aversion

Given the provenance of monetary policy cycles in differing macroeconomic, financial and political conditions over time, we might surmise that changes in spillovers result from changes in sentiment regarding global economic conditions. Recent literature on the information channel of monetary policy transmission argues that central banks affect asset prices via agents' beliefs not only about policy, but about the path of the economy ((Leombroni et al., 2021); Nakamura and Steinsson (2018); Melosi (2017); Jarociński and Karadi (2020)). This information falls into two broad categories. First, central banks can produce "Odyssean" forward guidance in the form of information about the path of policy. In the baseline analysis, results obtained using the expected path of short rates provides some evidence regarding the importance of this transmission channel for international spillovers. However, as mentioned previously in reference to the confidence channel of monetary policy transmission, the central bank may also generate "Delphic" information, wherein the announcement reveals news about the state of the economy. If, for example, the central bank enacts a more aggressive rate cut than expected or communicates a longer cycle than expected, market participants may infer that the central bank possesses better information on downside growth risks and update their beliefs accordingly.[9]

In the context of international yield spillovers, Delphic news shocks can propagate via two potential channels. The first mirrors that for domestic asset prices. That is, bad news gleaned from monetary policy decreases yields through downward revisions to (global) growth expectations. These revisions, in turn, should drive a lower path of (local) expected future interest rates. On the other hand, to the (albeit modest) extent that these sovereign bonds are subject to a risk premium, expansionary events revealing downside growth risk would raise term premia and compress the convenience yield if an information effect dominates. The second channel reflects flight to safety—increased risk revealed from monetary policy may induce capital to flow toward other safe assets, lowering their term premium.

Standard theory predicts that an expansionary announcement characterized only by information about the path of policy (without Delphic effects) should lead to a stock price rally through discount and dividend channels; that is, we would expect negative co-movement of surprises and equity returns (as in Bernanke and Kuttner (2005)). In turn, if market participants extract information suggesting a weaker outlook for economic or financial conditions, stock prices would rise less or even fall on reduced expectations of cash flows or of higher

[9]See Leombroni et al. (2021) for an in-depth discussion of the mechanism.

risk. Thus, looser monetary policy that is accompanied by a decrease in stock returns (positive co-movement) suggests diminished economic or financial conditions. Thus, the sign of high-frequency co-movement of stocks and the implied yields on futures contracts can help disentangle events with strong risk premium implications versus no (or weak) risk premium implications.

To test for the presence of risk-induced effects, we use a simplified version of Jarociński and Karadi (2020)'s decomposition method, separating surprises with positive equity return co-movement using a dummy variable indicating "informative" announcements. To pinpoint positive co-movement days, we use intradaily return on the STOXX 50 to estimate:

$$\Delta y^{(n)}_{US,t} = \alpha + \beta_1 \mathbb{1}[r_{i,t} \times MP^{ecb}_t > 0] + \beta_2 MP^{ecb}_t + \beta_3 \mathbb{1}[r_{i,t} \times MP^{ecb}_t > 0] * MP^{ecb}_t + \epsilon_{it} \quad (6)$$

Where $y^{(n)}_{it}$ is either the yield on the n-year Treasury bond, the n-year term premium, or the expected path of short rates over an n-year horizon.

Table 8 displays the results, suggesting that spillovers are strongly influenced by the degree to which the market interprets ECB monetary policy shocks as revealing macroeconomic news. However, column 6 suggests that essentially all of the reaction observed in the expected path of short rates emanates from a reassessment of expected macroeconomic conditions when ECB monetary policy engenders adverse market news. In contrast, the term premium does not appear to react forcefully enough to these news events to register a statistically significant impact.

Table 8a suggests that a loosening shock from the ECB lowers the expected path of the policy in the US. However, it may also transpire that the informational content of news becomes more relevant for updating beliefs about what the FOMC might do as the next meeting approaches. To test the degree to which the ECB serves as a "canary in the coal mine", we regress the U.S. yield decomposition on ECB monetary policy shocks, conditioning on whether the next FOMC meeting is within the forthcoming two weeks of the ECB decision. If ECB monetary policy shocks have signaling content over and above revealing the state of the global economy, spillovers to the expected short rate should be larger when an FOMC meeting is coming up. Indeed, Table 8b suggests that is the case.

Table 8: The Signalling Channel

(a) Spillovers to U.S. yields conditional on stock-shock co-movement

	Yield			**Term Premium**			**Exp. Path of Short Rates**		
	(1) Y_1	(2) Y_5	(3) Y_{10}	(4) TP_1	(5) TP_5	(6) TP_{10}	(7) SR_1	(8) SR_5	(9) SR_{10}
ECB	-0.71***	-0.90**	-0.96**	-0.29**	-0.62**	-0.41	0.24	-0.25	-0.26
	(0.21)	(0.43)	(0.45)	(0.11)	(0.27)	(0.31)	(0.25)	(0.24)	(0.21)
Information shock=1	-0.74**	-1.67**	-1.55**	0.02	-0.70	-0.79	-0.98**	-0.85**	-0.80**
	(0.35)	(0.72)	(0.76)	(0.19)	(0.45)	(0.52)	(0.42)	(0.40)	(0.35)
Information shock=1 × ECB	-0.93**	-2.47***	-2.13**	-0.11	-0.55	-0.53	-1.39***	-1.30***	-1.27***
	(0.42)	(0.86)	(0.91)	(0.23)	(0.54)	(0.62)	(0.50)	(0.48)	(0.41)
Constant	0.50**	1.40***	1.64***	0.32**	1.04***	1.14***	0.37	0.56**	0.56**
	(0.24)	(0.48)	(0.51)	(0.13)	(0.30)	(0.35)	(0.28)	(0.27)	(0.23)
Observations	234	234	234	234	234	234	234	234	234

(b) Spillovers to U.S. yields, conditional on proximate FOMC meeting

	Yield			**Term Premium**			**Exp. Path of Short Rates**		
	(1) Y_1	(2) Y_5	(3) Y_{10}	(4) TP_1	(5) TP_5	(6) TP_{10}	(7) SR_1	(8) SR_5	(9) SR_{10}
ECB	-0.91***	-1.37***	-1.40***	-0.43***	-0.89***	-0.77**	-0.40*	-0.38	-0.52**
	(0.22)	(0.46)	(0.48)	(0.12)	(0.28)	(0.31)	(0.24)	(0.24)	(0.21)
FFR_{t-1}	-0.01	-0.12	-0.15	-0.00	0.02	-0.02	0.03	-0.04	-0.08
	(0.11)	(0.22)	(0.24)	(0.06)	(0.14)	(0.15)	(0.12)	(0.12)	(0.10)
Close to FOMC=1	-0.15	-1.03	-0.87	0.21	-0.19	-0.11	-0.62	-0.45	-0.50
	(0.41)	(0.88)	(0.92)	(0.24)	(0.54)	(0.59)	(0.45)	(0.46)	(0.41)
Close to FOMC=1 × ECB	-0.58	-1.11	-0.48	0.66***	0.61	1.52***	-1.75***	-1.82***	-1.29***
	(0.39)	(0.84)	(0.87)	(0.23)	(0.51)	(0.56)	(0.43)	(0.44)	(0.39)
$Y - Y^{eu}$	0.33**	0.29	-0.21	-0.05	-0.22	-0.62**	0.40**	0.24	0.22
	(0.14)	(0.37)	(0.49)	(0.08)	(0.23)	(0.31)	(0.16)	(0.20)	(0.22)
Constant	-0.01	0.79	1.56**	0.32**	0.87**	1.31***	-0.29	0.07	0.21
	(0.26)	(0.58)	(0.66)	(0.15)	(0.35)	(0.42)	(0.29)	(0.30)	(0.29)
Observations	227	227	227	227	227	227	227	227	227

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Returning to the time-varying nature of spillovers, we repeat the rolling regressions from section 2 with an added term meant to capture the impact an announcement has on perceptions of macroeconomic and financial risk. Following Leombroni et al. (2021), we decompose the monetary policy reaction into the future path of interest rates from default-free rate changes in these narrow intervals (MP_t^{ecb}), and the equity reaction that is orthogonal to changes in the short rate and path, ($\tilde{r}_t^{ecb}$). This term is informative about risk premia and provides an identification of risk premium shocks of monetary policy communication.

$$\begin{aligned} \Delta y_{US,t}^{(n)} &= \alpha + \beta_1 MP_t^{ecb} + \beta_2 \tilde{r}_t^{ecb} + \epsilon_{it} \\ \tilde{r}_t^{ecb} &= r_t - Proj[r_t | MP_t^{ecb}] \end{aligned}$$

Figure 6 displays estimates from the rolling regression, along with the estimates from the baseline, in black. The baseline and the estimates controlling from for $\tilde{r}_t^{ecb}$ (in red) tend not to vary dramatically from one another, with one important exception. The interval between the start of Fed QE and the "Whatever it takes" speech, wherein spillovers from the ECB grew even before that institution showed signs of engaging in quantitative easing, evince substantial reactions to announcement-induced changes to risk premia. In this period from 2008 until 2013, the response to "pure" monetary policy shocks is estimated to be smaller than the baseline. This helps to explain the growth of spillovers linked to the expected path of short rates in advance of ECB LSAPs.

Time varying spillovers may also result from a changing risk environment. From a signaling standpoint, the information contained in an ECB monetary policy announcement may be more influential during periods of heightened policy or macroeconomic uncertainty. Given that preferred habitat investors become less willing to substitute to other maturities of the same broad asset when risk bearing capacity is low, we might surmise that willingness to substitute between international markets might also be suppressed under these conditions. To that end, we condition the impact of the monetary policy shock on four lagged uncertainty indices: the VIX, the MOVE index of option implied Treasury market volatility, the economic policy uncertainty index of Baker, Bloom, and Davis (2016), and the monetary policy uncertainty index developed by Bundick, Herriford, and Smith (2024).

Table 9 suggests that the risk environment bears an inconsistent relationship with ECB spillovers to yields. While Columns 1 and 2 suggest that spillovers to the term premium fall when policy rate uncertainty is elevated, column 6 conveys some evidence that spillovers to the expected path of short rates rise in times of elevated broad economic policy uncertainty. At the same time, spillovers to the expected path of short rates shrink when option implied volatility in equity and Treasury markets rise (Columns 9 and 12). This mix of find-

Figure 6: Time-varying ECB spillovers to the U.S. yield curve redux

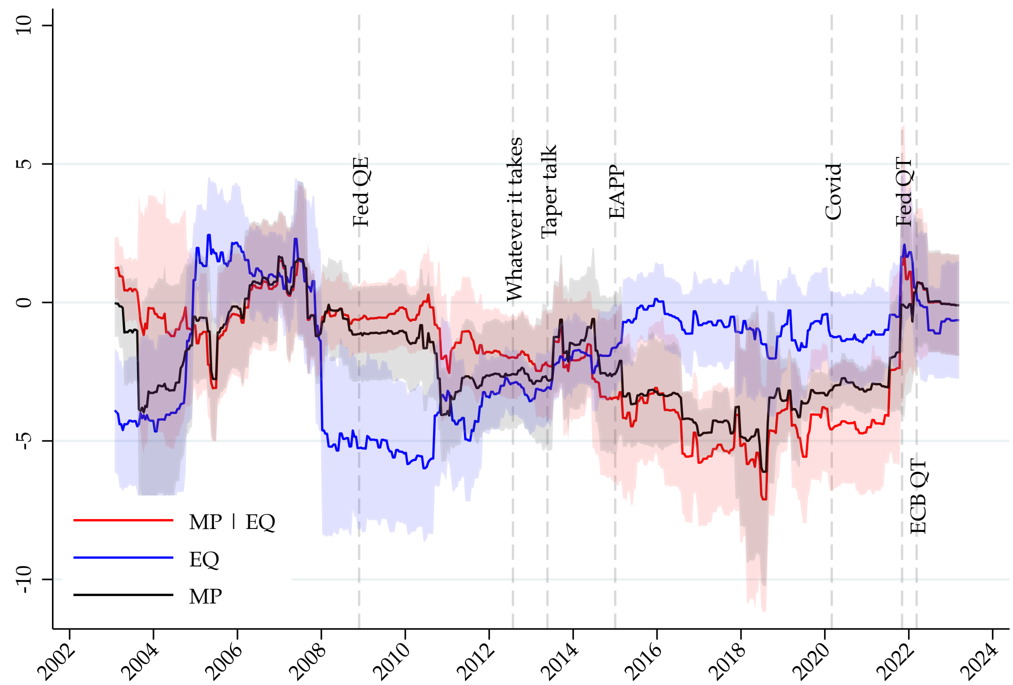


Figure 6 depicts estimates from a 700 business day (24 - 25 announcement) rolling regression of changes in 1-, 5-, and 10-year U.S. zero coupon bond yields on the z-scores of ECB. Shocks comprise the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Shaded areas denote 90% robust confidence intervals.

ings suggests that broad uncertainty and/or risk aversion does not alter the size of signaling spillovers much.

Returning to columns 1 and 2, the baseline results showing that term premium fell more in response to ECB shocks from 2012 until just before the covid crisis do coincide with historically low policy rate uncertainty prevailing over that period.[10] However, further investigation shows that this relationship likely reflects the convenience results obtained above, rather than an independent impact of policy rate uncertainty on spillovers. Three pieces of evidence point to this conclusion. First, we would expect signaling spillovers from monetary policy to have the opposite sign. That is, when the path of policy is well known, foreign monetary policy should introduce less interest rate risk, and thus the magnitude spillovers would increase

[10]See the KC PRU index for an overview: https://www.kansascityfed.org/data-and-trends/kansas-city-fed-policy-rate-uncertainty/

with policy rate uncertainty. Second, the period of lowest policy rate uncertainty coincides with a persistent drop in the convenience yield of Treasuries. Indeed, the policy rate uncertainty index is positively correlated with swap spreads of every maturity (¿ 0.5). Second, when we include the interaction of ECB shocks and U.S. convenience yields in the specification with policy rate uncertainty, the interaction of ECB shocks with policy rate uncertainty becomes statistically insignificant. Altogether, these results suggest that the uncertainty environment does not play a substantial role in driving the size of spillovers from the ECB to U.S. Treasuries.

Table 9: ECB Spillovers Conditional on Risk Sentiment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Y_{10}	TP_{10}	SR_{10}	Y_{10}	TP_{10}	SR_{10}	Y_{10}	TP_{10}	SR_{10}	Y_{10}	TP_{10}	SR_{10}
ECB	-1.57***	-0.91***	-0.83***	-1.62***	-0.82***	-0.60***	-2.07***	-0.77**	-1.00***	-1.97***	-0.52	-1.09***
	(0.40)	(0.27)	(0.18)	(0.42)	(0.29)	(0.19)	(0.49)	(0.33)	(0.22)	(0.48)	(0.32)	(0.21)
MPU_{t-1}	-0.15	0.29	-0.10									
	(0.44)	(0.30)	(0.19)									
ECB × MPU_{t-1}	0.81*	0.99***	-0.28									
	(0.42)	(0.29)	(0.19)									
EPU_{t-1}				0.18	0.18	0.13						
				(0.42)	(0.28)	(0.18)						
ECB × EPU_{t-1}				0.28	0.37	-0.40**						
				(0.40)	(0.27)	(0.18)						
$MOVE_{t-1}$							0.25	0.85***	-0.20			
							(0.37)	(0.25)	(0.17)			
ECB × $MOVE_{t-1}$							0.34	0.24	0.25*			
							(0.33)	(0.23)	(0.15)			
VIX_{t-1}										-0.17	0.86***	-0.46***
										(0.39)	(0.27)	(0.17)
ECB × VIX_{t-1}										0.13	0.04	0.34**
										(0.31)	(0.21)	(0.13)
Constant	0.84**	1.00***	0.10	0.77*	0.67**	0.19	0.90**	0.87***	0.13	0.83**	0.92***	0.11
	(0.42)	(0.28)	(0.19)	(0.42)	(0.28)	(0.18)	(0.38)	(0.26)	(0.17)	(0.38)	(0.26)	(0.17)
Observations	234	234	234	234	234	234	233	233	233	233	233	233

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

6 Concluding Remarks and Directions for Future Research

In this paper, we utilize high frequency identification, a shadow rate term structure model and rolling regressions to identify the effect of monetary policy spillovers to the U.S. from the ECB across the yield curve over time. we provide evidence for the existence of heightened spillovers to the U.S. from ECB during the period of U.S. monetary policy normalization, with the most persistent spillovers arising during the period of U.S. monetary policy normalization.

Results suggest that the ECB's programs of unconventional monetary policy compressed long-term bond yields in Treasury markets primarily through the term premium, indicating the dominance of the portfolio balance and (to a lesser extent) confidence channels of transmission over signaling. In particular, we find that advanced economy spillovers to U.S. long term yields have increased with the rise of two phenomena: wide scale adoption of unconventional monetary policy among advanced economies and the changing dynamics facing the Treasury market.

The mechanisms of unconventional monetary policy that distinguish it from conventional monetary policy imply unique challenges to the withdrawal of monetary stimulus, particularly in the presence of spillovers. Long-term bond yields compressed during the period of unconventional monetary policy may be less upwardly sensitive to conventional policy given the role of term premia in determining long-term interest rates, especially in an environment marked by scarcity of safe assets. In the face of ongoing quantitative easing in other systemic, advanced economies, this implies that normalizing central banks conduct monetary policy primarily by exerting pressure on the expected path of short-rates (which is diminishing in maturity) compared to periods of quantitative easing, while international spillovers have the potential to exert force in the opposite direction on the term premium (which increases with maturity) (Hamilton (2009)).

Asynchronicity of unconventional monetary policy in these systemically important markets makes the cross-country spillovers that we document particularly salient. For example, the evidence presented here suggests that U.S. monetary policy normalization preceding the COVID-19 crisis effectively exerted contractionary monetary policy on European bond yields. This implies that the ECB would have needed to withdraw its stimulus more slowly (or even increase it) in order to keep credit conditions from tightening more than intended when it ultimately halts its asset purchases. From another angle, in the absence of international portfolio balance effects, domestic long-term bond yields would be more responsive to quantitative easing.

In future work, we plan to calibrate the model, and to examine the degree to which similar patterns emerge in spillovers from the ECB to the U.K., and from the Federal Reserve back to the Euro area. Another area of expansion includes adding new announcement types to data set including speeches by both the Chair and by committee members.

References

Acharya, V. V., & Laarits, T. (2023). *When do treasuries earn the convenience yield?: A hedging perspective* (Tech. Rep.).

Altavilla, C., Brugnolini, L., Gürkaynak, R. S., Motto, R., & Ragusa, G. (2019). Measuring euro area monetary policy. *Journal of Monetary Economics*, *108*, 162–179.

Baker, S. R., Bloom, N., & Davis, S. J. (2016). Measuring economic policy uncertainty. *The quarterly journal of economics*, *131*(4), 1593–1636.

Bauer, M. D., & Neely, C. J. (2014). International channels of the Fed's unconventional monetary policy. *Journal of International Money and Finance*, *44*, 24–46.

Bauer, M. D., & Rudebusch, G. D. (2014). The signaling channel for Federal Reserve bond purchases. *International Journal of Central Banking*, *10*(3), 233–289.

Bernanke, B. S. (2009). The crisis and the policy response. *Stamp Lecture, London School of Economics, January*, *13*, 2009.

Bernanke, B. S., & Kuttner, K. N. (2005). What explains the stock market's reaction to federal reserve policy? *The Journal of Finance*, *60*(3), 1221–1257.

Blattner, T. S., & Joyce, M. A. (2020). The euro area bond free float and the implications for qe. *Journal of Money, Credit and Banking*, *52*(6), 1361–1395.

Bluwstein, K., & Canova, F. (2016). Beggar-thy-neighbor? The international effects of ECB unconventional monetary policy measures. *International Journal of Central Banking*, *12*(3), 69–120.

Borovicka, J., Hansen, L. P., & Scheinkman, J. A. (2014). Shock Elasticities and Impulse Responses. *NBER Working Paper*.

Braun, R., Miranda-Agrippino, S., & Saha, S. (2023). Measuring monetary policy in the uk: the uk monetary policy event-study database. *Bank of England Working Paper*.

Brunnermeier, M., Merkel, S., & Sannikov, Y. (2024). Safe assets. *Journal of Political Economy*.

Bruno, V., & Shin, H. S. (2015). Capital flows and the risk-taking channel of monetary policy. *Journal of monetary economics*, *71*, 119–132.

Brusa, F., Savor, P., & Wilson, M. (2020). One central bank to rule them all. *Review of Finance*, *24*(2), 263–304.

Bundick, B., Herriford, T., & Smith, A. L. (2024). The term structure of monetary policy uncertainty. *Journal of Economic Dynamics and Control*, *160*, 104803.

Campbell, J. Y., Sunderam, A., Viceira, L. M., et al. (2017). Inflation bets or deflation hedges? the changing risks of nominal bonds. *Critical Finance Review*, *6*(2), 263–301.

Cetorelli, N., & Goldberg, L. S. (2012). Banking globalization and monetary transmission. *The Journal of Finance*, *67*(5), 1811–1843.

Chari, A., Dilts Stedman, K., & Lundblad, C. (2021). Taper tantrums: Quantitative easing, its aftermath, and emerging market capital flows. *The Review of Financial Studies*, *34*(3), 1445–1508.

Christensen, J. H., & Rudebusch, G. D. (2012). The response of interest rates to us and uk quantitative easing. *The Economic Journal*, *122*(564), F385–F414.

Cochrane, J. H., & Piazzesi, M. (2002). The fed and interest rates-a high-frequency identification. *American Economic Review*, *92*(2), 90–95.

Cœuré, B. (2015). Embarking on public sector asset purchases.

Curcuru, S. E., De Pooter, M., & Eckerd, G. (2018). Measuring Monetary Policy Spillovers between US and German Bond Yields. *International Finance Discussion Papers*, *1226*.

Curcuru, S. E., Kamin, S. B., Li, C., & Rodriguez, M. (2018). International Spillovers of Monetary Policy: Conventional Policy vs. Quantitative Easing. *Working Paper*.

Curdia, V., & Woodford, M. (2011). The central-bank balance sheet as an instrument of monetarypolicy. *Journal of Monetary Economics*, *58*(1), 54–79.

D'Amico, S., & King, T. B. (2013). Flow and stock effects of large-scale treasury purchases: Evidence on the importance of local supply. *Journal of Financial Economics*, *108*(2), 425–448.

de Sola Perea, M., & Van Nieuwenhuyze, C. (2014). Financial integration and fragmentation in the euro area. *Economic Review*(i), 99–125.

Droste, M., Ray, W., & Gorodnichenko, Y. (2023). Unbundling quantitative easing: taking a cue from treasury auctions. *Journal of Political Economy*.

Du, W., Hébert, B., & Huber, A. W. (2023). Are intermediary constraints priced? *The Review of Financial Studies*, *36*(4), 1464–1507.

Du, W., Hébert, B., & Li, W. (2023). Intermediary balance sheets and the treasury yield curve. *Journal of Financial Economics*, *150*(3), 103722.

Du, W., Im, J., & Schreger, J. (2018). The us treasury premium. *Journal of International Economics*, *112*, 167–181.

Duffie, D. (2023). Resilience redux in the us treasury market. In *Jackson hole symposium, federal reserve bank of kansas city.*

Ehrmann, M., & Fratzscher, M. (2005). Equal size, equal role? Interest rate interdependence between the euro area and the United States. *The Economic Journal*, *115*(506), 928–948.

Falagiarda, M., McQuade, P., & Tirpák, M. (2015). *Spillovers from the ECB's non-standard monetary policies on non-euro area EU countries: evidence from an event-study analysis* (No. 1869). ECB Working Paper.

Fratzscher, M., Duca, M. L., & Straub, R. (2016). ECB unconventional monetary policy: Market impact and international spillovers. *IMF Economic Review*, *64*(1), 36–74.

Fratzscher, M., Lo Duca, M., & Straub, R. (2018). On the international spillovers of US quantitative easing. *The Economic Journal*, *128*(608), 330–377.

Gagnon, J., Raskin, M., Remache, J., & Sack, B. (2011). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking*, *7*(1), 3–43.

Georgiadis, G., & Gräb, J. (2016). Global financial market impact of the announcement of the

ECB's asset purchase programme. *Journal of Financial Stability*, *26*, 257–265.

Gertler, M., & Karadi, P. (2011). A model of unconventional monetary policy. *Journal of monetary Economics*, *58*(1), 17–34.

Gertler, M., & Karadi, P. (2015). Monetary policy surprises, credit costs, and economic activity. *American Economic Journal: Macroeconomics*, *7*(1), 44–76.

Gourinchas, P.-O., Ray, W. D., & Vayanos, D. (2022). A preferred-habitat model of term premia, exchange rates, and monetary policy spillovers. *NBER Working Paper*.

Greenwood, R., & Vayanos, D. (2014). Bond supply and excess bond returns. *The Review of Financial Studies*, *27*(3), 663–713.

Gürkaynak, R. S., Levin, A. T., & Swanson, E. T. (2006). Does inflation targeting anchor long-run inflation expectations? evidence from long-term bond yields in the us, uk and sweden. *Journal of the European Economic Association*, *8*(6), 1208–1242.

Gürkaynak, R. S., Sack, B., & Swanson, E. T. (2005). Do Actions Speak Louder Than Words? The Response of Asset Prices to Monetary Policy Actions and Statements. *International Journal of Central Banking*.

Gürkaynak, R. S., Sack, B., & Wright, J. H. (2007). The us treasury yield curve: 1961 to the present. *Journal of monetary Economics*, *54*(8), 2291–2304.

Hamilton, J. D. (2009). Daily changes in fed funds futures prices. *Journal of Money, Credit and Banking*, *41*(4), 567–582.

Hamilton, J. D., & Wu, J. C. (2012). The effectiveness of alternative monetary policy tools in a zero lower bound environment. *Journal of Money, Credit and Banking*, *44*, 3–46.

Harvey, C., Lundblad, C. T., & Siegel, S. (2011). What segments equity markets? *Review of Financial Studies*, *24*(12), 3847–3890.

Hofmann, B., & Takáts, E. (2015). International monetary spillovers. *BIS Quarterly Review*, 105.

Jarociński, M., & Karadi, P. (2020). Deconstructing monetary policy surprises—the role of information shocks. *American Economic Journal: Macroeconomics*, *12*(2), 1–43.

Jermann, U. (2020). Negative swap spreads and limited arbitrage. *The Review of Financial Studies*, *33*(1), 212–238.

Kearns, J., Schrimpf, A., & Xia, F. D. (2023). Explaining monetary spillovers: The matrix reloaded. *Journal of Money, Credit and Banking*, *55*(6), 1535–1568.

Klingler, S., & Sundaresan, S. (2023). Diminishing treasury convenience premiums: Effects of dealers' excess demand and balance sheet constraints. *Journal of Monetary Economics*, *135*, 55–69.

Kose, M. A., Otrok, C., & Whiteman, C. H. (2003). International business cycles: World, region, and country-specific factors. *American Economic Review*, *93*(4), 1216–1239.

Krishnamurthy, A., & Vissing-Jorgensen, A. (2011). The effects of quantitative easing on interest rates: channels and implications for policy. *NBER Working Paper*.

Krishnamurthy, A., & Vissing-Jorgensen, A. (2012). The aggregate demand for treasury debt.

Journal of Political Economy, *120*(2), 233–267.

Kuttner, K. N. (2001). Monetary policy surprises and interest rates: Evidence from the Fed funds futures market. *Journal of Monetary Economics*, *47*(3), 523–544.

Leombroni, M., Vedolin, A., Venter, G., & Whelan, P. (2021). Central bank communication and the yield curve. *Journal of Financial Economics*, *141*(3), 860–880.

Melosi, L. (2017). Signalling effects of monetary policy. *The Review of Economic Studies*, *84*(2), 853–884.

Miranda-Agrippino, S., & Nenova, T. (2022). A tale of two global monetary policies. *Journal of International Economics*, *136*, 103606.

Morais, B., Peydró, J.-L., Roldán-Peña, J., & Ruiz-Ortega, C. (2019). The international bank lending channel of monetary policy rates and qe: Credit supply, reach-for-yield, and real effects. *The Journal of Finance*, *74*(1), 55–90.

Mueller, P., Tahbaz-Salehi, A., & Vedolin, A. (2017). Exchange rates and monetary policy uncertainty. *The Journal of Finance*, *72*(3), 1213–1252.

Nagel, S. (2016). The liquidity premium of near-money assets. *The Quarterly Journal of Economics*, *131*(4), 1927–1971.

Nakamura, E., & Steinsson, J. (2018). High frequency identification of monetary non-neutrality: The information effect. *Quarterly Journal of Economics*.

Neely, C. J. (2015). Unconventional monetary policy had large international effects. *Journal of Banking & Finance*, *52*, 101–111.

Rogers, J. H., Scotti, C., & Wright, J. H. (2014). Evaluating asset-market effects of unconventional monetary policy: a multi-country review. *Economic Policy*, *29*(80), 749–799.

Rogers, J. H., Scotti, C., & Wright, J. H. (2018). Unconventional monetary policy and international risk premia. *Journal of Money, Credit and Banking*, *50*(8), 1827–1850.

Shah, N. (2022). Doubly heterogeneous monetary spillovers. *International Finance*.

Shin, H. (2017). Is there a risk of snapback in long-dated yields. *Retrieved from Bank for International Settlements: https://www. bis. org/speeches/sp170925. htm*.

Sims, E. R., & Wu, J. C. (2020). Are QE and Conventional Monetary Policy Substitutable? *International Journal of Central Banking*, *16(1)*, 195–230.

Swanson, E. T. (2021). Measuring the effects of federal reserve forward guidance and asset purchases on financial markets. *Journal of Monetary Economics*, *118*, 32–53.

Vayanos, D., & Vila, J.-L. (2021). A preferred-habitat model of the term structure of interest rates. *Econometrica*, *89*(1), 77–112.

Wolcott, E. L. (2020). Impact of foreign official purchases of us treasuries on the yield curve. In *Aea papers and proceedings* (Vol. 110, pp. 535–40).

Wright, J. H. (2012). What does Monetary Policy do at the Zero Lower Bound ? *Economic Journal*, *122*(564), 447–466. doi: 10.1111/j.1468-0297.2012.02556.x.

Wu, J. C., & Xia, F. D. (2016). Measuring the macroeconomic impact of monetary policy at the zero lower bound. *Journal of Money, Credit and Banking*, *48*(2-3), 253–291.

Zhang, T. (2022). Monetary policy spillovers through invoicing currencies. *The Journal of Finance*, *77*(1), 129–161.

A Proofs

A.1 Proof of 3.1

Begin by assuming $\alpha_H(\tau) \equiv \alpha_1(\tau), \alpha_F(\tau) \equiv \alpha_2(\tau) \in C^b(\mathbb{R})$, the Banach space of bounded functions. Consider the following equation which implicitly solves for M:

$$\Gamma^\top - \left(\theta_e e_3 - \alpha_e M^{-1}(e_1 - e_2)\right)] \otimes (e_1 - e_2) M^{-\top} Q = M + \left[\sum_{j=1}^{2} \int_0^T \left(\theta_j(\tau) e_{3+j} - \alpha_j(\tau) a_j(\tau)\right) \otimes a_j(\tau) d\tau\right] Q \tag{7}$$

where e_k represents the kth standard basis of $\mathbb{R}^5$. $Q \equiv a\Sigma \otimes \Sigma \in Sym_5, \Gamma \in \mathbb{M}_{5\times 5}, \theta_e \in \mathbb{R}$, $\alpha_e \in \mathbb{R}_+$, and $\theta_j(\tau) \in C^b(\mathbb{R})$ are given. $\otimes$ is the tensor product. The notational change in the subscript of α is only for notational expedience.

Consider the following level set $\Xi = \{M, \alpha_H, \alpha_F : X(M, \alpha_H, \alpha_F) = 0\}$ where

$$\begin{aligned} X(M, \alpha_H, \alpha_F) &= M - \Gamma^\top + Y(M, \alpha_H, \alpha_F) Q + Z(M, \alpha_H, \alpha_F) Q \\ Y(M, \alpha_H, \alpha_F) &= \sum_{j=1}^{2} \int_0^T \left(\theta_j(\tau) e_{3+j} - \alpha_j(\tau) a_j(\tau)\right) \otimes a_j(\tau) d\tau \\ Z(M, \alpha_H, \alpha_F) &= \left[\theta_e e_3 - \alpha_e M^{-1}(e_1 - e_2)\right] \otimes (e_1 - e_2) M^{-\top} \end{aligned} \tag{8}$$

By the Implicit Function Theorem on Banach spaces, we have the following

Theorem A.1. The set $\{M, \alpha_H, \alpha_F : M = \mu(\alpha_H, \alpha_F)\}$ is locally equivalent to the set Ξ if

1. Ξ is non-empty
2. $\partial_M X\left(M^0, \alpha_H^0, \alpha_F^0\right)$ is invertible for $\left\{M^0, \alpha_H^0, \alpha_F^0\right\} \in \Xi$.

We assume the first condition is satisfied, given the work by ? (?). In order to prove the second, notice that

$$X : GL(5) \times C^b(\mathbb{R}) \times C^b(\mathbb{R}) \to \mathbb{M}_{5\times 5}\ C^1$$

In other words, as long as $\{\alpha_1, \alpha_2\}$ belong to a Banach space of bounded functions equipped with the sup norm, then X is a continuous mapping. Furthermore, $\partial_M X$ is a continuous, linear mapping. Therefore, by Banach's theorem, $(\partial_M X)^{-1}$ is an open and dense mapping.

A.2 Proof of 3.2

We begin by using the definition of $a_j(\tau)$ with follows a linear ODE system:

$$\begin{aligned} a_j'(M, \tau) &= -M a_j(M, \tau) + e_j,\ j \in \{1, 2\} \\ a_j(M, 0) &= 0 \end{aligned}$$

where e_j represents the jth standard basis of $\mathbb{R}^5$. The solution to the ODE is

$$a_j(M, \tau) = \left(I - e^{-M\tau}\right) M^{-1} e_j \tag{9}$$

Using the definition of the Gateaux differential we have

$$\left(\partial_M a_j(M, \tau)\right)[H] = \frac{d}{d\epsilon} \left| \left(I - e^{-(M+\epsilon H)\tau}\right) (M + \epsilon H)^{-1} e_j \right|_{\epsilon=0}$$

One particular term will occur quite frequently in the coming proofs, so we devote the following corollary to it:

Corollary A.1. The following holds:

$$\begin{aligned}
\frac{d}{d\epsilon}\left|\left(I-e^{-(M+\epsilon H)\tau}\right)(M+\epsilon H)^{-1}\right|_{\epsilon=0} &= \tau e^{-\tau M} H M^{-1} - \left(I-e^{-\tau M}\right) M^{-1} H M^{-1} \\
&= \left[\tau e^{-\tau M} - \left(I-e^{-\tau M}\right) M^{-1}\right] H M^{-1} \\
&= \left(I-e^{-\tau M}\right)\left[\tau\left(I-e^{-\tau M}\right)^{-1} e^{-\tau M} - M^{-1}\right] H M^{-1}
\end{aligned}$$

where Y is taken to mean the matrix-valued direction of the differential.

Proof 6. Let $Z = \frac{\tau}{2}M$. Then using properties of the matrix exponential:

$$\begin{aligned}
I-e^{-\tau M} &= I-e^{-2Z} \\
&= 2e^{-Z}\sinh Z \\
\left(I-e^{-\tau M}\right)^{-1} &= \frac{1}{2}e^{Z}\operatorname{csch} Z \\
&= \frac{1}{2}e^{Z}\frac{2}{e^{Z}-e^{-Z}} \\
&= \frac{e^{\frac{\tau}{2}M}}{e^{\frac{\tau}{2}M}-e^{-\frac{\tau}{2}M}}
\end{aligned}$$

Thus

$$\left(I-e^{-M\tau}\right)^{-1} e^{-\tau M} = \frac{e^{-\frac{\tau}{2}M}}{e^{\frac{\tau}{2}M}-e^{-\frac{\tau}{2}M}}$$

Plugging in, we have

$$\left(\partial_M a_j(M,\tau)\right)[H] = \left(I-e^{-\tau M}\right)\left[\tau\frac{e^{-\frac{\tau}{2}M}}{e^{\frac{\tau}{2}M}-e^{-\frac{\tau}{2}M}} - M^{-1}\right] H M^{-1} e_j$$

Given

$$a_j(\tau)\left(I-e^{-M\tau}\right)^{-1} = M^{-1}e_j$$

we have

$$\left(\partial_M a_j(M,\tau)\right)[H] = \left(I-e^{-\tau M}\right)\left[\tau\frac{e^{-\frac{\tau}{2}M}}{e^{\frac{\tau}{2}M}-e^{-\frac{\tau}{2}M}} - M^{-1}\right] H a_j(\tau)\left(I-e^{-M\tau}\right)^{-1} \tag{10}$$

A.3 Proof of 3.3

Consider equation 8. We take the functional derivative in pieces:

$$\left(\partial_M X\right)[H] = H + \left\{\left(\partial_M Y\right)[H] + \left(\partial_M Z\right)[H]\right\} Q$$

The first piece is

$$\left(\partial_M Y\right)[H] = \sum_{j=1}^{2} \int_0^T \left\{ \left[\theta_j(\tau)\, e_{3+j} - \alpha_j(\tau)\, a_j(\tau)\right] \otimes \left(\partial_M a_j\right)[H] - \alpha_j(\tau) \left(\partial_M a_j\right)[H] \otimes a_j(\tau) \right\} d\tau$$

and the second piece is

$$\begin{aligned}\left(\partial_M Z\right)[H] &= \alpha_e M^{-1} H M^{-1} (e_1 - e_2) \otimes (e_1 - e_2) M^{-\top} + \left[\alpha_e M^{-1} (e_1 - e_2) - \theta_e e_3\right] \otimes (e_1 - e_2) \left(M^{-1} H M^{-1}\right)^{\top} \\ &= \alpha_e M^{-1} \left[H M^{-1} (e_1 - e_2) \otimes (e_1 - e_2) + \left(e_1 - e_2 - \frac{\theta_e}{\alpha_e} M e_3\right) \otimes (e_1 - e_2) M^{-\top} H^{\top}\right] M^{-\top}\end{aligned}$$

By the Implicit Function Theorem, $\left(\partial_{\alpha_k} \mu\right)[\phi_k]$ exists and is given by

$$\sum_{k=1}^{2} \left(\partial_{\alpha_k} \mu\right)[\phi_k] = -\left\{\left(\partial_M X\right)\left[\left(\partial_{\alpha_k} \mu\right)[\phi_k]\right]\right\}^{-1} \left\{\sum_{k=1}^{2} \left(\partial_{\alpha_k} X\right)[\phi_k]\right\}$$

for which

$$\begin{aligned}\left(\partial_{\alpha_k} X\right)[\phi_k] &= \left(\partial_{\alpha_k} Y\right)[\phi_k]\, Q \\ &= -\left[\int_0^T \phi_k(\tau)\, a_k(\tau) \otimes a_k(\tau)\, d\tau\right] Q\end{aligned}$$

Therefore

$$\sum_{k=1}^{2} \left(\partial_{\alpha_k} \mu\right)[\phi_k] = \left\{H + \left\{\left(\partial_M Y\right)[H] + \left(\partial_M Z\right)[H]\right\} Q\right\}^{-1} \left\{\sum_{k=1}^{2} \int_0^T \phi_k(\tau)\, a_k(\tau) \otimes a_k(\tau)\, d\tau\right\} Q \Bigg|_{H = \left(\partial_{\alpha_k} \mu\right)[\phi_k],\, M = \mu(\alpha_1, \alpha_2)}$$

A.4 Proof of 3.1

Begin by defining $\Phi(\tau, q_t) \equiv \sum_{k \in \{H,F\}} \left(\partial_{\alpha_k} \log P_{jt}^{(\tau)}\right)[\phi_k]$ for a given perturbation $\phi_k(\tau)$. Using Ito's Lemma we have

$$\begin{aligned}d\Phi(\tau, q_t) &= \Phi_\tau(\tau, q_t)\, d\tau + \Phi_q(\tau, q_t) \otimes dq + \frac{1}{2} \Phi_{qq}(\tau, q_t)\, (dq)^2 \\ &= \Phi_\tau(\tau, q_t)\, d\tau + \Phi_q(\tau, q_t) \otimes \left[\Gamma(\bar{q} - q_t)\, dt + \Sigma db_t\right] + \frac{1}{2} \Phi_{qq}(\tau, q_t)\, Q dt\end{aligned}$$

Given that $\Phi(\tau, q_t)$ is affine in q_t, $\Phi_{qq} = 0$. Furthermore, we focus on the price of each maturity in a vaccuum, setting $d\tau = 0$. Therefore

$$d\Phi(\tau, q_t) = \Phi_q(\tau, q_t) \otimes \left[\Gamma(\bar{q} - q_t)\right] dt + \Phi_q(\tau, q_t) \otimes \Sigma db_t$$

Now consider the expected change in the future. Following ? (?), we think of this as a linear VAR so that the impulse response in period $s \geq t$ to a shock of size $h_t \in \mathbb{R}^5$ in period t is defined by the Malliavin derivative $\mathcal{D}_0 \Phi(\tau, q_s) = Z_s^y \Sigma + \Phi_q(\tau, q_s)^{\top} \Sigma$ where

$$\begin{aligned}dZ_t^y &= -\Phi_q(\tau, q_t)^{\top}\, \Gamma Z_t^x dt \\ dZ_t^x &= -\Gamma Z_t^x\end{aligned}$$

Solving the second ODE gives $Z_t^x = \exp\{-t\Gamma\}$ so that

$$Z_t^y = \Phi_q(\tau, q_t)^\top \exp\{-t\Gamma\}$$

Thus the impulse response is

$$h_t \cdot \mathcal{D}_0\Phi(\tau, q_s) = h_t \cdot \left\{\Phi_q(\tau, q_s)^\top [I + \exp\{-(s-t)\Gamma\}]\Sigma\right\}$$

A.5 Proof of 3.4

We aim to solve for

$$(d_{\alpha_k}c_j)[\phi_k] = (\partial_M c_j)[(\partial_{\alpha_k}\mu)[\phi_k]] \times (\partial_{\alpha_k}\mu)[\phi_k] + (\partial_{\alpha_k}c_j)[\phi_k]$$

Begin with the vector-valued ODE for $c_j \in \mathbb{R}^5$

$$c_j' = a_j(\tau)^\top \left[\lambda_c + \Gamma\bar{q} + Qa_e 1_{j=F}\right] - \frac{1}{2}a_j(\tau)^\top Qa_j(\tau) \tag{11}$$

where $\bar{q} \in \mathbb{R}^5$, $1_{j=F}$ is the indicator function which equals one iff $j = F$, and

$$a_e = M^{-1}(e_1 - e_2) \tag{12}$$

$$\lambda_c = aQ\left[(\zeta_e - \alpha_e c_e)a_e + \sum_{j=H,F}\int_0^T \left(\zeta_j(\tau) - \alpha_j(\tau)c_j(\tau)\right)a_j(\tau)\,d\tau\right] \tag{13}$$

such that $\zeta_e, \alpha_e \in \mathbb{R}$, $\zeta_j(\tau) \in C^b(\mathbb{R})$, $\lambda_c \in \mathbb{R}^5$, and $c_e \in \mathbb{R}$ solves

$$-a_e^\top\Gamma\bar{q} - (\pi_F - \pi_H) + \frac{1}{2}a_e^\top Qa_e = a_e^\top\lambda_c$$

Proposition A.1. $c_j(\tau)$ is an nonautonomous function of the form

$$c_j\left(\tau, M, \alpha_{k\in\{H,F\}}\right) = -\frac{1}{2}f_j(\tau, M) + e_j^\top M^{-\top}\left[\tau I - M^{-1}\right]^\top Q\left[\chi_j\left(M, \alpha_{k\in\{H,F\}}\right) - \gamma_j\left(M, \alpha_j\right)\right]$$

Proof 7. Notice that, through 13, 11 is a Fredholm integro-differential equation:

$$\begin{aligned}
c_j' = &-\frac{1}{2}a_j(\tau)^\top Qa_j(\tau) \\
&+ a_j(\tau)^\top Q\left[Q^{-1}\Gamma\bar{q} + a_e 1_{j=F} + a(\zeta_e - \alpha_e c_e)a_e\right] \\
&+ aa_j(\tau)^\top Q\left[\sum_{k=H,F}\int_0^T \zeta_k(t)a_k(t)\,dt - \int_0^T \alpha_{-j}(t)c_{-j}(t)a_{-j}(t)\,dt\right] \\
&- aa_j(\tau)^\top Q\left[\int_0^T \alpha_j(t)c_j(t)a_j(t)\,dt\right]
\end{aligned}$$

Note that the kernel is already in separable form $-aa_j(\tau)^\top Q\left[\int_0^T \alpha_j(t)c_j(t)a_j(t)\,dt\right] = g(\tau)\int_0^T f(t)\,dt$. Thus we set $\gamma_j = a\int_0^T \alpha_j(t)c_j(t)a_j(t)\,dt \in \mathbb{R}^5$, define $\chi_j \equiv a\sum_{k=H,F}\int_0^T \zeta_k(t)a_k(t)\,dt - a\int_0^T \alpha_{-j}(t)c_{-j}(t)a_{-j}(t)\,dt + Q^{-1}\Gamma\bar{q} + a_e 1_{j=F} + a(\zeta_e - \alpha_e c_e)a_e$ and solve the following problem:

$$c_j' = -\frac{1}{2} a_j(\tau)^\top Q a_j(\tau) + a_j(\tau)^\top Q [\chi - \gamma]$$

Integrating both sides we get

$$c_j(\tau) = c_j(0) - \frac{1}{2}\int_0^\tau a_j(t)^\top Q a_j(t)\, dt + \int_0^\tau a_j(t)^\top dt Q [\chi - \gamma]$$

where $c_j(0) = 0$ by definition. Using 9 we have

$$\begin{aligned}\int_0^\tau a_j(t)\, dt &= \int_0^\tau \left(I - e^{-tM}\right) dt M^{-1} e_j \\ &= \left[\tau I - M^{-1}\right] M^{-1} e_j\end{aligned}$$

Not sure about this... for now, define $f_j(\tau) \equiv \int_0^\tau a_j(t)^\top Q a_j(t)\, dt$. Then

$$c_j(\tau) = -\frac{1}{2} f_j(\tau) + e_j^\top M^{-\top} \left[\tau I - M^{-1}\right]^\top Q [\chi - \gamma]$$

Plugging this into the definition of γ we get

$$\gamma = a \int_0^T \alpha_j(t) \left[-\frac{1}{2} f_j(t) + e_j^\top M^{-\top} \left[t I - M^{-1}\right]^\top Q [\chi - \gamma]\right] a_j(t)\, dt$$

Therefore the functional derivative with respect to M is

$$\begin{aligned}(\partial_M c_j)[Y] = &-\frac{1}{2}(\partial_M f_j(\tau, M))[Y] - e_j^\top M^{-\top} Y^\top M^{-\top}\left[\tau I - M^{-1}\right]^\top Q\left[\chi(M, \alpha_j) - \gamma(M, \alpha_j)\right] \qquad (14) \\ &+ e_j^\top M^{-\top}\left[M^{-1} Y M^{-1}\right]^\top Q\left[\chi(M, \alpha_j) - \gamma(M, \alpha_j)\right] \\ &+ e_j^\top M^{-\top}\left[\tau I - M^{-1}\right]^\top Q\left[(\partial_M \chi_j)[Y] - (\partial_M \gamma_j)[Y]\right]\end{aligned}$$

where

$$(\partial_M f_j(\tau, M))[Y] = \int_0^\tau (\partial_M a_j(t))[Y]^\top Q a_j(t) + a_j(t)^\top Q (\partial_M a_j(t))[Y]\, dt \qquad (15)$$

and

$$\begin{aligned}(\partial_M \chi_j)[Y] = &\; a \sum_{k=H,F} \int_0^T \zeta_k(t)(\partial_M a_k(t))[Y]\, dt + (\partial_M c_{-j}(t))[Y]\, 1_{j=F} + a(\zeta_e - \alpha_e c_e) a_e \qquad (16) \\ &- a\int_0^T \alpha_{-j}(t)\left[(\partial_M c_{-j}(t))[Y] a_{-j}(t) + c_{-j}(t)(\partial_M a_{-j}(t))[Y]\right] dt \\ &+ (\partial_M a_e)[Y]\left\{1_{j=F} + a(\zeta_e - \alpha_e c_e)\right\} - a\alpha_e(\partial_M c_e)[Y] a_e\end{aligned}$$

and

$$
\begin{aligned}
\left(\partial_M \gamma_j\right)[Y] = &-\frac{a}{2}\int_0^T \alpha_j(t)\left(\partial_M f_j(t,M)\right)[Y]\, a_j(t)\, dt \\
&- a\int_0^T \alpha_j(t)\left[e_j^\top M^{-\top} Y^\top M^{-\top}\left[tI - M^{-1}\right]^\top Q\left[\chi-\gamma\right]\right] a_j(t)\, dt \\
&+ a\int_0^T \alpha_j(t)\left[e_j^\top M^{-\top}\left[M^{-1} Y M^{-1}\right]^\top Q\left[\chi-\gamma\right]\right] a_j(t)\, dt \\
&+ a\int_0^T \alpha_j(t)\left[e_j^\top M^{-\top}\left[tI - M^{-1}\right]^\top Q\left[\left(\partial_M \chi_j\right)[Y] - \left(\partial_M \gamma_j\right)[Y]\right]\right] a_j(t)\, dt \\
&+ a\int_0^T \alpha_j(t)\left[-\frac{1}{2} f_j(t,M) + e_j^\top M^{-\top}\left[tI - M^{-1}\right]^\top Q\left[\chi-\gamma\right]\right]\left(\partial_M a_j(t)\right)[Y]\, dt
\end{aligned}
\tag{17}
$$

The partial functional derivative with respect to $\alpha_k(\tau)$ is

$$
\left(\partial_{\alpha_k} c_j\right)[\phi_k] = e_j^\top M^{-\top}\left[\tau I - M^{-1}\right]^\top Q\left[\left(\partial_{\alpha_k}\chi_j\right)[\phi_k] - \left(\partial_{\alpha_k}\gamma_j\right)[\phi_k]\right] \tag{18}
$$

where

$$
\begin{aligned}
\left(\partial_{\alpha_k}\chi_j\right)[\phi_k] = &-a 1_{j\neq k}\int_0^T \phi_k(t)\, c_k(t)\, a_k(t)\, dt - a\int_0^T \alpha_{-j}(t)\left(\partial_{\alpha_k} c_{-j}\right)[\phi_k]\, a_{-j}(t)\, dt \\
&- a\alpha_e\left(\partial_{\alpha_k} c_e\right)[\phi_k]\, a_e
\end{aligned}
\tag{19}
$$

and

$$
\left(\partial_{\alpha_k}\gamma_j\right)[\phi_k] = a 1_{j=k}\int_0^T \phi_k(t)\, c_k(t)\, a_k(t) + \alpha_k(t)\left(\partial_{\alpha_k} c_j\right)[\phi_k]\, a_k(t)\, dt \tag{20}
$$

There are still three quantities missing: $(\partial_M a_e)[Y]$, $(\partial_M c_e)[Y]$, and $(\partial_{\alpha_k} c_e)[\phi_k]$. The first is straightforward:

$$
\left(\partial_M a_e\right)[Y] = -M^{-1} Y M^{-1}\left(e_1 - e_2\right) \tag{21}
$$

The latter two will require another use of the Implicit Function Theorem on Banach spaces. c_e implicitly solves the following equation:

$$
-a_e^\top \Gamma \bar{q} - \left(\pi_F - \pi_H\right) + \frac{1}{2} a_e^\top Q a_e = a_e \otimes \lambda_c
$$

where λ_c is defined in 13. Define the level set $\Xi_2 = \{M, \alpha_H, \alpha_F : X_2(C_e, M, \alpha_H, \alpha_F) = 0\}$ where

$$
X_2\left(C_e, M, \alpha_H, \alpha_F\right) = a_e \otimes \lambda_c\left(C_e, M, \alpha_H, \alpha_F\right) + a_e^\top \Gamma \bar{q} + \pi_F - \pi_H - \frac{1}{2} a_e^\top Q a_e
$$

and it is understood that $a_e \equiv a_e(M) : GL(5) \to \mathbb{R}$ as defined in 12. The following corollary to 3.1 applies.

Corollary A.2. $\exists \mu_c(M, \alpha_H, \alpha_F) : GL(5) \times C^b(\mathbb{R}) \times C^b(\mathbb{R}) \to \mathbb{R} \big| C_e = \mu_c(M, \alpha_H, \alpha_F)$ represents a graph identical to the level set Ξ_2 in a neighborhood $U_M \bigcup U_{ah} \bigcup U_{af}$ of $\left\{M^0, \alpha_H^0, \alpha_F^0\right\} \in \Xi_2$ such that $U_M \subset GL(5)$ and $U_{ah}, U_{af} \subset C^b(\mathbb{R})$.

Proof 8. Appeal to A.1 and the fact that $X_2 : \mathbb{R} \times GL(5) \times C^b(\mathbb{R}) \times C^b(\mathbb{R}) \to \mathbb{R}$ is C^1. We show that $\left(\partial_{C_e} X_2\right)^{-1}$ exists directly:

$$\left(\partial_{C_e} X_2\right)[H] = -a\alpha_e H a_e^\top Q a_e \tag{22}$$

as long as $a, \alpha_e \neq 0$ and Q is not skew-symmetric (satisfied by definition), then the only solution to $\left(\partial_{C_e} X_2\right)[H] = 0$ is the trivial one.

This allows us to use the following equations:

$$\begin{aligned}
\left(\partial_M c_e\right)[Y] &= \left(\partial_{C_e} X_2\right)^{-1}\left(\partial_M X_2\right)[Y] \\
\left(\partial_{\alpha_k} c_e\right)[\phi_k] &= \left(\partial_{C_e} X_2\right)^{-1}\left(\partial_{\alpha_k} X_2\right)[\phi_k]
\end{aligned}$$

As $\left(\partial_{C_e} X_2\right)^{-1}$ is already given directly from 22, we need only derive $\left(\partial_M X_2\right)[Y]$ and $\left(\partial_{\alpha_k} X_2\right)[\phi_k]$. The latter is more straightforward, so we begin there.

$$\begin{aligned}
\left(\partial_{\alpha_k} X_2\right)[\phi_k] &= a_e \otimes \left(\partial_{\alpha_k} \lambda_c\right)[\phi_k] \\
&= a_e \otimes \left\{ Q\left(\partial_{\alpha_k} \chi_j\right)[\phi_k] - Q\left(\partial_{\alpha_k} \gamma_j\right)[\phi_k] \right\}
\end{aligned}$$

using equations 19 and 20. For the former,

$$\begin{aligned}
\left(\partial_M X_2\right)[Y] = &\left(\partial_M a_e\right)[Y] \otimes [\lambda_c + \Gamma \bar{q}] + a_e \otimes \left(\partial_M \lambda_c\right)[Y] \\
&- \frac{1}{2}\left[\left(\partial_M a_e\right)[Y]^\top Q a_e + a_e^\top Q \left(\partial_M a_e\right)[Y]\right]
\end{aligned}$$

where

$$\begin{aligned}
\left(\partial_M \lambda_c\right)[Y] = &\, Q\left\{\left(\partial_M \chi_j\right)[Y] - \left(\partial_M \gamma_j\right)[Y]\right\} \\
&- Q\left\{\left(\partial_M a_e\right)[Y]\left\{1_{j=F} + a\left(\zeta_e - \alpha_e c_e\right)\right\} + a\alpha_e \left(\partial_M c_e\right)[Y]\, a_e\right\}
\end{aligned}$$

B Figures and Tables

Table 1: Breakpoints in the impact of ECB spillovers

Breaks	LL	UL
Mar 3, 2005	Feb 18, 2005	Mar 16, 2005
Mar 6, 2008	Mar 2, 2008	Mar 10, 2008
Feb 3, 2011	Dec 13, 2010	Mar 27, 2011
Feb 6, 2014	May 21, 1976	Oct 25, 2051
Jun 14, 2018	Jun 6, 2018	Jun 22, 2018

Table 1 displays estimated break points from a Bai Perron unknown breakpoint test, the mean of the ten year swap spread between break dates, the change in mean relative to the previous period, and 95% confidence intervals.

Figure 1: Monetary Policy Shocks

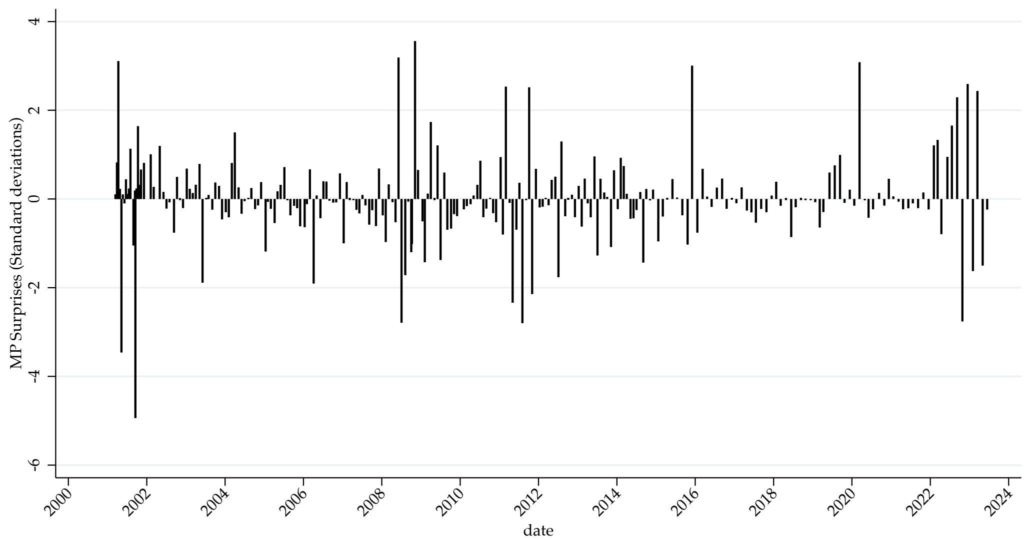


Figure 1 depicts z-scores of ECB monetary policy shocks, before loosening normalization. Shocks comprise the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields.

Figure 2: ECB "News" shocks

Figure 2 depicts z-scores of ECB monetary policy shocks, before loosening normalization. Shocks comprise the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Red shaded bars indicate negative stock-monetary policy comovement on the announcement day, while blue bars denote announcements marked by positive stock-bond comovement.

Table 2: Spillovers to the 1 year Treasury yield, conditional on convenience yields

	(1) Y_1	(2) Y_1	(3) Y_1	(4) Y_1	(5) Y_1	(6) Y_1
ECB	-1.04***	-1.05***	-0.99***	-0.69***	-0.63***	-1.11***
	(0.18)	(0.19)	(0.20)	(0.19)	(0.20)	(0.19)
Y_1^{us} - Y_1^{eu}					-0.31	-0.31
					(0.46)	(0.43)
FFR_{t-1}			0.39**		0.52	0.56
			(0.15)		(0.43)	(0.40)
MRO_{t-1}			-0.44**		-0.70	-0.83
			(0.19)		(0.56)	(0.52)
Swap spread$_1^{US}$		-0.06	-0.27	0.19	-0.00	0.15
		(0.21)	(0.26)	(0.24)	(0.36)	(0.34)
Swap spread$_1^{EU}$				-0.44**	-0.34	-0.14
				(0.21)	(0.29)	(0.27)
ECB × Swap spread$_1^{US}$		-0.07	0.28	0.19	0.51**	
		(0.17)	(0.18)	(0.21)	(0.22)	
ECB × Swap spread$_1^{EU}$				-0.40***	-0.30*	
				(0.15)	(0.16)	
ECB × Y_1^{us} - Y_1^{eu}						0.15
						(0.13)
Constant	0.14	0.11	0.03	0.19	0.40	0.56
	(0.17)	(0.18)	(0.31)	(0.18)	(0.54)	(0.51)
Observations	234	228	228	229	230	230

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 2 displays estimates regressing changes in 1-year U.S. zero coupon bond yields, term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of Treasury and Bund convenience yields. Shocks comprise first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Shaded areas denote 90% robust confidence intervals. Convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap and are normalized to have zero mean and unit variance. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

Table 3: Spillovers to the 1 year Treasury yield decomposition, conditional on convenience yields

	(1) Y_1	(2) Y_1	(3) TP_1	(4) TP_1	(5) SR_1	(6) SR_1
Target EU	0.07	0.03	-0.41***	-0.39***	0.70***	0.61***
	(0.20)	(0.20)	(0.12)	(0.12)	(0.23)	(0.22)
Path EU	-1.17***	-1.16***	-0.16	-0.19	-1.04***	-1.03***
	(0.21)	(0.21)	(0.12)	(0.12)	(0.23)	(0.23)
LSAP EU	-0.16	-0.19	-0.42***	-0.42***	-0.07	-0.05
	(0.21)	(0.21)	(0.12)	(0.13)	(0.24)	(0.24)
Y_1^{us} - Y_1^{eu}		-0.35		-0.31		0.57
		(0.44)		(0.26)		(0.49)
FFR_{t-1}		0.54		0.22		-0.24
		(0.41)		(0.25)		(0.46)
MRO_{t-1}		-0.71		-0.33		0.85
		(0.55)		(0.33)		(0.61)
Swap spread$_1^{US}$	0.06	0.39	-0.02	-0.06	-0.40*	-0.81**
	(0.19)	(0.35)	(0.11)	(0.21)	(0.21)	(0.39)
Swap spread$_1^{EU}$		-0.20		0.12		-0.01
		(0.28)		(0.17)		(0.31)
Target EU × Swap spread$_1^{US}$	0.67***	0.57***	0.31***	0.29***	0.33*	0.40**
	(0.15)	(0.16)	(0.09)	(0.09)	(0.17)	(0.17)
Path EU × Swap spread$_1^{US}$	-0.24*	-0.31**	-0.10	-0.09	-0.27*	-0.30*
	(0.14)	(0.14)	(0.08)	(0.09)	(0.16)	(0.16)
LSAP EU × Swap spread$_1^{US}$	-0.28	-0.30	0.02	0.02	-0.58	-0.59*
	(0.31)	(0.31)	(0.18)	(0.19)	(0.36)	(0.35)
Constant	0.07	0.48	0.39***	0.69**	-0.37*	-1.49**
	(0.18)	(0.53)	(0.11)	(0.31)	(0.20)	(0.59)
Observations	233	233	233	233	233	233

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3 displays estimates regressing changes in the 1-year U.S. term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of Treasury and Bund convenience yields (expressed as z-scores). Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year Gilt yields. Convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

Table 4: Spillovers to the 5 year Treasury yield, conditional on convenience yields

	(1) Y_5	(2) Y_5	(3) Y_5	(4) Y_5	(5) Y_5	(6) Y_5
ECB	-1.58***	-1.78***	-1.78***	-1.78***	-1.94***	-1.93***
	(0.37)	(0.41)	(0.41)	(0.45)	(0.45)	(0.39)
Y_5^{us} - Y_5^{eu}					-1.14	-1.37
					(0.86)	(0.86)
FFR_{t-1}			0.11		0.73	0.89
			(0.32)		(0.59)	(0.58)
MRO_{t-1}			-0.24		-1.34	-1.61
			(0.74)		(1.05)	(1.04)
Swap spread$_5^{US}$		-0.23	-0.02	-0.45	-0.15	-0.24
		(0.39)	(1.02)	(0.39)	(1.07)	(1.06)
Swap spread$_5^{EU}$				-0.51	-0.48	-0.54
				(0.37)	(0.41)	(0.41)
ECB × Swap spread$_5^{US}$		0.61**	0.58*	0.52*	0.38	
		(0.30)	(0.30)	(0.30)	(0.30)	
ECB × Swap spread$_5^{EU}$				-0.09	-0.03	
				(0.32)	(0.33)	
ECB × Y_5^{us} - Y_5^{eu}						-0.02
						(0.37)
Constant	0.64*	0.59	0.76	0.47	2.18	2.45*
	(0.36)	(0.36)	(1.03)	(0.37)	(1.45)	(1.43)
Observations	234	230	230	230	230	230

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4 displays estimates regressing changes in 5-year U.S. zero coupon bond yields, term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of Treasury and Bund convenience yields. Shocks comprise first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, 5-, 10-year German, Italian, French, and Spanish bond yields. Shaded areas denote 90% robust confidence intervals. Convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap and are normalized to have zero mean and unit variance. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

Table 5: Spillovers to the 5 year Treasury yield decomposition, conditional on convenience yields

	(1) Y_5	(2) Y_5	(3) TP_5	(4) TP_5	(5) SR_5	(6) SR_5
Target EU	-0.46	-0.30	-0.51*	-0.52*	-0.18	-0.15
	(0.47)	(0.47)	(0.30)	(0.31)	(0.27)	(0.27)
Path EU	-2.40***	-2.57***	-0.73***	-0.75***	-1.33***	-1.37***
	(0.41)	(0.41)	(0.26)	(0.27)	(0.23)	(0.24)
LSAP EU	-0.39	-0.26	-0.07	-0.02	-0.28	-0.22
	(0.57)	(0.58)	(0.37)	(0.37)	(0.32)	(0.33)
Y_5^{us} - Y_5^{eu}		-1.29		-0.35		-0.63
		(0.84)		(0.55)		(0.48)
FFR_{t-1}		0.84		0.10		0.53
		(0.57)		(0.37)		(0.32)
MRO_{t-1}		-1.20		-0.13		-0.74
		(1.01)		(0.66)		(0.57)
Swap $spread_5^{US}$	-0.35	-0.59	0.11	-0.05	0.07	0.11
	(0.38)	(1.04)	(0.25)	(0.68)	(0.22)	(0.59)
Swap $spread_5^{EU}$		-0.32		0.05		-0.05
		(0.41)		(0.26)		(0.23)
Target EU $\times$ Swap $spread_5^{US}$	0.12	-0.12	0.07	0.07	0.40**	0.32*
	(0.31)	(0.32)	(0.20)	(0.21)	(0.18)	(0.18)
Path EU $\times$ Swap $spread_5^{US}$	0.08	0.09	0.18	0.19	-0.15	-0.11
	(0.28)	(0.29)	(0.18)	(0.19)	(0.16)	(0.16)
LSAP EU $\times$ Swap $spread_5^{US}$	-0.18	-0.01	0.45	0.47	-0.47	-0.40
	(0.65)	(0.66)	(0.42)	(0.43)	(0.37)	(0.37)
Constant	0.42	1.81	0.66***	0.98	0.05	0.80
	(0.36)	(1.40)	(0.23)	(0.91)	(0.20)	(0.80)
Observations	233	233	233	233	233	233

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5 displays estimates regressing changes in the 5-year U.S. term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of Treasury and Bund convenience yields (expressed as z-scores). Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year Gilt yields. Convenience yields are proxied by the spread between the sovereign bond yield and the maturity matched overnight index swap. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

Table 6: Spillovers to the 10 year Treasury yield decomposition, conditional on net bond supply

	Term Premium				Expected Path of Short Rates			
	(1) TP_{10}	(2) TP_{10}	(3) TP_{10}	(4) TP_{10}	(5) SR_{10}	(6) SR_{10}	(7) SR_{10}	(8) SR_{10}
ECB	-0.78***	-0.79***	-0.70**	-0.72**	-0.73***	-0.73***	-0.73***	-1.08***
	(0.28)	(0.28)	(0.28)	(0.28)	(0.18)	(0.18)	(0.19)	(0.18)
Float/GDP (US)	-0.35	-0.52	0.02	0.07	-0.03	-0.01	-0.15	-0.36
	(0.26)	(0.33)	(0.59)	(0.68)	(0.17)	(0.22)	(0.40)	(0.43)
FFR_{t-1}		-0.16	-0.03	-0.17		0.02	-0.06	0.73***
		(0.20)	(0.26)	(0.39)		(0.13)	(0.17)	(0.25)
Y_{10}^{us} - Y_{10}^{eu}			-0.59	-0.28			0.16	-1.31**
			(0.55)	(0.80)			(0.37)	(0.51)
Float/GDP (EU)				0.18				-0.07
				(0.37)				(0.23)
MRO_{t-1}				0.23				-1.56***
				(0.60)				(0.38)
ECB $\times$ Float/GDP (US)	-0.39	-0.40	-0.34	-0.39	-0.50***	-0.50***	-0.50***	-0.01
	(0.28)	(0.28)	(0.27)	(0.28)	(0.18)	(0.18)	(0.18)	(0.18)
Constant	0.77***	1.02***	1.29***	0.85	0.21	0.18	0.14	2.35***
	(0.26)	(0.39)	(0.44)	(1.10)	(0.17)	(0.26)	(0.29)	(0.70)
Observations	234	234	230	228	234	234	230	228

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6 displays estimates regressing changes in 10-year U.S. zero coupon term premia, and expected path of short rates on the z-scores of ECB monetary policy shocks, conditional on the lagged level of U.S. and Euro area debt outstanding (less central bank purchases) as a percent of GDP, expressed in z-scores and lagged one quarter. ”Float/GDP” in the table refers to debt outstanding that is available to the public (e.g., net of central bank holdings). Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year yields. Estimates are obtained using Huber biweights, robust standard errors appear in parentheses.

Table 7: Spillovers to the 10 year Treasury yield decomposition, conditional on intermediary constraints

	Term Premium			Expected Path of Short Rates		
	(1)	(2)	(3)	(4)	(5)	(6)
	TP_{10}	TP_{10}	TP_{10}	SR_{10}	SR_{10}	SR_{10}
ECB	-0.86***	-0.86***	-0.81***	-0.88***	-0.88***	-0.88***
	(0.29)	(0.29)	(0.28)	(0.19)	(0.19)	(0.19)
10yr G10 CIP deviations	-0.04	-0.02	0.58	0.07	0.11	0.04
	(0.26)	(0.35)	(0.41)	(0.17)	(0.22)	(0.28)
FFR_{t-1}		0.02	0.16		0.03	-0.02
		(0.21)	(0.22)		(0.14)	(0.15)
Y^{us}_{10} - Y^{eu}_{10}			-0.90**			0.08
			(0.37)			(0.25)
ECB × 10yr G10 CIP deviations	-0.61**	-0.61**	-0.60*	-0.10	-0.10	-0.12
	(0.31)	(0.31)	(0.31)	(0.20)	(0.20)	(0.21)
Constant	0.83***	0.81**	1.33***	0.17	0.12	0.10
	(0.26)	(0.40)	(0.43)	(0.17)	(0.26)	(0.29)
Observations	233	233	229	233	233	229

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7 displays estimates regressing changes in the 10-year Treasury term premium and expected path pf short rates on ECB monetary policy shocks, conditional the first principal component of G10 cross currency bases against the USD, expressed in z-scores and lagged by one calendar day. Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year sovereign bond yields. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

Table 8: Spillovers to the 10 year Treasury yield, conditional on intermediary constraints

	Yield			**Term Premium**			**Exp. Path of Short Rates**		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Y_1	Y_5	Y_{10}	TP_1	TP_5	TP_{10}	SR_1	SR_5	SR_{10}
ECB	-1.09***	-1.98***	-1.72***	-0.21*	-0.71***	-0.53*	-0.60**	-1.00***	-0.91***
	(0.20)	(0.42)	(0.43)	(0.11)	(0.26)	(0.30)	(0.23)	(0.23)	(0.20)
FFR_{t-1}									
End of Quarter=1	0.15	-0.41	-2.41*	-0.22	-1.03	-1.72**	-0.39	0.59	0.18
	(0.55)	(1.14)	(1.27)	(0.32)	(0.76)	(0.87)	(0.63)	(0.63)	(0.54)
End of Quarter=1 × ECB	1.50***	1.70*	-1.43	-1.64***	-1.92**	-2.97***	2.34***	1.71***	1.46***
	(0.45)	(0.93)	(1.42)	(0.36)	(0.85)	(0.97)	(0.52)	(0.52)	(0.44)
Constant	0.16	0.73*	1.06***	0.35***	0.75***	0.90***	-0.10	0.09	0.18
	(0.19)	(0.38)	(0.40)	(0.10)	(0.24)	(0.27)	(0.21)	(0.21)	(0.18)
Observations	234	234	233	233	233	233	234	234	234

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8 displays estimates regressing changes in 10-year Treasury yields on ECB monetary policy shocks, conditional an indicator equal to one in the last three weeks of the month. Shocks comprises the first principal component of intradaily changes in the following: 1-, 3-, 6-, and 24-month OIS rates, along with 5- and 10-year sovereign bond yields. Estimates are obtained using Huber biweights and robust standard errors appear in parentheses.

Table 9: Spillovers to the 10 year Treasury yield, conditional on inflation anchoring

	Term Premium				Expected Path of Short Rates			
	(1) TP_{10}	(2) TP_{10}	(3) TP_{10}	(4) TP_{10}	(5) SR_{10}	(6) SR_{10}	(7) SR_{10}	(8) SR_{10}
ECB	0.07	0.07	0.11	0.06	-0.36	-0.36	-0.31	-0.29
	(0.34)	(0.34)	(0.34)	(0.34)	(0.23)	(0.23)	(0.23)	(0.24)
$\pi^e \notin \{Q25, Q75\}$=1	-0.76	-0.81	-0.72		-0.67*	-0.72**	-0.77**	
	(0.51)	(0.54)	(0.53)		(0.34)	(0.36)	(0.36)	
FFR_{t-1}		-0.05	-0.12	-0.09		-0.06	-0.09	-0.10
		(0.16)	(0.16)	(0.16)		(0.11)	(0.11)	(0.11)
Y^{us}_{10} - Y^{eu}_{10}			-0.41	-1.17***			0.18	0.25
			(0.30)	(0.44)			(0.20)	(0.30)
$\pi^e > Q75$=1				-1.64**				-0.68
				(0.65)				(0.45)
$\pi^e < Q25$=1				0.81				-0.94
				(0.86)				(0.59)
$\pi^e \notin \{Q25, Q75\}$=1 $\times$ ECB	-2.13***	-2.14***	-2.14***		-1.11***	-1.11***	-1.17***	
	(0.54)	(0.54)	(0.53)		(0.36)	(0.36)	(0.36)	
$\pi^e > Q75$=1 $\times$ ECB				-1.63***				-1.39***
				(0.59)				(0.41)
$\pi^e < Q25$=1 $\times$ ECB				-3.48***				-0.53
				(0.83)				(0.57)
Constant	1.14***	1.25**	1.60***	2.09***	0.54**	0.65**	0.53	0.49
	(0.36)	(0.49)	(0.53)	(0.56)	(0.24)	(0.32)	(0.36)	(0.39)
Observations	234	234	230	230	234	234	230	230

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

9

Table 10: ECB Spillovers Conditional on Risk Sentiment

	(1) Y_5	(2) TP_5	(3) SR_5	(4) Y_5	(5) TP_5	(6) SR_5	(7) Y_5	(8) TP_5	(9) SR_5	(10) Y_5	(11) TP_5	(12) SR_5
ECB	-1.60***	-0.95***	-1.13***	-1.60***	-0.98***	-0.77***	-2.23***	-0.91***	-1.09***	-2.33***	-0.71**	-1.17***
	(0.38)	(0.23)	(0.20)	(0.40)	(0.25)	(0.21)	(0.47)	(0.30)	(0.26)	(0.45)	(0.29)	(0.25)
MPU_{t-1}	-0.33	0.07	-0.10									
	(0.42)	(0.25)	(0.22)									
ECB × MPU_{t-1}	0.18	0.70***	-0.75***									
	(0.40)	(0.25)	(0.21)									
EPU_{t-1}				0.21	0.15	0.14						
				(0.39)	(0.24)	(0.21)						
ECB × EPU_{t-1}				-0.15	0.41*	-0.54***						
				(0.38)	(0.24)	(0.20)						
$MOVE_{t-1}$							-0.23	0.41*	-0.24			
							(0.35)	(0.22)	(0.20)			
ECB × $MOVE_{t-1}$							0.39	0.15	0.19			
							(0.32)	(0.20)	(0.18)			
VIX_{t-1}										-0.73**	0.31	-0.51**
										(0.37)	(0.23)	(0.20)
ECB × VIX_{t-1}										0.29	-0.06	0.45***
										(0.29)	(0.18)	(0.16)
Constant	0.45	0.80***	0.01	0.57	0.58**	0.17	0.56	0.75***	0.08	0.51	0.73***	0.07
	(0.40)	(0.24)	(0.21)	(0.39)	(0.24)	(0.21)	(0.36)	(0.23)	(0.20)	(0.36)	(0.23)	(0.20)
Observations	234	234	234	234	234	234	233	233	233	233	233	233

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

bloop