Central Bank Communication and the Yield Curve*

Matteo Leombroni
Stanford[†]

Andrea Vedolin
LSE[‡]

Gyuri Venter
CBS[§]

Paul Whelan
CBS[¶]

Abstract

We extract novel measures of ECB target rate announcement and communications shocks using high frequency data on money market rates and study their impact on yields of Eurozone countries. We find that (i) target rate shocks have little effect on changes in bond yields of Eurozone countries, while communication shocks have a significant impact, with intermediate maturities being affected the most; (ii) positive (negative) communication shocks significantly lower (raise) the yield spread between the peripheral and core countries; (iii) this cross-sectional difference arises after the 2008 financial crisis; (iv) higher credit risk amplifies the effect of communication shocks, and more so for core countries. Taken together our findings suggest that forward-guidance had the unintended consequence of reversing unconventional monetary policy tools designed to reducing yields in peripheral countries. We rationalize these findings in a parsimonious international term structure model in which interest rates are determined by the interaction between risk-averse arbitrageurs and reaching-for-yield investors.

Keywords: interest rates, monetary policy, sovereign bonds, reaching for yield.

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†Department of Economics, Email: leombm@stanford.edu

‡Department of Finance & CEPR, Email: a.vedolin@lse.ac.uk

§Department of Finance, Email: gv.fi@cbs.dk

¶Department of Finance, Email: pawh.fi@cbs.dk

The effectiveness of monetary policy does not depend solely on the control of short-term interest rates, but also on the central bank's ability to shape market expectations of how interest rates and inflation are likely to evolve over time.[1] The two key challenges when studying the transmission mechanism of monetary policy on asset prices are i) the correct identification of monetary policy shocks, since changes in interest rates are not exogenous to the economy, and ii) to disentangle the effect of target rate changes from forward guidance, i.e., information about the intended future path of interest rates.[2] Recent research using US data shows that monetary policy shocks extracted around central bank announcements have significant effects on asset prices, and that much of the news about monetary policy at the time of announcements arises from forward guidance; this is because changes in the current target rate are often fully expected.

In this paper, we propose a novel methodology to extract monetary policy shocks around European Central Bank (ECB) announcements based on high-frequency data that allows for an identification of target rate and communication shocks, and study their impact on yields of Eurozone countries. We first document that target rate shocks have an insignificant effect on bond yields of most countries and maturities. On the other hand, shocks during the communication window have both economically large and highly statistically significant effects on bond yields, especially at intermediate maturities; hence, forward guidance matters. Further, while the effect of monetary policy on bond yields is not statistically different across core and peripheral countries before the 2008 financial crisis, we observe large cross-sectional differences across countries when focusing on the most recent years, with yields in peripheral countries being less affected than in core countries. We rationalize these findings in a parsimonious international

[1] Some monetary economists argue that the management of expectations is *the* task of monetary policy. For example, Svensson (2004) writes: "monetary policy is to a large extent the management of expectations," and, according to Woodford (2003), "not only do expectations about policy matter, but ... very little else matters."

[2] To address the endogeneity problem, the literature has proposed the use of structural vector autoregressions (Christiano, Eichenbaum, and Evans (1999)), using changes in interest rates orthogonal to the information contained in internal Fed forecasts (Romer and Romer (2004)), a heteroskedasticity approach on the variance-covariance matrix of daily yields (Boyarchenko, Haddad, and Plosser (2015)), and identification using high frequency changes to interest rates around announcements (Cochrane and Piazzesi (2002)). Furthermore, in order to separate target from forward guidance shocks, latent factors extracted from high-frequency yield changes in a narrow window around FOMC announcements are rotated and normalized in a way, such that the second factor is restricted to only affect longer maturity yields (Gürkaynak, Sack, and Swanson (2005)).

term structure model where interest rates are determined by the interaction between risk-averse arbitrageurs and reaching-for-yield investors.

Most central banks inform the public about their monetary policy decisions on the day they are taken; however, they differ starkly in how they communicate decisions to the market. For example, the Federal Reserve provides a short press release containing the policy decision, a concise explanation of its underlying reasoning, and (at times) some forward guidance at the same time. In contrast, the ECB not only releases a press statement with the current policy decision, but also holds a press conference on the day of Governing Council meetings, including a question and answer session, 45 minutes after the rate decision has been publicised.[3] Hence, the institutional details of the ECB allow us to decompose intraday changes in the Euro area money market yield curves into news related to the level of the ECB policy interest rate and news related to the future path of monetary policy.[4] We measure the two separate effects by extracting monetary policy shocks using high-frequency data on money market rates in a narrow window bracketing the target rate announcement and press conference and study their impact on yields of sovereign bonds in six Eurozone countries for the years 2001 to 2014.

We document the following empirical findings: First, while we find little effect of target rate shocks on changes in bond yields of Eurozone countries, communication shocks have a significant impact, with intermediate maturities being affected the most. The effect of communication shocks on bond yields is not only statistically significant but also economically relevant; for example, two-year German bond yields move 75bps as a response to a 100bp change in the communication shock. The strong effect of monetary policy shocks decreases as we move from core to peripheral countries, core countries defined as Germany, France, and Netherlands, and peripheral countries being Italy, Spain,

[3]The ECB publishes a press release announcing its policy rate, i.e., the minimum bid rate for the main refinancing operations of the Eurosystem, decision at 13:45 CET. The press release normally only contains information about the ECB's policy rates. At 14:30 CET, the ECB president and Vice-President hold a press conference, during which they discuss the future path of monetary policy (forward guidance on interest rates), as well as announcing any additional non-standard measures.

[4]The ECB explicitly acknowledges the importance of its monthly press conference. For example, in its Monthly Bulletin of November 2002 (p. 62), they write: "a correct interpretation by the market of the monetary policy decisions taken by the central bank reduces the volatility of interest rates," and hence "a good understanding of monetary policy allows private agents to better manage and hedge their risks, which may contribute to reducing market uncertainty and enhancing economic welfare."

and Portugal.[5] For example, for any 100bp communication shock, there is on average a 40bp change in bond yields of peripheral countries – a 12% weaker effect compared to core countries. Second, a positive (negative) communication shock significantly lowers (raises) the yield spread at intermediate maturities between the peripheral and core countries. Since the cumulative effect of communication shocks in the aftermath of the financial crisis is negative, we conclude that forward guidance has increased the yield spread. This is notable, because the effect of communication dampened the intentions of the unconventional monetary policy tools aiming to decrease bond yields of peripheral countries, such as the Securities Markets Program (SMP), the Outright Monetary Transaction (OMT), and the Long-Term Refinancing Operations (LTROs). Third, we investigate the effect of cross-country heterogeneity in credit risk. In panel regressions, we find that higher credit risk amplifies the effect of communication shocks, and more so for core countries than for peripheral ones. The effect of target rate shocks, on the other hand, decreases when the credit risk of a peripheral country increases, while it is largely unaffected in core countries. Last, given these results, we study how the importance of announcements has changed over time. Excluding the recent Eurozone crisis period, we find that positive (negative) target rate shocks significantly increase (decrease) bond yields, with the effect being the strongest at the short-end and becoming insignificant as bond maturities exceed seven years. Moreover, this effect is basically indistinguishable between core and peripheral countries. In contrast, when focusing on the crisis period only, we find the effect of communication shocks to be significantly larger on core countries compared to peripheral countries.

We rationalize our empirical findings in a parsimonious international dynamic equilibrium term structure model in which interest rates are determined through the interaction between risk-averse arbitrageurs and yield-oriented investors. Our focus on reaching for yield investors is motivated by recent empirical evidence that documents a tilt towards risky assets as a response to to announcements of forward guidance (see e.g., DiMaggio and Kacperczyk (2016) for the U.S. and Barbu, Fricke, and Moench (2016) for the Eurozone). These investors, instead of focusing purely on the risk-return tradeoff when investing in bonds, the latter type of agents also care about the shape of the current

[5]Our sample of countries accounts for about 84% of the total GDP of the Eurozone.

yield curve: in effect, if the yield (or forward) curve is upward sloping, reaching-for-yield investors want to buy more long-maturity bonds for each unit of interest rate risk the bond bears.[6] Because bond yields are the average expected returns earned through the lifetime of bonds, which depend on expected future risk-free rates and risk premia, when the central bank announces changes to either the current target rate or the intended future path of monetary policy, yield curves can be affected via two channels.

A direct impact operates through the expectation channel. A positive current target rate shock increases all future expected target rates, but due to mean reversion, its effect dies out over time. Thus, current long yields are less sensitive to target rate shocks than short yields. At the same time, forward guidance provides information about intended future (medium-term) target rates, so a positive communication shock increases medium-term yields while leaving short and long yields intact, corresponding to a hump-shaped response across maturities.

The second, indirect effect works through the risk premium channel: shocks, by influencing the demand of yield-oriented investors, effectively manifest as changes to the relative net supply of bonds that risk-averse arbitrageurs have to hold in equilibrium. A positive target rate shock that lifts short-term yields more than long-term yields implies that reaching-for-yield investors are less willing to hold long-term bonds against short-term bonds. As the former are riskier, risk-averse arbitrageurs, who have to hold more in equilibrium, demand a higher risk premium on them. Hence, the risk premium channel amplifies the direct effect of target rate shocks for all maturities. At the same time, a positive communication shock that lifts medium-term yields more than short or long yields via the expectation channel also shifts the relative demand of yield-oriented investors for medium-term bonds instead of long bonds. In turn, this change in relative net supplies translates to a decreasing equilibrium risk premium on medium-term bonds, but an increasing one on long bonds. Therefore, the risk premium channel dampens the direct effect of a communication shocks on medium-term yields, while amplifies

[6]For empirical evidence on investors "reaching for yield," in the Eurozone see, e.g., Acharya and Steffen (2015). In their paper, the authors show that some of the European commercial banks pursued high economic risk and return investing in high-yielding long-term government debt financed with low-yielding short-term wholesale funds. Barbu, Fricke, and Moench (2016) empirically document a strong link between expectations about future short-rates and reaching for yield behavior of German investment funds since 2009.

it for long yields: the hump shifts towards longer maturities. The difference in the proportion of yield-oriented investors across countries implies that the indirect effect is more prominent in peripheral countries than in core countries. Hence, our model provides an understanding of how target rate and communication shocks affect the term structure in equilibrium, both in the cross-section of maturities and across countries.

Related literature: A large empirical literature extracts monetary policy shocks from money market rates. Kuttner (2001) measures the unexpected change in the current policy rate with changes in the price of Federal Funds futures that settles in the month containing the meeting. Kohn and Sack (2004) measure the variance of asset price changes on days of FOMC meetings with and without accompanying post-meeting statements, and find that issuing a statement substantially increases the variance of fed funds futures contracts dated 3 months ahead as well as Eurodollar futures contracts dated 2 and 4 quarters ahead. Gürkaynak, Sack, and Swanson (2005) measure changes in fed funds futures and eurodollar futures contracts with one year or less to expiration over a 30 minute windows centered on FOMC announcements. They then demonstrate that these changes have a two-factor structure, labelled as the target and path factor, which account for nearly all of the sample variance, and the latter captures the effect of forward guidance on expected future policy rates. Swanson (2016) adapts the method of Gürkaynak, Sack, and Swanson (2005) to account for the zero lower bound period and extracts two factors, one representing forward guidance and the other "large-scale asset purchases." He shows that forward guidance is more effective at moving short-term yields, while LSAPs are more effective at longer maturity yields and corporate bond yields. Boyarchenko, Haddad, and Plosser (2015) consider changes in the variance-covariance matrix of the entire nominal yield curve around scheduled FOMC meetings, and identify the covariance matrix of monetary policy shocks.

Further, several papers study the effect of monetary policy shocks extracted from high-frequency data on the U.S. term structure during conventional and unconventional monetary policy. For example, Hanson and Stein (2015) find large responses of long-term nominal and real rates to monetary policy shocks, and explore the transmission of monetary policy on real term premia using changes in the two-year nominal yield.

Similarly, Nakamura and Steinsson (2015) show that long-term nominal and real interest rates respond roughly one to one to monetary policy shocks extracted as the first principal component from a cross-section of different interest rate futures. Different from these papers, by focusing on the ECB, we can clearly identify both target rate and communication shocks as these are announced at different times.

Our paper also contributes to a recent empirical literature that analyzes the effects of ECB policies on yields. Most of the literature focuses on the most recent period when the ECB started to implement unconventional monetary policy tools such as the direct purchases of government debt (the SMP), conditional commitments to purchase government debt (the OMT), and 3-year loans to banks which banks partly used to buy government debt (the LTROs), aimed to lower bond yields of distressed countries.[7] Different from these papers, we focus on the effect of conventional monetary policy over a 14-year period with a special emphasis on the difference between target rate and communication shocks.

Several papers have studied how central bank communication can affect asset prices. Ehrmann and Fratzscher (2005) compare the communication strategies of the Federal Reserve, the Bank of England, and the ECB. Their findings suggest that central bank communication is a key determinant of the market's ability to anticipate monetary policy decisions and the future path of interest rates. Rosa and Verga (2008) examine the effect of ECB communication on the price discovery process in the Euribor futures market using a tick-by-tick dataset. Their results show that the unexpected component of ECB explanations has a significant and sizeable impact on Euribor futures prices. Brand, Buncic, and Turunen (2010) extract target and communication shocks for ECB announcements using the factor rotation methodology of Gürkaynak, Sack, and Swanson (2005) and study their impact on forward rates. Different from these papers, we study the effect of target rate and communication shocks across countries, both empirically and theoretically.

Finally, our paper also contributes to the theoretical literature that explores the effect of monetary policy and bond supply on the term structure of interest rates. We build on

[7] See, e.g., Altavilla, Giannone, and Lenza (2014), Krishnamurthy, Nagel, and Vissing-Jorgensen (2015), Acharya, Eisert, Eufinger, and Hirsch (2015), and Falagiarda and Reitz (2015), among others.

the framework developed by Vayanos and Vila (2009), in which risk-averse arbitrageurs demand higher risk premiums on bonds if their exposure to interest-rate risk increases due to shifts in the net supply of bonds. Greenwood and Vayanos (2014) use this theoretical framework to study the implications of a change in the maturity structure of government debt supply, and Hanson (2014) and Malkhozov, Mueller, Vedolin, and Venter (2016) extend the model to include mortgage backed securities. In these papers risk premia are driven solely by net supply, and they cannot be extended trivially to account for news on future policy rates. In contrast, our framework incorporates forward guidance into the risk premium channel, while also providing a multi-country setting that can allow for additional dimensions of heterogeneity, including the amount of government debt and credit risk.

The rest of the paper is organized as follows. Section 1 outlines an identification strategy to back out target rate and communication shocks. Section 2 describes how we extract monetary policy shocks and describes the other data used. Section 3 contains our main empirical findings regarding the effect of monetary policy shocks on Eurozone countries' yields. These findings are then rationalized in a parsimonious general equilibrium model in Section 4. Finally, Section 5 concludes.

1 Identification of Monetary Policy Shocks

In this section, we outline the identification strategy for monetary policy shocks around target rate announcement and the press conference. Earlier literature (see, e.g., Gürkaynak, Sack, and Swanson (2005)) identifies target and path factors using principal component analysis in a tight window bracketing monetary policy announcements. As rate announcements and forward guidance happen at the same time in the U.S., the identification is done by restricting the second principal component to have no effect on the short-end of the yield curve after a factor rotation. In contrast, since target rate and forward guidance take place in different time windows for ECB announcements, our approach does not rely on imposing any restrictions and the two shocks can be identified separately. In the following, we present a simple model of the term structure to illustrate how we identify monetary policy shocks.

Assume the existence of default-free zero-coupon yield and swap curves. The short rate r_t paid on an instantaneous money market account is exogenous, and its dynamics under the physical probability measure follows

$$dr_t = \kappa_r (\theta_t - r_t)\, dt + \sigma_r dB_{r,t}, \tag{1}$$

where

$$d\theta_t = \kappa_\theta \left(\bar{\theta} - \theta_t\right) dt + \sigma_\theta dB_{\theta,t}. \tag{2}$$

According to (1), the short rate r_t mean-reverts to θ_t, which is itself time-varying; κ_r and κ_θ denote the speed of mean reversion of the short rate and its mean, respectively, σ_r and σ_θ are the instantaneous volatilities, and $\bar{\theta}$ is the unconditional long-run mean of θ_t and hence of r_t. We think of r_t as being the target rate set by the central bank, and interpret $dB_{r,t}$ as changes to the target rate unexpected by investors, and $dB_{\theta,t}$ as the unexpected component of changes to the future path of interest rates, i.e., forward guidance or communication shocks.

In this setting, one obtains an exponential affine bond pricing function so long as the market prices of risk are affine. If the affine prices of risk only depend on the two above factors, bond yields are also affine in r_t and θ_t, and Itô's lemma implies yield dynamics are given by

$$dy_t^\tau = \mu_t^\tau dt + \sigma_{y,r}^\tau dB_{r,t} + \sigma_{y,\theta}^\tau dB_{\theta,t}, \tag{3}$$

with constant volatilities $\sigma_{y,r}^\tau$ and $\sigma_{y,\theta}^\tau$.

The goal is to identify the Brownian motions $B_{r,t}$ and $B_{\theta,t}$ that correspond to the target rate and communication shocks, respectively. In a frictionless world, under the assumption of having only two Brownians, we can back out the two processes from observing the time series of any two yields. Moreover, if the target rate and communication shocks happen at different times, e.g., we know that $dB_{\theta,t} = 0$ in a certain time window, we can recover the Brownian process $dB_{r,t}$ from the time series of any yield changes. In fact, in this case (3) simplifies to

$$dy_t^\tau = \mu_t^\tau dt + \sigma_{y,r}^\tau dB_{r,t}, \tag{4}$$

and for any dt time interval we obtain

$$\frac{1}{dt}Var_t\left[dy_t^\tau\right] = \left(\sigma_{y,r}^\tau\right)^2. \tag{5}$$

Estimating yield volatility from the time series restricted to the target window allows us to recover a proxy for the Brownian innovation from maturity-τ yields for any τ:

$$\widehat{dB}_{r,t}^\tau = \frac{1}{\widehat{\sigma}_{y,r}^\tau}dy_t^\tau. \tag{6}$$

The same approach can also provide a proxy $\widehat{dB}_{\theta,t}^\tau$ for the time series of communication shocks.

2 Estimation of Monetary Policy Shocks

We work with tick-by-tick high frequency data that runs from February 1, 2001, to December 31, 2014. There is one scheduled ECB meeting per month, except for the years 2001 and 2008 when there were 20 and 13 meetings, respectively. This leaves us with 177 announcement days from which we exclude 17 announcements that were either not followed by a press conference, were unscheduled, or contained significant news about unconventional monetary policy.[8] The exclusion dates are summarized in Table 1. Our final sample thus consists of 160 announcement days: there are 16 days when the main refinancing rate was raised, 21 days when the interest rate was decreased, and 123 meetings with no change.

2.1 Market reaction around target rate announcement and press conference

The ECB publishes a press release announcing its policy rate decision at 13:45 CET. The press release normally only contains information about the ECB's policy rates. At 14:30

[8] We exclude the five dates with news about unconventional monetary policy, because the mechanism underlying how target rate and communication shocks affect yields during those periods are potentially different from reactions to more conventional ECB announcements. More specifically, the Securities Market Program (SMP) introduced on May 10, 2010 involved the purchase of government bonds of Greece, Ireland, and Portugal. A second round of SMP included the bonds of Italy and Spain. Upon termination of the SMP, Outright Monetary Transactions (OMTs) were introduced on September 6, 2012, which are conditional commitments to buy bonds with maturities between one and three years. Finally, the Long-Term Refinancing Operations (LTRO), which are three-year loans to Eurozone banks, partially to buy government debt, were introduced on December 8, 2011.

Table 1
Excluded ECB Announcement Days

This table lists ECB announcement dates which are excluded from our analysis. Excluded dates either include announcements which were not followed by a press conference, unscheduled meetings or days when unconventional monetary policy decisions were taken.

date	Type of announcement
February 15, 2001	No press conference
March 15, 2001	No press conference
March 29, 2001	No press conference
April 26, 2001	No press conference
May 23, 2001	No press conference
August 2, 2001	No press conference
September 17, 2001	Meeting following terrorists' attacks
September 27, 2001	No press conference
October 25, 2001	No press conference
August 1, 2002	No press conference
July 31, 2003	No press conference
October 8, 2008	Coordinated rate cut of 50bps with other central banks
May 7, 2009	Announcement of three one-year LTROs, CBPP
August 4, 2011	Announcement that SMP will cover Spain and Italy
December 8, 2011	Announcement of two three-year LTROs
August 2, 2012	Announcement of the OMT programme
September 4, 2014	Announcement of ABSPP and CBPP3 programmes

CET, the ECB President and Vice-President hold a press conference, during which they discuss the future path of monetary policy (forward guidance on interest rates), as well as announcing any additional non-standard measures. The press conference consists of an introductory statement and the Question and Answer session. The structure of the introductory statements has remained the same since the very beginning: (i) the first part reports a summary of the ECB's monetary policy decision and balance of risks to price stability, and since July 2013 it includes also an open-ended forward guidance; (ii) the second part discusses both real and monetary developments in the Euro area, and since May 2003 it is followed by a "sum-up and cross-check" paragraph, which repeats the initial synthetic assessment; (iii) finally, the ECB President concludes with some considerations on fiscal policy and structural reforms.

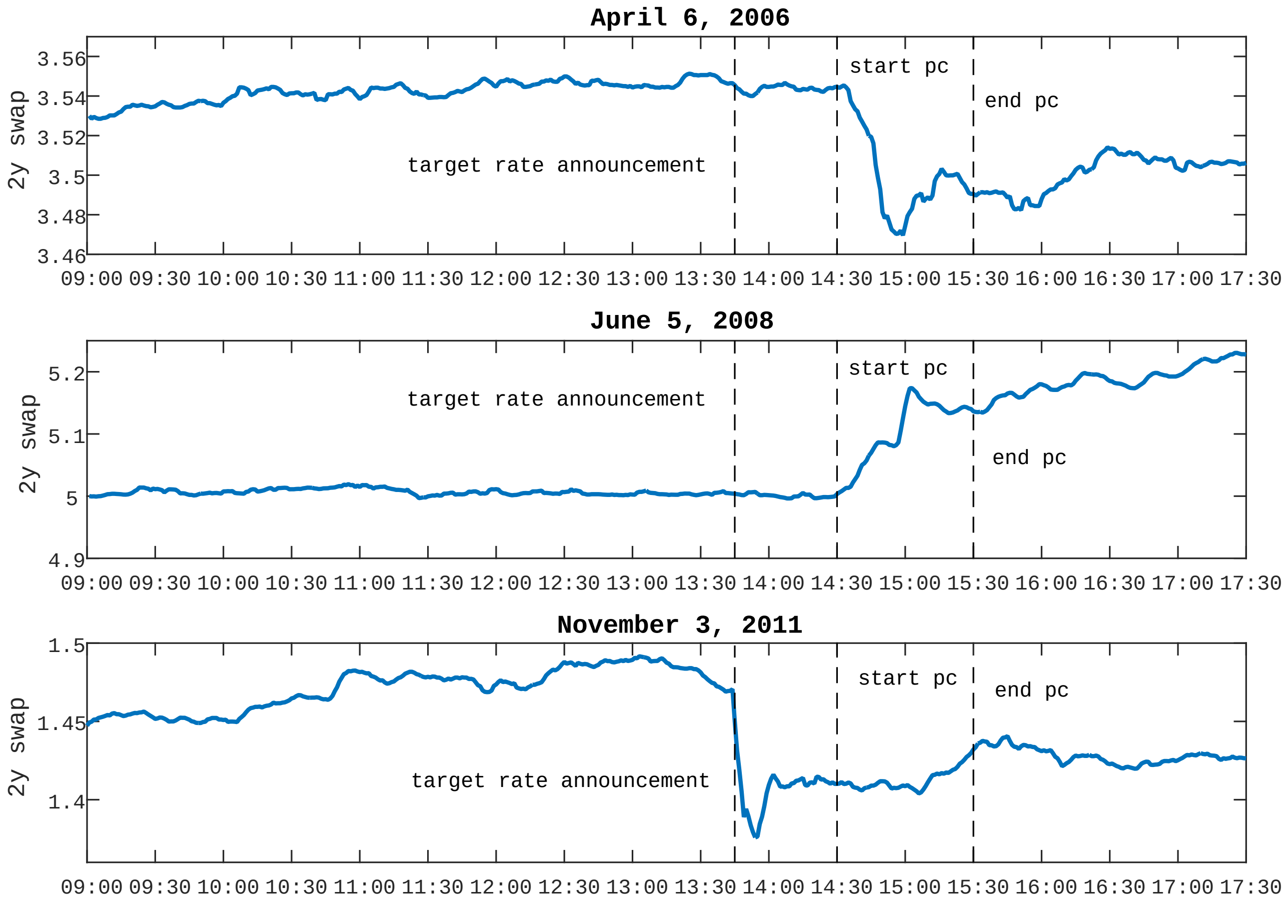

Figure 1. Two-year Swap Rate during Target Announcement and Press Conference

The figure plots the two-year swap rate on April 6, 2006 (upper panel), June 5, 2008 (middle panel) and November 3, 2011 between 09:00 and 17:30. Vertical lines represent the target rate announcement (13:45), the start of the press conference (14:30), and the end of the press conference (15:30). All times are in CET.

To get a first impression of how the target rate announcement and the press conference affect interest rates, we illustrate the market reaction in high frequency at three specific announcements. Figure 1 plots the two-year Euribor swap rate throughout the day from 09:00 to 17:30 CET for April 6, 2006 (upper panel), June 5, 2008 (middle panel) and November 3, 2011 (lower panel).

April 6, 2006: The ECB decided to keep interest rates unchanged, following a 25bps increase after the previous meeting in March. Indeed, while we find no reaction in the swap rate at the target rate announcement, there is a sharp decrease right after the start of the press conference at 14:30, when the swap rate fell from 3.54% to 3.48% within 30 minutes. Market participants did not expect any change in interest rates for the April meeting but expected an interest rate hike later in the year. However, when at the press conference Jean-Claude Trichet told the press that "the current suggestions regarding the high probability of an increase of rates in our next meeting do not correspond to the present sentiment of the Governing Council," money market rates started to fall rapidly as the market revised its expectations about future interest rates downward.

June 5, 2008: The ECB decided to keep interest rates unchanged; Trichet, however, indicated that risks to price stability have increased, and that inflation has risen significantly. The press statement also included that the Governing Council was in a "state of heightened alertness" and struck a hawkish note by emphasizing that "risks to price stability over the medium term have increased further." The first question at the Q&A was what "heightened alertness" means compared to "strong vigilance," an expression that the ECB had used previously to signal upcoming hikes. Trichet then went on to say that "we could decide to move our rates by a small amount in our next meeting." As can be seen from the lower panel, the swap rate increased from 5% to 5.15% within the first 30 minutes of the press conference. Indeed, a rate hike was then decided by the Governing Council in the next meeting, on July 3, 2008.

November 3, 2011: The ECB unexpectedly cut interest rates by 25bps for the first time in two years at Mario Draghi's first meeting as new chairman. Consequently, we see that the two-year swap rate drops from 1.46% to 1.37% within 10 minutes and then stabilizes around this level with no reaction at the press conference. The fact that the market seemed surprised by the interest rate cut is manifested in a question that a journalist asked Mario Draghi during the press conference: "President Draghi, welcome to Frankfurt. I have a few questions about today's rate decision, which came as a bit of a *surprise*. Was the decision unanimous? And can you explain the reasoning behind it, because if the economy needs it and there are very few upside risks to inflation left, why did you not cut by 50 basis points, or are you going to do that next month?"

These examples illustrate two noteworthy points: First, the importance of using high-frequency data instead of daily data, as most of the action happens within tight

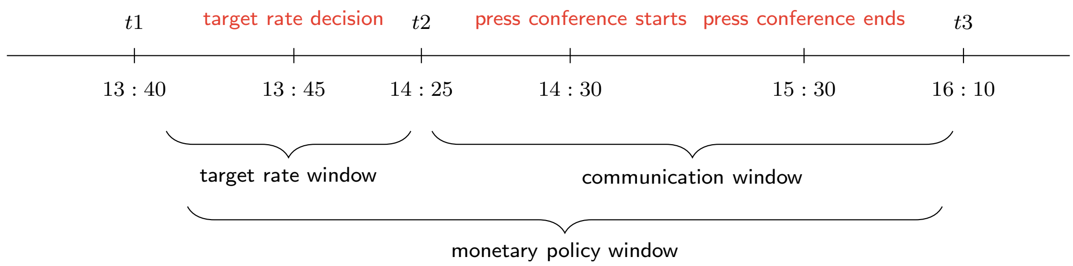

Figure 2. Monetary policy decision window

The figure illustrates the time line of ECB announcements. All times are in Central European Times (CET).

windows of several minutes, and second, the fact that "communication" can move asset prices without any specific actions taken.

2.2 Estimation

The intraday interest rate data that we employ consist of real time quotes from Reuters TickHistory. The data are unsmoothed, but we filter for mispriced quotes and sample the data at the five minute interval. To construct our monetary policy shocks, we rely on overnight index swap rates with maturities ranging between one and twelve months, and swap rates with maturities between two and five years. The target rate window is defined as a 45 minute window bracketing the 13:45 CET announcement, starting at 13:40 and ending at 14:25 CET. The communication window starts at 14:25 CET, and ends at 15:30 CET, 40 minutes after the press conference is over. We illustrate this in Figure 2. We refer to the entire window, which encompasses both the target rate and communication windows, as the monetary policy window.

Our procedure to back out target and communication shocks follows in two steps. First, while our framework presented in Section 1 assumes there is only one shock during the target rate and communication windows, we need to establish in the data how many factors are present in each window. Then we can back out the shocks using equation (6) by calculating changes in the 16 interest rates and their respective standard deviations. To establish the number of factors, we use principal components analysis on the 160 (number of announcements) $\times$ 16 (maturities) matrix of swap changes.

Table 2
Principal Components in Different Windows

An eigenvalue decomposition of a positive definite covariance matrix is $cov(dy_t^N) = Q\Lambda Q^\top$. The columns of Q contain eigenvectors and the diagonal elements of Λ contain eigenvalues. Principle components are formed by $PC_t = Qdy_t^N$. The fraction of explained variance of the k'th PC is given by $\Lambda(k,k)/\sum_k \Lambda(k,k)$. Target (Communication) captures change in yields between 13:40 and 14:25 CET (14:25 and 16:10 CET), while the monetary policy window measures yield changes between 13:40 and 16:10 CET.

	PC1	PC2	PC3
Monetary Policy	82.91%	9.94%	2.81%
Target	79.99%	12.05%	1.60%
Communication	79.86%	8.80%	5.49%

Table 2 summarizes the results for the target and communication window, as well as the monetary policy window. We note that for each of the three windows the first PC explains around 80%, and the first two PCs explain around 90% of the variation. To get a sense of the nature of these factors, Figure 3 plots the loadings of each PC on the changes in swap rates. As can be seen from Figure 3, the first PCs load virtually identically across all maturities, especially during the target rate announcement. For the communication window, PC1 has an almost zero loading on the shortest maturity interest rates, then increases until the six-month maturity and remains flat. The second components load heavily on the shortest maturity, but drop to zero around the one-year maturity and then turn negative.

To assess the statistical significance of these factors, we regress swap rate changes on the first and second PC of both the target and communication window; regression coefficients and corresponding t-statistics for each maturity are presented in Table 3. Panel A contains our results for PCs constructed during the target rate window. For PC1, we find that the t-statistics are highly significant from the shortest maturity swap rate (one month) out to five years, and adjusted R^2s range between 51% for the shortest maturity to 15% for the longest one. The second row in Panel A reports regression results for PC2; notice the significant drop in the explanatory power as well as the low t-statistics. For intermediate maturities, between five months and two years, the second

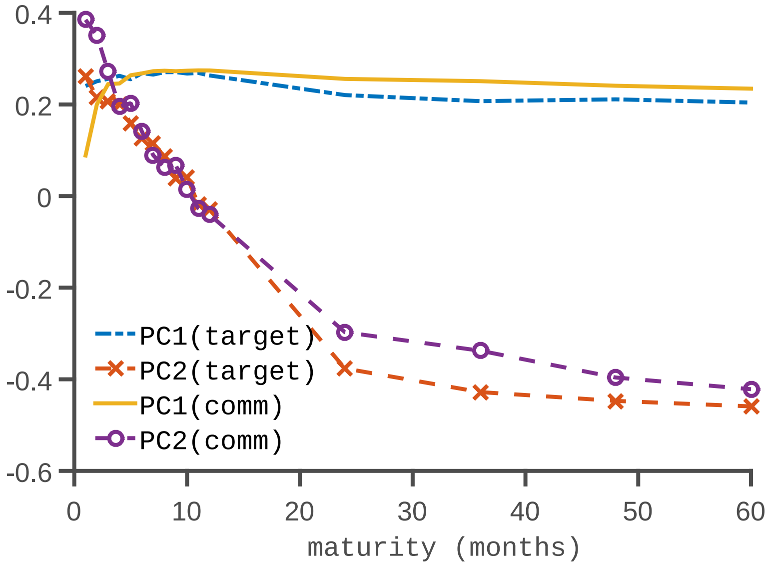

Figure 3. Principal Component Loadings

This figure plots the loadings of the first and second principal component onto swap changes with maturities ranging between one month and five years. Target refers to the principal components extracted during the target rate announcement, i.e. between 13:40 and 14:25 CET, whereas communication refers to PCs calculated from swap changes in the 14:25 to 16:10 CET window.

PC is insignificant, and then becomes negative and borderline significant going out to five years.

A very similar picture emerges for the communication window in Panel B. While the first PC is highly significant throughout all maturities, the second PC is insignificant at the short end, and estimated coefficients are negative and significant at the long end. Different from Panel A, however, coefficients for the first PC are mostly significant at the one and two year maturity, with a corresponding R^2 over 70%. This implies that the important shocks during the communication window mainly affect interest rates at intermediate maturities, whereas shocks in the target rate window mainly have an impact on the short end of the curve.

Overall, we conclude that one shock extracted from the target rate and the communication window can well explain the variation of yields throughout the day. Whereas the former is mostly responsible for movements at the short end of the term structure, communication shocks affect intermediate maturities around one and two years.

Table 3
Loadings PCs Swaps

This table reports estimated coefficients from univariate regressions from daily changes in swap rates onto the first (PC1) and second (PC2) principal components constructed from swap changes in the target or communication window around ECB monetary policy announcements:

$$dy_t^\tau = \beta_1 \times \text{shock}_t + \epsilon_t^\tau,$$

where shock_t is either the target rate (dB_t^r) or communication (dB_t^θ) shock. t-statistics are calculated using Newey and West (1987) allowing for serial correlation. Data runs from 2001 to 2014.

	1m	2m	5m	10m	1y	2y	3y	4y	5y
					Panel A: Target Window				
PC1	0.240	0.251	0.255	0.268	0.263	0.221	0.207	0.211	0.204
t-stat	(14.90)	(13.77)	(19.32)	(19.95)	(16.20)	(11.29)	(10.42)	(9.03)	(7.88)
R^2	73.96%	80.43%	83.20%	91.61%	88.74%	62.24%	54.97%	57.09%	53.37%
PC2	0.262	0.216	0.159	0.042	-0.030	-0.376	-0.428	-0.447	-0.459
t-stat	(2.89)	(2.61)	(1.89)	(0.55)	(-0.40)	(-5.82)	(-6.79)	(-5.73)	(-6.16)
R^2	13.22%	8.98%	4.86%	0.33%	0.17%	27.31%	35.30%	38.54%	40.63%
					Panel B: Communication Window				
PC1	0.074	0.172	0.197	0.238	0.240	0.240	0.229	0.224	0.219
t-stat	(2.38)	(8.42)	(11.67)	(24.20)	(22.05)	(12.26)	(11.02)	(10.07)	(9.66)
R^2	7.04%	37.99%	49.70%	72.57%	73.40%	73.50%	67.12%	64.24%	61.05%
PC2	0.118	0.113	0.047	-0.068	-0.109	-0.278	-0.324	-0.373	-0.385
t-stat	(0.88)	(1.34)	(0.42)	(-0.58)	(-0.88)	(-2.16)	(-2.61)	(-3.32)	(-3.45)
R^2	1.98%	1.81%	0.31%	0.65%	1.66%	10.92%	14.77%	19.55%	20.82%

We can now compute target rate and communication shocks as prescribed in Section 1. Given that in practice our Brownian estimates can vary depending on the maturity τ used for estimation, we apply the method of (4)-(6) to all observed yields from one-month to 5 years separately, and use the average of the $\widehat{dB}_{r,t}^{\tau}$ estimates as our final proxy $\widehat{dB}_{r,t}$ for $dB_{r,t}$. We proceed the same way to back out the communication shocks $\widehat{dB}_{\theta,t}$. We present summary statistics of the target rate and communication shocks in Table 4.[9]

[9]Notice that a more general approach can also be applied to uncover the two shocks $dB_{r,t}$ and $dB_{\theta,t}$ jointly from at least two series of yield changes over the entire window; this involves estimating a variance-covariance matrix, and multiplying yield change time-series with its inverse. As a robustness

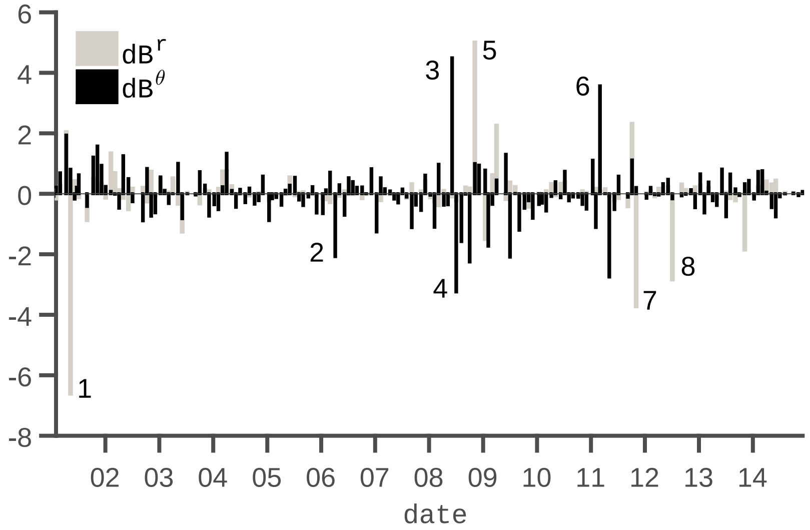

Figure 4. Time-Series of Target and Communication Shocks

This figure plots the target and communication shocks between 2001 and 2014. Target and communication shocks are calculated as in equation (6). 1) May 10, 2001: surprise 25bps cut after bad industrial production and unemployment numbers from Germany. 2) April 6, 2006: Market expected increase at next meeting but Trichet told press that this does not correspond to the current sentiment of the Governing Council. 3) June 5, 2008: Trichet announces rate hike for next meeting. 4) July 3, 2008: 25bps rate hike as expected but market expected an additional rate hike for next meeting. Trichet did not hint at possibility. 5) November 6, 2008: Largely expected cut of 50bps but market expected larger cut after the Bank of England shocked markets with a 150bps cut the same morning. 6) March 3, 2011: Trichet announces interest rate hike at next meeting. 7) November 3, 2011: Surprise 25bps cut at Draghi's first meeting. 8) July 5, 2012: 25bp cut and Draghi's announcement that "ECB will do whatever it takes."

Both target rate and communication shocks are on average positive, however, target rate shocks are a multiple larger than communication shocks: the average shock size in the target rate window is around 0.022, while it is 0.0055 in the communication window. The standard deviation is almost equally large for both shocks, however, we note that while target rate shocks feature a negative skewness, the skewness for communication shocks is positive. Finally, both target rate and communication shocks have negative first and second order autocorrelation.

Figure 4 plots the time-series of the target rate and communication shocks. The figure also contains brief annotations that help to explain some of the larger observations in the

check we perform this analysis, and obtain very similar time series as in the case that exploits the separation of the two types of shocks.

Table 4
Summary Statistics Target and Communication Shocks

This table presents summary statistics for the target and communication shocks. Target (communication) shocks are calculated from equation (6) applied to swap rate changes with maturities ranging between one-month and five years sampled between 13:40 and 14:25 CET (14:25 and 16:10 CET) on days that the ECB announces its monetary policy. Data is sampled between 2001 and 2014.

	dB^r	dB^θ
Mean	0.0222	0.0055
Std Dev	0.8908	0.8799
Min	−6.6271	−3.2502
Max	5.0223	4.5011
Skew	−1.9783	0.5581
Kurtosis	29.6300	9.3065
AR(1)	−0.1542	−0.1605
AR(2)	−0.0780	−0.0989
AR(3)	−0.0062	0.0871

figure. The first one coincides with the May 10, 2001, meeting when the ECB surprisingly cut the refinancing rate by 25bps; reasons for the surprise easing were the disappointing unemployment and industrial production numbers from Germany, published on May 8 and 9, 2001, indicating a significant slowdown of the German economy. The second event corresponds to the April 6, 2006, meeting discussed earlier. The third event is June 5, 2008, when Trichet hinted at a rate hike at the following meeting discussed before. The meeting took place on July 3, 2008 (fourth event), when indeed the ECB increased key interest rates by 25bps. Markets, however, were expecting future hikes, which Trichet usually announced with the expressions "heightened alertness" or "strong vigilance." Since he did not use either of these words at the press conference, the market revised its expectations downward. The fifth event: On November 6, 2008, the ECB lowered interest rates by an additional 50bps after a coordinated rate cut by the Federal Reserve, ECB, Bank of Canada, Bank of England, Sveriges Riksbank and the Swiss National Bank in the previous October meeting. However, the market expected a larger cut as the Bank of England announced a surprise 150bp cut the same morning. The sixth event corresponds to March 3, 2011, when Trichet hinted at a interest rate tightening at next meeting by saying at the press conference that “strong vigilance is warranted.” On November 3, 2011, Draghi surprised the market by a 25bp cut at his first meeting (seventh event). Finally, the eighth event highlighted on Figure 4: On July 5, 2012, the ECB cut interest rates by 25bps and Draghi spoke at the press conference using the now famous words “the ECB will do whatever it takes.”

2.3 Additional Data

Bond yields: We use daily bond yields of Germany, Netherlands, France, Italy, Spain and Portugal, with maturities ranging between three months and 30 years, available from Bloomberg.

Credit risk: One policy relevant question is whether monetary policy can have differential effects across countries in the Eurozone. In our empirical analysis, we focus on one particular cross-sectional heterogeneity which is credit risk. To measure the credit risk of each country, we use five-year credit default swaps (CDS) available from Markit. Since sovereign CDS data only starts to be traded frequently after 2002 and due to liquidity concerns in the early sample, we start our analysis involving CDS in January 2002. We present a summary statistic of all variables used in Table 5.

On average, German bond yields are the lowest for all maturities, and Portuguese yields are the highest. Minimum yields of the core countries Germany, Netherlands, and France are on average even negative up to a maturity of two years. Five-year CDS also increase from core to peripheral countries. For example, German CDS are on average 17bps, while Spanish and Italian CDS are almost 1% on average, and Portuguese CDS are around 2%. We also note that the Portugese CDS reached as high as 15%, while the maximum value for Germany is not even 1%.

3 Empirical analysis

In this section we study the effect of target rate and communication shocks on bond yield changes for different maturities for days on which the ECB makes their monetary policy announcements. We start with univariate regressions, then look at the effect of

Table 5
Summary Statistics CDS and Bond Yields

This table presents summary statistics for five-year CDS (first column) and bond yields (columns 2 to 10). Data is in percent and is sampled between 2002 (2001) and 2014 for CDS (bond yields).

	5y CDS	3m	6m	1y	2y	5y	10y	15y	20y	30y
					Panel A: Germany					
mean	0.173	1.869	1.898	1.984	2.124	2.687	3.374	3.772	3.988	4.034
stdev	0.175	1.543	1.539	1.530	1.489	1.394	1.175	1.096	1.072	1.090
max	0.914	4.914	4.835	4.731	4.703	4.995	5.355	5.627	5.759	6.172
min	0.013	-0.139	-0.625	-0.097	-0.104	0.021	0.574	0.915	1.213	1.431
					Panel B: Netherlands					
mean	0.295	1.881	1.910	2.007	2.207	2.845	3.577	3.870	4.051	4.113
stdev	0.265	1.542	1.541	1.521	1.472	1.311	1.101	1.022	1.025	1.066
max	1.299	4.855	4.834	4.750	4.815	5.062	5.465	5.601	5.811	6.235
min	0.011	-0.135	-0.523	-0.075	-0.040	0.095	0.718	1.050	1.262	1.490
					Panel C: France					
mean	0.311	1.923	1.937	2.013	2.228	2.895	3.673	4.065	4.222	4.357
stdev	0.354	1.521	1.503	1.488	1.424	1.231	0.964	0.865	0.840	0.799
max	1.987	4.740	4.682	4.660	4.831	4.919	5.432	5.747	5.955	6.195
min	0.015	-0.058	-0.068	-0.051	-0.048	0.183	0.851	1.408	1.661	2.003
					Panel D: Italy					
mean	0.957	2.200	2.328	2.531	2.896	3.707	4.543	5.059	5.309	5.263
stdev	1.127	1.358	1.344	1.252	1.148	0.957	0.766	0.802	0.785	0.629
max	5.015	6.530	7.904	8.169	7.842	7.761	7.347	8.232	8.597	7.370
min	0.053	0.135	0.149	0.210	0.345	1.030	2.048	2.826	3.295	3.659
					Panel E: Spain					
mean	0.912	2.108	2.246	2.455	2.867	3.673	4.480	4.866	5.008	5.180
stdev	1.114	1.341	1.283	1.220	1.097	0.969	0.891	0.929	0.897	0.798
max	5.042	5.770	6.027	6.070	6.854	7.690	7.692	7.836	7.829	7.714
min	0.023	0.016	0.046	0.114	0.192	0.776	1.678	2.428	2.681	3.273
					Panel F: Portugal					
mean	2.041	2.627	2.830	3.321	4.203	5.000	5.407	5.485	5.352	5.253
stdev	3.091	1.561	1.741	2.578	3.437	3.186	2.089	1.885	1.467	1.184
max	15.540	8.689	11.703	19.667	23.559	23.425	14.073	12.724	9.794	8.902
min	0.039	0.068	0.127	0.227	0.431	1.602	2.916	3.471	3.461	3.451

the two types of shocks jointly. Our findings reveal that target shocks matter little, while communication shocks have a highly significant impact, both statistically and economically. Regressions start in February 2001 and end in December 2014. Regressions that exclude the Eurozone crisis end in July 2008, and regressions that include CDS start in January 2002. All regression coefficients are standardized, meaning we de-mean and divide each variable by its standard deviation before running the regression. With each estimated coefficient, we report t-statistics adjusted for Newey and West (1987) standard errors.

3.1 *Univariate results*

We first want to assess the effect of target rate and communication shocks on bond yield changes. To this end, we regress daily yield changes for different countries on the target rate shock:

$$dy^{\tau}_{i,t} = \beta^{\tau}_{i,r}\widehat{dB}_{r,t} + \epsilon^{\tau}_{i,r,t}$$

and communication shock:

$$dy^{\tau}_{i,t} = \beta^{\tau}_{i,\theta}\widehat{dB}_{\theta,t} + \epsilon^{\tau}_{i,\theta,t},$$

where $dy^{\tau}_{i,t}$ is the daily change of the maturity-τ yield of country i at time t. The results are reported in Tables 6 (target rate shocks) and 7 (communication shocks).

Table 6 illustrates that, essentially, target rate shocks do not matter for any maturities in any of the countries. Except for the German and French (and borderline Dutch and Portuguese) two-year yields, we find insignificant t-statistics throughout. Communication shocks, on the other hand, are highly statistically significant, especially for intermediate maturities. For example, in Germany (Panel A), we find that for any one standard deviation change in the communication shock, there is a 0.295 standard deviation change in the shortest maturity yield, which translates to a $0.295 \times 0.8799 \times 100 = 26$ (slope coefficient times standard deviation of the communication shock) basis point change for any 100bp change in the communication shock. For the two-year maturity, this effect increases to 0.849 standard deviations or 75bps, equivalently, which then decreases again as the maturity increases. For the longest maturity, we find the effect to be 0.292 standard deviations. These estimates are all highly statistically significant

Table 6
Bond yield response to target rate shock

This table reports the results of univariate regressions of daily changes in bond yields across different maturities on target shocks for German (Panel A), France (Panel B), Netherlands (Panel C), Italy (Panel D), Spain (Panel E), and Portugal (Panel F):

$$dy^{\tau}_{i,t} = \beta^{\tau}_{i,r} dB^{r}_{t} + \epsilon^{\tau}_{i,r,t},$$

where $\tau = 3m, \ldots, 30y$. t-statistics are calculated using Newey and West (1987) allowing for serial correlation. Data runs from January 2001 to December 2014.

	3m	6m	1y	2y	5y	10y	15y	20y	30y
					Panel A: Germany				
dB^r	-0.039	0.079	0.278	0.257	0.169	0.099	0.056	0.066	0.009
t-stat	(-0.49)	(0.87)	(1.59)	(2.16)	(1.54)	(1.01)	(0.58)	(0.81)	(0.12)
R^2	0.15	0.63	7.73	6.63	2.85	0.98	0.32	0.43	0.01
					Panel B: France				
dB^r	0.308	0.364	0.292	0.259	0.138	0.026	-0.007	-0.007	-0.089
t-stat	(1.73)	(1.79)	(1.83)	(2.30)	(1.26)	(0.21)	(-0.09)	(-0.10)	(-1.38)
R^2	9.46	13.28	8.51	6.70	1.91	0.07	0.01	0.01	0.79
					Panel C: Netherlands				
dB^r	0.061	0.108	0.126	0.228	0.130	0.055	0.061	0.077	-0.009
t-stat	(0.58)	(0.82)	(0.92)	(1.66)	(0.98)	(0.47)	(0.67)	(0.97)	(-0.12)
R^2	0.37	1.16	1.59	5.22	1.69	0.30	0.37	0.59	0.01
					Panel D: Italy				
dB^r	0.192	0.104	0.040	0.024	-0.008	-0.090	-0.096	-0.065	-0.113
t-stat	(0.96)	(0.55)	(0.29)	(0.20)	(-0.08)	(-1.06)	(-1.79)	(-1.10)	(-2.03)
R^2	3.69	1.08	0.16	0.06	0.01	0.81	0.92	0.43	1.27
					Panel E: Spain				
dB^r	-0.017	-0.029	-0.135	-0.055	-0.099	-0.143	-0.142	-0.139	-0.181
t-stat	(-0.07)	(-0.11)	(-0.66)	(-0.34)	(-0.76)	(-1.28)	(-1.36)	(-1.40)	(-1.88)
R^2	0.03	0.09	1.81	0.31	0.99	2.05	2.02	1.92	3.28
					Panel F: Portugal				
dB^r	0.046	0.045	0.062	0.084	0.057	−0.020	−0.030	−0.032	0.045
t-stat	(0.77)	(0.75)	(1.12)	(1.73)	(1.16)	(−0.43)	(−0.75)	(−0.50)	(0.96)
R^2	0.21	0.20	0.39	0.70	0.33	0.04	0.09	0.10	0.20

with t-statistics ranging between 2.78 (30-year maturity) to 14.17 (two-year maturity). The effect of communication shocks seems weaker for Spain (Panel E) and Portugal (Panel F), as the communication shock neither moves Spanish nor Portuguese yields at the shortest maturity, but the effect is still highly statistically significant for maturities between one and 20 years.

Table 7
Bond yield response to communication shocks

This table reports the results of univariate regressions of daily changes in bond yields across different maturities on communication shocks for France (Panel A), Germany (Panel B), Italy (Panel C), Netherlands (Panel D), Spain (Panel E), and Portugal (Panel F):

$$dy_{i,t}^{\tau} = \beta_{i,c}^{\tau} dB_t^{\theta} + \epsilon_{i,c,t}^{\tau},$$

where $\tau = 3m, \ldots, 30y$. t-statistics are calculated using Newey and West (1987) allowing for serial correlation. Data runs from January 2001 to December 2014.

	3m	6m	1y	2y	5y	10y	15y	20y	30y
					Panel A: Germany				
dB^{θ}	0.295	0.533	0.844	0.849	0.744	0.555	0.420	0.335	0.292
t-stat	(4.31)	(8.76)	(12.50)	(14.17)	(13.28)	(7.77)	(5.17)	(3.19)	(2.78)
R^2	6.72	21.97	55.21	55.80	42.89	23.85	13.63	8.70	6.62
					Panel B: France				
dB^{θ}	0.448	0.642	0.779	0.851	0.727	0.503	0.405	0.308	0.268
t-stat	(5.62)	(7.37)	(10.31)	(16.23)	(14.10)	(7.73)	(5.54)	(3.37)	(2.42)
R^2	15.54	31.93	46.99	56.04	40.94	19.61	12.71	7.34	5.55
					Panel C: Netherlands				
dB^{θ}	0.483	0.546	0.784	0.855	0.728	0.528	0.437	0.332	0.297
t-stat	(3.90)	(5.50)	(6.41)	(15.61)	(13.81)	(7.82)	(5.30)	(3.13)	(2.76)
R^2	18.04	23.04	47.62	56.65	41.01	21.62	14.81	8.51	6.82
					Panel D: Italy				
dB^{θ}	0.305	0.486	0.519	0.460	0.407	0.278	0.214	0.089	0.121
t-stat	(3.31)	(6.19)	(9.84)	(6.53)	(6.50)	(5.01)	(3.13)	(1.06)	(1.56)
R^2	7.19	18.25	20.89	16.42	12.83	5.98	3.55	0.61	1.13
					Panel E: Spain				
dB^{θ}	0.167	0.193	0.188	0.455	0.378	0.268	0.225	0.130	0.065
t-stat	(1.20)	(1.83)	(2.25)	(6.31)	(5.66)	(4.42)	(3.30)	(1.99)	(1.04)
R^2	2.15	2.87	2.75	16.03	11.05	5.55	3.93	1.30	0.33
					Panel F: Portugal				
dB^{θ}	0.025	0.078	0.157	0.211	0.220	0.129	0.074	0.139	0.092
t-stat	(0.46)	(1.50)	(3.03)	(4.99)	(3.19)	(2.29)	(1.43)	(2.16)	(1.22)
R^2	0.06	0.62	2.46	4.45	4.83	1.67	0.54	1.93	0.85

It is also instructive to compare the effect of target and communication shocks on core versus peripheral countries. For example for communication shocks, the estimated coefficient on the German two-year yield change is 0.849, whereas it is only 0.211 for Portugal. The cross-sectional pattern is very similar across all maturities: Yields of core countries, such as Germany, Netherlands and France, react more to communication shocks than those of peripheral countries, such as Italy, Spain, and Portugal.

3.2 Multivariate results and cross-country differences

Since target and communication shocks do not occur independently, we test their effect on bond yield changes in a multivariate regression. To this end, we regress changes in yields onto the target rate and communication shocks jointly:

$$dy_{i,t}^{\tau} = \beta_{i,m,r}^{\tau} \widehat{dB}_{r,t} + \beta_{i,m,\theta}^{\tau} \widehat{dB}_{\theta,t} + \epsilon_{i,m,t}^{\tau},$$

where $dy_{i,t}^{\tau}$ is the daily yield change of country i with maturity τ. We summarize the results in Figures 5 (core countries) and 6 (peripheral countries).

In line with the univariate results reported before, we find that the effect of target rate shocks is generally decreasing with maturity and not significant. In contrast, the effect of communication shocks is most pronounced for intermediate maturities: coefficients are small at the short-end of the term structure, increasing until the two-year maturity, and then decreasing again as the maturity prolongs. Comparing core versus peripheral countries, we find the former to be affected more by monetary policy shocks than the latter. For example, any one standard deviation shock in the communication shock leads to an almost 0.8 standard deviation change in the two-year bond yields for Germany, France and the Netherlands, while the same effect halves for Portugal, Italy, and Spain. Figures 5 and 6 also reveal that the economic and statistical significance of the shocks remain very close to the univariate results reported in Tables 6 and 7.

Finally, we study how monetary policy shocks affect the yield differential between core and peripheral countries. Ever since the introduction of the Euro and more recently the implementation of unconventional monetary policy, one question that has consistently been raised is whether “one fits it all.” In a currency union comprised of

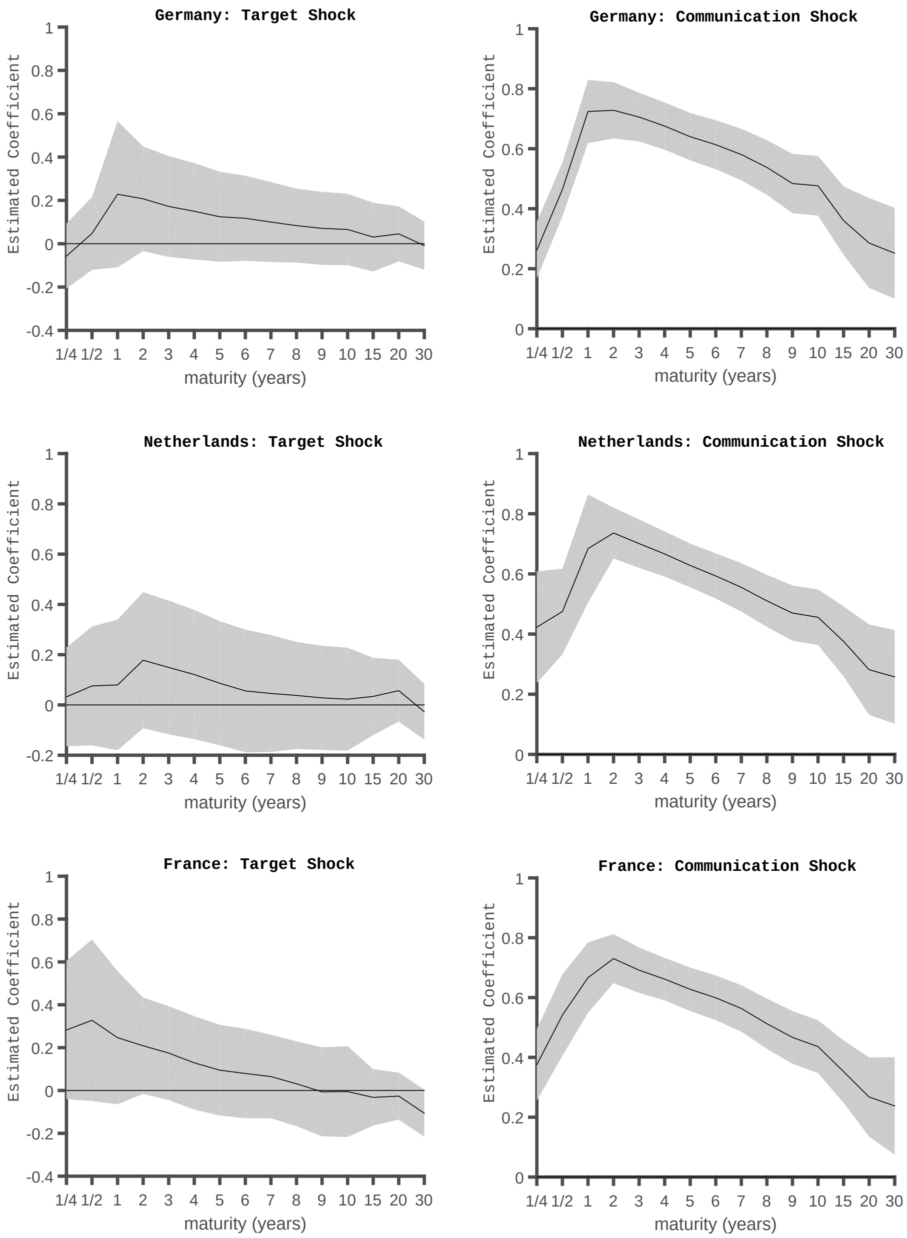

Figure 5. Core Countries' Yield Response to Target and Communication Shock

This figure plots the response of core countries' bond yields at different maturities for a target rate (left) and communication (right) shock on ECB announcement days:

$$dy^{\tau}_{i,t} = \beta^{\tau}_{i,r} dB^{r}_{t} + \beta^{\tau}_{i,c} dB^{\theta}_{t} + \epsilon^{\tau}_{i,c,t},$$

where $\tau = 3m, \ldots, 30y$. 90% confidence intervals are based on Newey and West (1987) standard errors. The sample period is from January 2001 to December 2014.

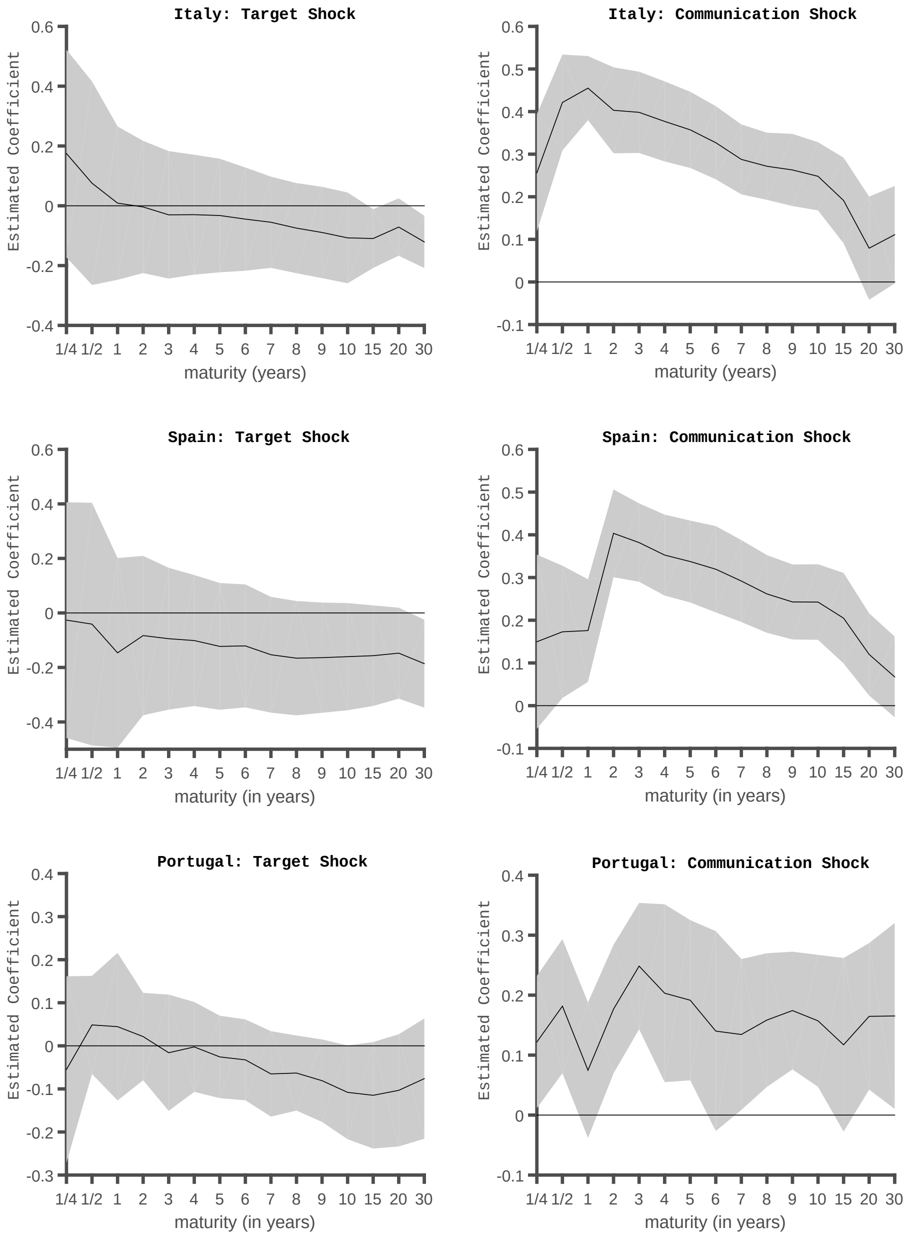

Figure 6. Peripheral Countries' Yield Response to Target and Communication Shock

This figure plots the response of peripheral countries' bond yields at different maturities for a target rate (left) and communication (right) shock on ECB announcement days:

$$dy_{i,t}^{\tau} = \beta_{i,r}^{\tau} dB_t^r + \beta_{i,c}^{\tau} dB_t^{\theta} + \epsilon_{i,p,t}^{\tau},$$

where $\tau = 3m, \ldots, 30y$. 90% confidence intervals are based on Newey and West (1987) standard errors. The sample period is from January 2001 to December 2014.

countries in dramatically different economic conditions, it is natural to ask how monetary policy has affected the funding conditions of each country. While our previous results hint towards the fact that core countries' yields seem to be affected more by monetary policy shocks, we explore this in more detail by running a regression on the yield spread between peripheral and core countries:

$$d\left(y^{\tau}_{p,t} - y^{\tau}_{c,t}\right) = \beta^{\tau}_{pc}\ \text{shock}_t + \epsilon^{\tau}_{pc,t},$$

where $y^{\tau}_{p,t}$ is the average maturity-τ yield of all peripheral countries and $y^{\tau}_{c,t}$ is the corresponding yield of core countries at time t, and shock_t is either $\widehat{dB}_{r,t}$ or $\widehat{dB}_{\theta,t}$. We summarize the results on target rate shocks in the left panel and on communication shocks in the right panel of Figure 7.

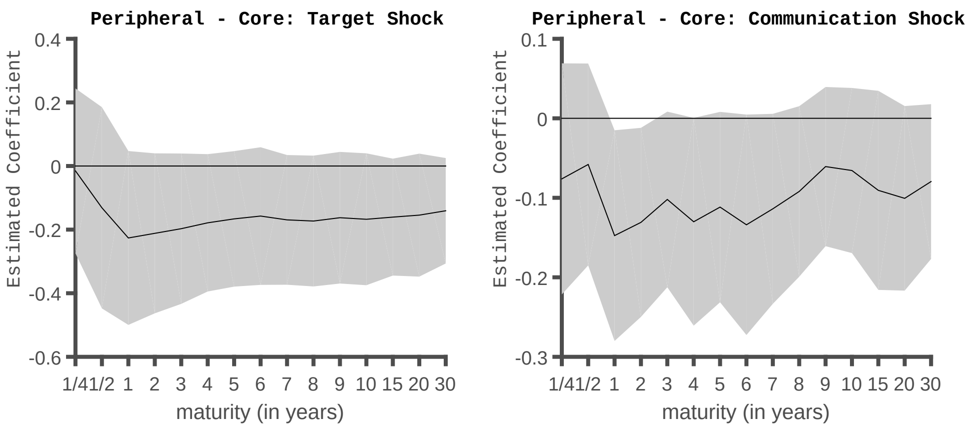

Figure 7. Peripheral Minus Core Countries' Bond Yields

This figure plots the response of peripheral minus core countries' bond yields at different maturities for a target (left panel) and communication shock (right panel) on ECB announcement days:

$$d\left(y^{\tau}_{p,t} - y^{\tau}_{c,t}\right) = \beta^{\tau}_{pc}\text{shock}_t + \epsilon^{\tau}_{pc,t},$$

where $\tau = 3m, \ldots, 30y$ and shock_t is either the target announcement or communication shock. The sample period is from January 2001 to December 2014. 90% confidence intervals are based on Newey and West (1987) standard errors.

Not very surprisingly, we find estimated coefficients to be insignificant for target rate shocks. Communication shocks are also insignificant except for the one- and two-year maturity for which estimated coefficients are negative. The estimated coefficients imply that for any 100bp change in the communication shock, there is a 13bps (= slope coefficient × standard deviation of the communication shock) drop in the spread between peripheral and core countries for bonds with maturities between one and two years.

3.3 Monetary Policy Shocks before the Crisis

Against the backdrop of our previous result, we now want to focus on two different aspects of ECB monetary policy. First, we want to study whether monetary policy has affected bond yields differently over time, and second, whether the effect has changed between core and peripheral countries.

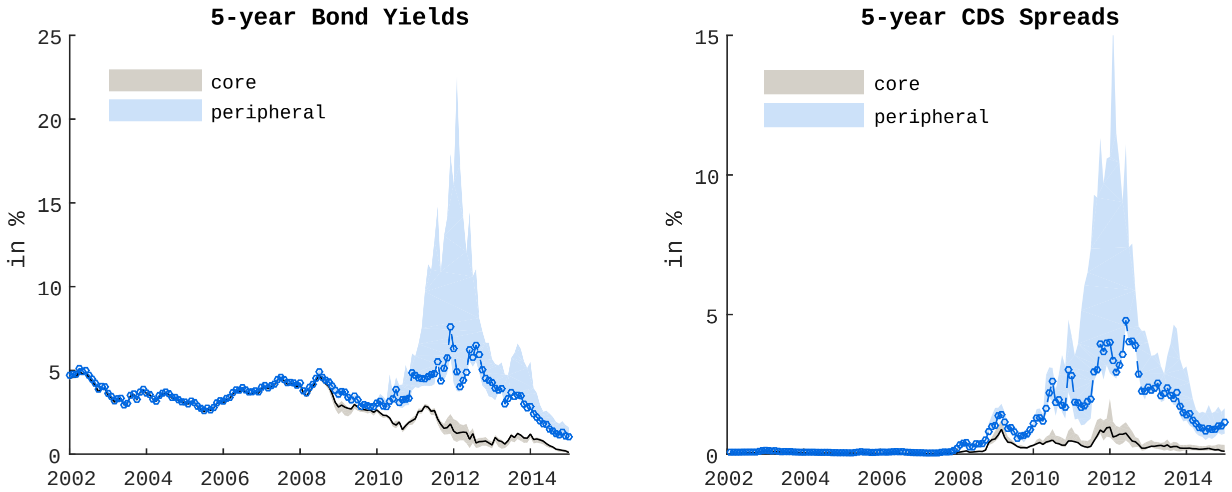

Figure 8. Five-year bond yields and CDS core and peripheral countries

The left (right) panel plots 5y bond yields (CDS) for core (solid line) and peripheral (dashed line) countries. Core countries are Germany, Netherlands and France, peripheral countries are Portugal, Spain and Italy. The solid line is the median of core and peripheral countries and shaded areas present the minimum and maximum. Data is monthly and running from January 2002 to December 2014.

Figure 8 plots five-year bond yields (left panel) and CDS (right panel) for core and peripheral countries. We notice that right up until the Eurozone crisis, neither the bond yields nor the CDS are significantly different between core and peripheral countries. However, the core and peripheral yields diverge after the eruption of the Eurozone debt crisis in the summer of 2008. In the following, we want to explore whether target rate and communication shocks had a different effect before and after the financial crisis.[10] To

[10] It is important to emphasize that we exclude announcements from our analysis that contain information about unconventional monetary policy tools such as the outright purchases of government debt of distressed countries aimed at lowering their bond yields. Krishnamurthy, Nagel, and Vissing-Jorgensen (2015) document that some but not all programs significantly reduced bond yields of distressed debt.

this end, we re-run the same analysis as before, but study announcements that took place until July 2008 (88 announcements) and those starting from August 2008 separately (72 announcements).

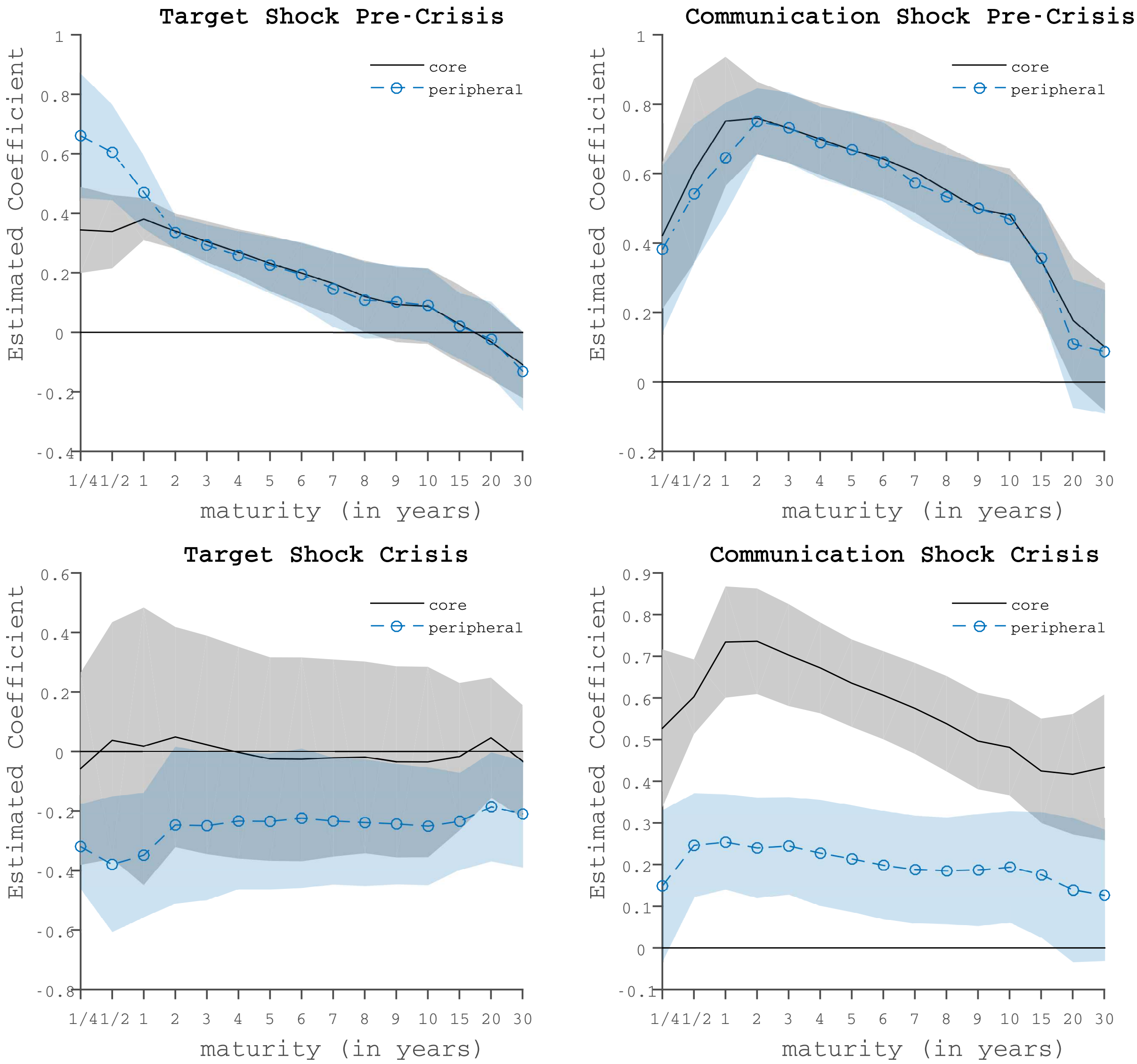

Figure 9. Core and Peripheral Countries' Yield Response before and after the onset of the crisis

This figure plots the response of core (solid line) and peripheral (dashed line) countries' bond yields at different maturities for a target rate (left) and communication (right) shock on ECB announcement days:

$$dy^{\tau}_{i,t} = \beta^{\tau}_{i,r} dB^{r}_{t} + \beta^{\tau}_{i,c} dB^{\theta}_{t} + \epsilon^{\tau}_{i,c,t},$$

where $\tau = 3m, \ldots, 30y$. 90% confidence intervals are based on Newey and West (1987) standard errors. The sample period is from January 2001 to July 2008 for the upper two panels and from August 2008 to December 2014 for the lower two panels.

The upper two panels plot the effect of target rate (left panel) and communication shocks (right panel) when we end the sample in summer 2008, for both core and peripheral countries. We note two results: First, coefficients for target rate shocks are highly significant when we exclude the recent sample. The effect is strongest for the shortest maturities and then decreases with maturity and becomes insignificant for bond yields with maturities exceeding eight years. For peripheral countries, we find that for any 100bp change in the target rate shock, there is a 53bp change (= 0.65 (estimated coefficient) $\times$ 0.8145 (standard deviation of the target shock pre crisis) $\times$ 100) in the shortest maturity bond yield, for core countries this number is 29bps. Second, communication shocks virtually have the same effect for core and peripheral countries with the strongest effect being at intermediate maturities of two years.

The lower two panels present the results for the crisis period only. In line with our earlier findings, there is no significant effect from target rate shocks on core countries; for peripheral countries, on the other hand, there is a negative effect that is significant mostly at the short end. Interestingly, we find estimated coefficients to be negative during the crisis period, indicating that target rate shocks lowered bond yields for peripheral countries even during announcements which did not include specific reference to unconventional monetary policy. The lower right panel depicts the effect of communication shocks during the crisis period. While we find the same hump-shaped pattern as before, there is a large difference between core and peripheral countries. For example, for any 100bp communication shock, there is a 63bp (= 0.72 (estimated coefficient) $\times$ 0.875 (standard deviation of communication shock during crisis period) $\times$100) change in the two-year yield for core countries whereas there effect on a two-year peripheral country bond yield is only 21bps (= 0.24 $\times$ 0.875 $\times$ 100).

Since the onset of the crisis in 2008, the ECB tried to ease money market distress and to reduce sovereign spreads mainly (i) by drastically lowering its target rate, (ii) by providing unprecedented amounts of liquidity support against a broader set of asset used as collateral, and more recently, (iii) by introducing quantitative easing in the form of the Asset Purchase Programme. Several studies have have analyzed the impact of different unconventional monetary policy announcements for bond yields of peripheral countries and the consensus is that bond yields of the riskiest countries such as Italy and Spain have fallen significantly around these unconventional monetary policy announcements (see e.g., Krishnamurthy, Nagel, and Vissing-Jorgensen (2015)). In the following, we want to study the effect of monetary policy during the crisis period with a special focus on core versus peripheral countries. Moreover, since we exclude announcements which entail any information on unconventional monetary policy measures, it is natural to ask whether more conventional monetary policy announcements helped to reduce the bond spread additionally. We first plot in Figure 10 the cumulative target and communication shocks for the period between August 2008 to December 2014. We notice that while the target rate shock remains always positive, the communication shock is negative throughout the whole period.

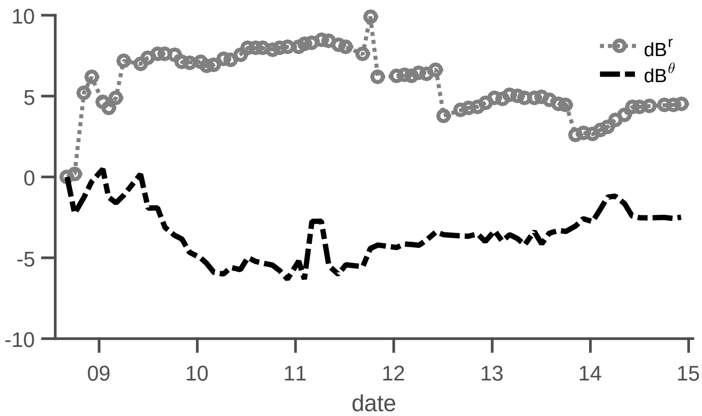

Figure 10. Cumulative Target and Communication Shocks Crisis

This figure plots the cumulative sum of target (dashed line with marker) and communication shocks (dashed line) for the crisis period August 2008 to December 2014.

Figure 11 plots estimated coefficients from regressing the bond spread between core and peripheral countries onto the target rate (left panel) and communication shocks (right panel). We notice that estimated coefficients are negative for all maturities for both shocks. Given that target rate shocks seem to be positive on aggregate, this implies that the spread between peripheral and core countries decreases as a response to shocks in the target rate. Moreover, this effect is significant for a maturity up to two years. Communication shocks, on the other hand, have a negative impact on the yield spread and given the negative cumulative effect, this implies that during the 2008 to 2014 period, communication shocks lead to an increase in the yield spread between peripheral and core countries. This effect is significant for bond yields with maturity up to eight years.

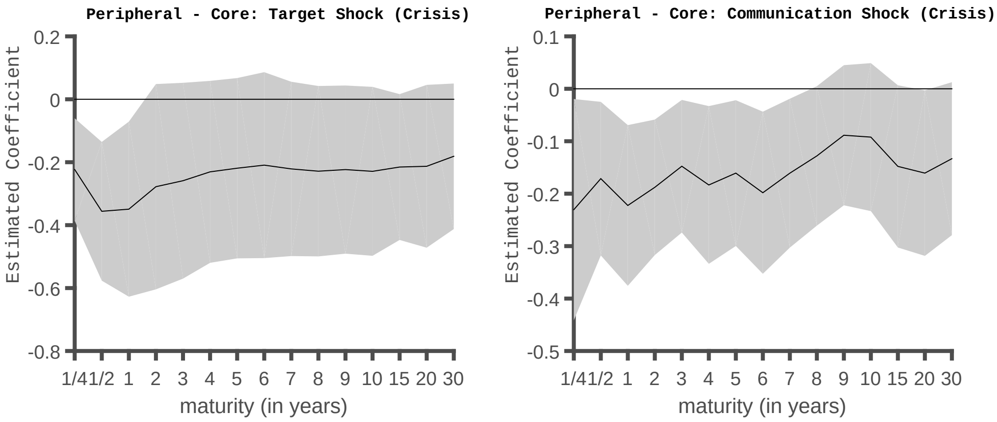

Figure 11. Peripheral Minus Core Countries' Bond Yields Crisis

This figure plots the response of peripheral minus core countries' bond yields at different maturities for a target (left panel) and communication shock (right panel) on ECB announcement days:

$$d\left(y^{\tau}_{p,t} - y^{\tau}_{c,t}\right) = \beta^{\tau}_{pc}\text{shock}_t + \epsilon^{\tau}_{pc,t},$$

where $\tau = 3m, \ldots, 30y$ and shock_t is either the target announcement or communication shock. The sample period is from August 2008 to December 2014. 90% confidence intervals are based on Newey and West (1987) standard errors.

Overall we conclude that while unconventional monetary policy announcements decrease the spread between the riskiest and safest countries in the Eurozone, communication shocks during more conventional announcements seem to increase this spread because core countries move more as a response to monetary policy than do peripheral countries.

3.4 Credit Risk

Finally, we want to assess the effect of monetary policy shocks on countries in the cross-section. One dimension of cross-sectional heterogeneity we are particularly interested in is countries' credit risk. In other words, we want to ask whether the credit conditions in each country matter for how monetary policy affects bond yields. To this end, we run a panel regression of changes in yields in country i onto their corresponding CDS interacted with the target rate and communication shock:

$$dy_{i,t}^{\tau} = \beta_c^{\tau}\left(\log \text{cds}_{i,t} * \mathbf{1}_c * \text{shock}_t\right) + \beta_p^{\tau}\left(\log \text{cds}_{i,t} * \mathbf{1}_p * \text{shock}_t\right) + \epsilon_{i,cds,t}^{\tau},$$

where $\mathbf{1}_c$ ($\mathbf{1}_p$) is an indicator function that takes the value of one if a country is a core (peripheral) country, shock_t is either the target rate shock, $\widehat{dB}_{r,t}$, or the communication shock, $\widehat{dB}_{\theta,t}$, and $\log \text{cds}_{i,t}$ is the log of the five-year CDS of country i. We account for country fixed-effects, and standard errors are clustered at the country level. Results of this regression are presented in Table 8.

Table 8
Panel regression bond yields and credit risk

This table reports the results of multivariate panel regressions of daily changes in bond yields across different maturities on CDS of country i interacted with the target (Panel A) or communication shock (Panel B),

$$dy_{i,t}^{\tau} = \beta_P^{\tau}\left(\log \text{cds}_{i,t} * 1_C * \text{shock}_t\right) + \beta_C^{\tau}\left(\log \text{cds}_{i,t} * 1_P * \text{shock}_t\right) + \epsilon_{i,cds,t}^{\tau},$$

where 1_C (1_P) is an indicator function that takes the value of one if a country is a core (peripheral) country and $\tau = 3m, \ldots, 30y$. t-statistics are calculated using robust standard errors clustered at the country level. Data runs from January 2002 to December 2014.

	3m	6m	1y	2y	5y	10y	15y	20y	30y
					Panel A: Target rate shocks				
$\log \text{cds} * 1_C * dB^r$	0.001	0.002	0.002	0.003	0.001	0.001	0.001	0.001	0.000
t-stat	(0.29)	(0.86)	(0.78)	(1.05)	(0.48)	(0.26)	(0.27)	(0.59)	(0.14)
$\log \text{cds} * 1_P * dB^r$	-0.004	-0.002	-0.004	-0.004	-0.004	-0.005	-0.004	-0.003	-0.003
t-stat	(-2.04)	(-1.52)	(-14.47)	(-2.58)	(-2.62)	(-2.64)	(-2.63)	(-2.76)	(-2.51)
R^2	3.48%	1.34%	1.39%	1.44%	1.67%	2.83%	2.39%	1.90%	1.75%
N	835	835	835	835	835	835	835	835	835
					Panel B: Communication shocks				
$\log \text{cds} * 1_C * dB^r$	0.007	0.011	0.014	0.019	0.016	0.009	0.008	0.006	0.006
t-stat	(5.36)	(6.58)	(8.39)	(10.65)	(10.34)	(7.13)	(6.14)	(4.68)	(3.73)
$\log \text{cds} * 1_P * dB^r$	0.002	0.005	0.004	0.008	0.007	0.004	0.002	0.002	0.002
t-stat	(1.83)	(2.69)	(1.30)	(3.14)	(3.16)	(2.83)	(1.74)	(1.45)	(1.52)
R^2	4.77%	8.40%	6.31%	13.34%	12.48%	6.75%	5.43%	4.35%	3.99%
N	835	835	835	835	835	835	835	835	835

In Panel A, we report the results for target rate shocks. We find that credit risk does not significantly affect how target rate shocks affect bond yields in core countries, as the estimated coefficients are insignificant for all maturities. Coefficients for peripheral countries, on the other hand, are negative and significant; with tighter credit conditions, the effect of monetary policy gets dampened. Panel B reports the result for communication shocks, with positive and highly significant estimates for both peripheral and core countries. Core countries' coefficients, however, are a multiple larger than those of peripheral countries, implying that when credit conditions deteriorate, the effect of communication shocks get amplified, and more so in core countries.

4 Model

In this section we propose a parsimonious dynamic equilibrium term structure model to rationalize our baseline empirical results about the role of central bank communication on the yield curve. Interest rates are determined by the interaction between risk-averse arbitrageurs and yield-oriented investors, who operate only in a subset of countries. Proofs of our main results, as well as alternative models, are presented in the Appendix.

4.1 Bond market

Time is continuous and goes from zero to infinity. Agents, specified below, can buy defaultable zero-coupon bonds of countries $i = 1, ..., I$ or put their money into an instantaneously riskfree money market account that pays net return r_t. We denote the time t price of a zero-coupon bond of country i paying one dollar at maturity $t+\tau$, $\tau \in (0, T]$, by $P^{\tau}_{i,t}$, its yield-to-maturity by

$$y^{\tau}_{i,t} = -\frac{\log P^{\tau}_{i,t}}{\tau}, \tag{7}$$

and the instantaneous forward rate by

$$f^{\tau}_{i,t} = \lim_{\Delta\tau \to 0} \left\{ -\frac{\log P^{\tau}_{i,t} - \log P^{\tau-\Delta\tau}_{i,t}}{\Delta\tau} \right\} = -\frac{\partial \log P^{\tau}_{i,t}}{\partial \tau}. \tag{8}$$

We assume that the net supply of bonds coming from governments, central banks, and other unmodelled market participants is exogenously given: at time t, the dollar value of the bond of country i with time-to-maturity τ supplied to investors is $s^{\tau}_{i,t}$. For simplicity, we assume that bond supply is constant over time for every i and τ, i.e., $s_{i,t}^{\tau} = s_i^{\tau}$.[11] We utilize our earlier framework for the dynamics of the target rate: the rate paid on the money market account, r_t, and the information about the future path of rates, θ_t, evolve according to the system (1)-(2) under the physical probability measure.

The default of country i is triggered by the jump of an unpredictable process $Z_{i,t} \equiv 1_{\{\upsilon_i \leq t\}}$, where υ_i is the random default time that occurs with default intensity $\lambda_{i,t}$ under the physical probability measure. Specifically, we have

$$\mathrm{E}_t^{\mathbb{P}}\left[dZ_{i,t}\right] = \mathrm{E}_t^{\mathbb{P}}\left[\left(dZ_{i,t}\right)^2\right] = \lambda_{i,t} 1_{\{\upsilon_i > t\}} dt. \tag{9}$$

We allow $\lambda_{i,t}$ to be stochastic; we assume that $\lambda_{i,t}$ is given by

$$d\lambda_{i,t} = \kappa_{\lambda,i}\left(\bar{\theta}_{\lambda,i} - \lambda_{i,t}\right) dt + \sigma_{\lambda,i} dB_{\lambda,i,t}, \tag{10}$$

independent of all $Z_{i,t}$s.[12] Finally, we assume that the Brownian motions of the model are pairwise independent of each other.[13]

Bonds are held by competitive financial institutions, who can be of two types. Institutions from the first class, in measure $0 < 1 - \phi \leq 1$, have mean-variance preference over the instantaneous change in the value of their bond portfolio. If $x_{i,t}^{\tau}$ denotes the dollar amount they hold in country-i maturity-τ bonds at time t, their budget constraint is

$$dW_t = \left(W_t - \sum_{i=1}^{I} \int_0^T x_{i,t}^{\tau} d\tau\right) r_t dt + \sum_{i=1}^{I} \int_0^T x_{i,t}^{\tau} \frac{dP_{i,t}^{\tau}}{P_{i,t^-}^{\tau}} d\tau, \tag{11}$$

[11]This assumption, for instance, implies that governments and central banks actively trading all bonds in a manner that keeps aggregate debt constant. In the Appendix we consider an alternative model in which the number of bonds remains constant over time but the dollar value changes due to price changes, which corresponds to governments issuing the longest possible maturity bond at all times but not actively participating in bond markets afterwards. In order to solve the model in closed form, we need to rely on a linear approximation, and we show that that specification leads to qualitatively similar predictions as the one considered here.

[12]Notice that under (10), $\lambda_{i,t}$ can go negative. Instead, we could assume a volatility term $\sqrt{m_i + n_i \lambda_{i,t}}$ that would keep $\lambda_{i,t}$ above a pre-specified level; this, while making our analytical solutions more elaborate, would lead to the same qualitative predictions as our current model.

[13]Alternatively, we could allow for stochastic bond supply, and set the default intensity constant over time but varying across countries. In that case, just as in the current setting, we would obtain an equilibrium with bond yields affine in the factors of the model. This alternative would not only lead to qualitatively similar predictions, but would in fact imply the same loadings on the short rate and the communication rate. Assuming that both bond supply and default intensity are stochastic, however, would take us outside the class of affine models.

and their optimization problem is given by

$$\max_{\left\{x^{\tau}_{i,t}\right\}_{i=1,\ldots,I;\tau\in(0,T]}} \mathrm{E}_t\left[dW_t\right] - \frac{\alpha}{2}\mathrm{Var}_t\left[dW_t\right], \tag{12}$$

where α is their absolute risk aversion. Financial institutions from the second class, referred to as yield-oriented or reaching-for-yield investors, are in measure ϕ. They have slightly different preferences from mean-variance investors that we discuss below, and their bond holdings are denoted by $z^{\tau}_{i,t}$. The two types of financial institutions have to hold all bonds in equilibrium, so the market clearing condition is

$$\left(1-\phi\right)x^{\tau}_{i,t} + \phi z^{\tau}_{i,t} = s^{\tau}_{i} \tag{13}$$

for all i, t, and τ.

4.2 Equilibrium term structures

We start by assuming that bond price processes can be written in the generic form

$$\frac{dP^{\tau}_{i,t}}{P^{\tau}_{i,t^-}} = \mu^{\tau}_{i,t}dt - \sigma^{\tau}_{r,i,t}dB_{r,t} - \sigma^{\tau}_{\theta,i,t}dB_{\theta,t} - \sigma^{\tau}_{\lambda,i,t}dB_{\lambda,i,t} - dZ_{i,t}. \tag{14}$$

Combining (11), (12) and (14), we obtain that the optimization problem of mean-variance investors is equivalent to

$$\begin{aligned}\max_{\left\{x^{\tau}_{i,t}\right\}_{i=1,\ldots,I;\tau\in(0,T]}} & \sum_{i=1}^{I}\int_0^T x^{\tau}_{i,t}\left(\mu^{\tau}_{i,t} - r_t - \lambda_{i,t}\right)d\tau - \frac{\alpha}{2}\left[\sum_{i=1}^{I}\int_0^T x^{\tau}_{i,t}\sigma^{\tau}_{r,i,t}d\tau\right]^2 \\ & - \frac{\alpha}{2}\left[\sum_{i=1}^{I}\int_0^T x^{\tau}_{i,t}\sigma^{\tau}_{\theta,i,t}d\tau\right]^2 - \frac{\alpha}{2}\sum_{i=1}^{I}\left[\int_0^T x^{\tau}_{i,t}\sigma^{\tau}_{\lambda,i,t}d\tau\right]^2 - \frac{\alpha}{2}\sum_{i=1}^{I}\lambda_{i,t}\left[\int_0^T x^{\tau}_{i,t}d\tau\right]^2.\end{aligned} \tag{15}$$

After some algebra, the FOC with respect to $x^{\tau}_{i,t}$ becomes

$$\begin{aligned}\mu^{\tau}_{i,t} - r_t - \lambda_{i,t} = {} & \alpha\sigma^{\tau}_{r,i,t}\left[\sum_{j=1}^{I}\int_0^T x^{\tau}_{j,t}\sigma^{\tau}_{r,j,t}d\tau\right] + \alpha\sigma^{\tau}_{\theta,i,t}\left[\sum_{j=1}^{I}\int_0^T x^{\tau}_{j,t}\sigma^{\tau}_{\theta,j,t}d\tau\right] \\ & + \alpha\sigma^{\tau}_{\lambda,i,t}\left[\int_0^T x^{\tau}_{i,t}\sigma^{\tau}_{\lambda,i,t}d\tau\right] + \alpha\lambda_{i,t}\left[\int_0^T x^{\tau}_{i,t}d\tau\right].\end{aligned} \tag{16}$$

Equation (16) states that a bond's expected excess return $\mu^{\tau}_{i,t} - r_t$ compensates bond-holders for all the risk they bear when holding bond τ of country i. These include the risks of target rate changes and communication shocks, and the default risk intensity of the given country ($\lambda_{i,t}$) and its stochastic nature. In particular, the four components of the right-hand side of (16) are all proportional to the amount of risk held per bond (e.g., $\sigma^{\tau}_{r,i,t}$ for the target rate shocks), and the proportionality coefficient ($\alpha \sum_{j=1}^{I} \int_0^T x^{\tau}_{j,t} \sigma^{\tau}_{r,j,t} d\tau$ in the case of the target rate shocks) is the market price of the corresponding risk factor. In turn, the market prices of risk depend on how much (target-rate) risk investors have to hold on aggregate, and it is the same for all bonds exposed to the specific risk factor, simply due to the absence of arbitrage and regardless of other ingredients of the model.

We directly write the optimization problem of the reaching-for-yield agents as

$$\max_{\{z^{\tau}_{i,t}\}_{\tau \in (0,T], i \in \mathcal{J}}} \sum_{i \in \mathcal{J}} \int_0^T z^{\tau}_{i,t} \left(f^{\tau}_{i,t} - r_t - \lambda_{i,t} \right) d\tau - \frac{\alpha}{2} \left[\sum_{i \in \mathcal{J}} \int_0^T z^{\tau}_{i,t} \sigma^{\tau}_{r,i,t} d\tau \right]^2 \tag{17}$$

$$- \frac{\alpha}{2} \left[\sum_{i \in \mathcal{J}} \int_0^T z^{\tau}_{i,t} \sigma^{\tau}_{\theta,i,t} d\tau \right]^2 - \frac{\alpha}{2} \sum_{i \in \mathcal{J}} \left[\int_0^T z^{\tau}_{i,t} \sigma^{\tau}_{\lambda,i,t} d\tau \right]^2 - \frac{\alpha}{2} \sum_{i \in \mathcal{J}} \lambda_{i,t} \left[\int_0^T z^{\tau}_{i,t} d\tau \right]^2,$$

and require $z^{\tau}_{i,t} = 0$ for $i \notin \mathcal{J}$.

Yield-oriented agents are assumed to be different from mean-variance investors in two aspects. The first difference between (15) and (17) is that we assume that reaching-for-yield investors buy (long-term) bonds of only a subset of the countries, potentially due to unmodelled entry or transaction costs; we denote this subset by $\mathcal{J}$ where $|\mathcal{J}| = J < I$.

Second, we replace the instantaneous drift of the bond price, $\mu^{\tau}_{i,t}$, with the instantaneous forward rate $f^{\tau}_{i,t}$. The motivation for this objective is that while yield-oriented investors dislike risk, they care about the shape of the current yield or forward curve instead of the expected instantaneous returns they can earn on bonds: Approximately, this term means that if the yield curve is upward sloping, then reaching-for-yield investors think of long-maturity bonds as a better deal than short-maturity bonds, and want to buy more of them for each unit risk of the bond.[14]

[14] The exact relationship of yields and forward rates, as implied by (7) and (8), is given by $f^{\tau}_{i,t} = \frac{\partial}{\partial \tau} \left(\tau y^{\tau}_{i,t} \right) = y^{\tau}_{i,t} + \tau \frac{\partial}{\partial \tau} y^{\tau}_{i,t}$, that is, the objective of yield-oriented investors is not equivalent to replacing $\mu^{\tau}_{i,t}$ by $y^{\tau}_{i,t}$. In the Appendix, we consider alternatives to this modelling choice, including having $y^{\tau}_{i,t}$ in the optimization problem instead of $f^{\tau}_{i,t}$. We show that some of these alternatives do not admit affine equilibria, whereas others result in a more elaborate analytical solution for the equilibrium term structure, while neither having any additional intuition, nor changing the qualitative results of this section. We further show that our specification with forward rates essentially generalizes the discrete-

Why the focus on remaining lifespan returns on bonds instead of instantaneous returns over the next dt period? This assumption arises naturally in the case of large financial institutions that classify debt as 'held-to-maturity' for accounting purposes. Unlike securities classified as 'available-for-sale' or for 'trading' purposes, which are marked to market, held-to-maturity-classified securities are reported as amortized cost and not subject to intermediate accounting losses. The amount of securities declared as 'held-to-maturity' typically constitute a large fraction of the balance sheet of financial institutions.[15] Overall, the two components of our assumption are rooted in the observation of Acharya and Steffen (2015), who find that European banks were pursuing risky investments in high-yielding long-term sovereign debt, and financed them with low-yielding short-term wholesale funds.

Similar to (16), the FOC with respect to $z_{i,t}^{\tau}$ for $i \in \mathcal{J}$ then becomes

$$f_{i,t}^{\tau} - r_t - \lambda_{i,t} = \alpha\sigma_{r,i,t}^{\tau}\left[\sum_{j\in\mathcal{J}}\int_0^T z_{j,t}^{\tau}\sigma_{r,j,t}^{\tau}d\tau\right] + \alpha\sigma_{\theta,i,t}^{\tau}\left[\sum_{j\in\mathcal{J}}\int_0^T z_{j,t}^{\tau}\sigma_{\theta,j,t}^{\tau}d\tau\right] \tag{18}$$
$$+ \alpha\sigma_{\lambda,i,t}^{\tau}\int_0^T z_{i,t}^{\tau}\sigma_{\lambda,i,t}^{\tau}d\tau + \alpha\lambda_{i,t}\int_0^T z_{i,t}^{\tau}d\tau.$$

Combining (13), (16), and (18), we obtain

$$\mu_{i,t}^{\tau} - r_t - \lambda_{i,t} = \frac{1}{1-\phi}\alpha\sigma_{r,i,t}^{\tau}\left[\sum_{j=1}^{I}\int_0^T s_i^{\tau}\sigma_{r,j,t}^{\tau}d\tau\right] + \frac{1}{1-\phi}\alpha\sigma_{\theta,i,t}^{\tau}\left[\sum_{j=1}^{I}\int_0^T s_i^{\tau}\sigma_{\theta,j,t}^{\tau}d\tau\right] \tag{19}$$
$$+ \frac{1}{1-\phi}\alpha\sigma_{\lambda,i,t}^{\tau}\int_0^T s_i^{\tau}\sigma_{\lambda,i,t}^{\tau}d\tau + \frac{1}{1-\phi}\alpha\lambda_{i,t}\int_0^T s_i^{\tau}d\tau - \mathbf{1}_{i\in\mathcal{J}}\frac{\phi}{1-\phi}\left(f_{i,t}^{\tau} - r_t - \lambda_{i,t}\right).$$

Next, we solve for equilibrium bond prices and confirm that they can indeed be written as (14). We look for bond prices in the specific form

$$P_{i,t}^{\tau}\left(r_t, \theta_t, \lambda_{i,t}\right) = e^{-[A_i(\tau)+B_i(\tau)r_t+C_i(\tau)\theta_t+D_i(\tau)\lambda_{i,t}]}\left(1 - Z_{i,t}\right), \tag{20}$$

time two-asset setup (short- and long-term bonds) of Hanson and Stein (2015) to continuous time with a continuum of bonds.

[15] According to an IMF analysis of sovereign holdings by European banks, 12% of these exposures were included in the trading book, 49% were classified as available for sale and 39% were classified as held to maturity. Some banks had the bulk of their exposure of sovereign bonds on their banking book. For example, the National Bank of Greece classified almost 70% of their sovereign bonds as held-to-maturity.

which also implies bond yields are affine in the factors r_t, θ_t and $\lambda_{i,t}$ as long as country i does not default. Applying Itô's lemma to (20) and comparing the result to (19), after some algebra, we obtain the equilibrium functions $A_i(.)$ to $D_i(.)$ for both $i \in \mathcal{J}$ and $i \notin \mathcal{J}$. We have the following results:

Theorem 1. *In the term structure model described above, there exists an equilibrium in which yields are affine and given by*

$$y_{i,t}^{\tau} = \frac{A_i(\tau) + B_i(\tau) r_t + C_i(\tau) \theta_t + D_i(\tau) \lambda_{i,t}}{\tau}. \tag{21}$$

The functional forms of $B_i(.)$, $C_i(.)$ and $D_i(.)$ are the following: In core countries, where yield-oriented investors are not present ($i \notin \mathcal{J}$), we have

$$B_i(\tau) = \frac{1 - e^{-\kappa_r \tau}}{\kappa_r}, \; C_i(\tau) = \frac{1 - e^{-\kappa_\theta \tau}}{\kappa_\theta} + \frac{e^{-\kappa_\theta \tau} - e^{-\kappa_r \tau}}{\kappa_\theta - \kappa_r}, \text{ and} \tag{22}$$
$$D_i(\tau) = \left(1 + \frac{1}{1-\phi} \alpha \int_0^T s_i^{\tau} d\tau\right) \frac{1 - e^{-\kappa_{\lambda,i} \tau}}{\kappa_{\lambda,i}}.$$

In peripheral countries, with yield-oriented investors ($i \in \mathcal{J}$), we have

$$B_i(\tau) = \frac{1 - e^{-\kappa_r^* \tau}}{\kappa_r^*}, \; C_i(\tau) = \frac{1 - e^{-\kappa_\theta^* \tau}}{\kappa_\theta^*} + \frac{e^{-\kappa_\theta^* \tau} - e^{-\kappa_r^* \tau}}{\kappa_\theta^* - \kappa_r^*}, \text{ and} \tag{23}$$
$$D_i(\tau) = \left(1 + \alpha \int_0^T s_i^{\tau} d\tau\right) \frac{1 - e^{-\kappa_{\lambda,i}^* \tau}}{\kappa_{\lambda,i}^*},$$

where $\kappa_r^* = \kappa_r(1-\phi) < \kappa_r$, $\kappa_\theta^* = \kappa_\theta(1-\phi) < \kappa_\theta$, and $\kappa_{\lambda,i}^* = \kappa_{\lambda,i}(1-\phi) < \kappa_{\lambda,i}$. The functional forms of A_i, for both $i \in \mathcal{J}$ and $i \notin \mathcal{J}$, are given in the appendix.

4.3 Model Predictions

Our model has a series of implications regarding the effect of target and communication shocks on bond yields, both across different maturities and across countries. We summarize them in three propositions that correspond to the tests presented in the empirical analysis.

We consider the effect of target rate and communication shocks in four specifications. We start with a univariate regression of yield changes of country-i bonds with maturity τ on the target rate shock, that is,[16]

$$dy_{i,t}^{\tau} = \alpha_{i,r}^{\tau} + \beta_{i,r}^{\tau} dB_{r,t} + \epsilon_{i,r,t}. \tag{24}$$

Next, to contrast the effect of communication shocks on yield changes with those of target shocks, we also consider running a univariate regression of yield changes of country-i bonds with maturity τ on the communication shock, in the form of

$$dy_{i,t}^{\tau} = \alpha_{i,\theta}^{\tau} + \beta_{i,\theta}^{\tau} dB_{\theta,t} + \epsilon_{i,\theta,t}. \tag{25}$$

Third, we look at multivariate regressions where the right-hand-side variables include both target rate shocks and communication shocks:

$$dy_{i,t}^{\tau} = \alpha_{i,m}^{\tau} + \beta_{i,m,r}^{\tau} dB_{r,t} + \beta_{i,m,\theta}^{\tau} dB_{\theta,t} + \epsilon_{i,m,t}. \tag{26}$$

Finally, to highlight cross-sectional differences, we look at regressions similar to (24) and (25), where the left-hand-side variable is changes in the yield difference of peripheral vs core countries:

$$d\left(y_{p,t}^{\tau} - y_{c,t}^{\tau}\right) = \alpha_{pc,r}^{\tau} + \beta_{pc,r}^{\tau} dB_{r,t} + \epsilon_{pc,r,t} \tag{27}$$

and

$$d\left(y_{p,t}^{\tau} - y_{c,t}^{\tau}\right) = \alpha_{pc,\theta}^{\tau} + \beta_{pc,\theta}^{\tau} dB_{\theta,t} + \epsilon_{pc,\theta,t}, \tag{28}$$

and the corresponding multivariate regression.

From (21), we have that yield changes are given by

$$dy_{i,t}^{\tau} = \frac{B_i(\tau)}{\tau} dr_t + \frac{C_i(\tau)}{\tau} d\theta_t + \frac{D_i(\tau)}{\tau} d\lambda_{i,t}, \tag{29}$$

implying $\beta_{i,\theta}^{\tau} = \frac{C_i(\tau)}{\tau}\sigma_r$ and $\beta_{i,r}^{\tau} = \frac{B_i(\tau)}{\tau}\sigma_\theta$. Further, since the Brownian increments driving the target rate and the communication rate are independent, the regression coefficients in the multivariate regression are identical to the corresponding univariate

[16] Defining the target shock as dr_t instead of the Brownian increment would only change the level of the coefficients proportionally, because the volatility of r_t, σ_r, is constant.

ones: $\beta^{\tau}_{i,m,\theta} = \beta^{\tau}_{i,\theta}$ and $\beta^{\tau}_{i,m,r} = \beta^{\tau}_{i,r}$. Our results on the theoretical slope coefficients that, for simplicity, we write in terms of the univariate coefficients are as follows. On the impact of target shocks, we obtain the following results:

Proposition 1. *We have* $\lim_{\tau \to 0} \beta^{\tau}_{i,r} = \sigma_r$ *and* $\lim_{\tau \to \infty} \beta^{\tau}_{i,r} = 0$, *and* $d\beta^{\tau}_{i,r}/d\tau < 0$ *for all* $\tau > 0$ *and* i. *Hence,* $\beta^{\tau}_{i,r}$ *is positive and decreasing across maturities, in both univariate and multivariate regressions.*

For communication shocks, we have the following results:

Proposition 2. *We have* $\lim_{\tau \to 0} \beta^{\tau}_{i,\theta} = \lim_{\tau \to \infty} \beta^{\tau}_{i,\theta} = 0$, *and there exists* $\bar{\tau}_i > 0$ *such that* $d\beta^{\tau}_{i,\theta}/d\tau > 0$ *for all* $\tau \in (0, \bar{\tau}_i)$ *and* $d\beta^{\tau}_{i,\theta}/d\tau < 0$ *for all* $\tau \in (\bar{\tau}_i, \infty)$. *Thus,* $\beta^{\tau}_{i,\theta}$ *is positive and hump-shaped across maturities for all countries* i, *in both univariate and multivariate regressions.*

Bond yields are the average expected returns earned through the lifetime of bonds, which in turn depend on expected future risk-free rates and risk premia. Therefore, when the central bank announces changes to either the current target rate or the intended future path of monetary policy, yield curves can be affected via two channels: a direct impact operates through the expectation channel, while the second, indirect effect works through the risk premium channel.

Propositions 1 and 2 are simply the results of the expectation hypothesis. A positive current target rate shock increases all future expected target rates, but due to mean reversion, its effect dies out over time. Thus, current long yields are less sensitive to target rate shocks than short yields: $\beta^{\tau}_{i,r}$ is positive and decreases with maturity. At the same time, a shock to θ_t provides information about intended future (medium-term) target rates, but does not affect the current rate r_t, and long-term yields are expected to mean-revert to the long-term mean $\bar{\theta}$ eventually. Hence, a positive communication shock increases medium-term yields while leaving short and long yields intact, corresponding to a hump-shaped response across maturities.

Next we study the effect of the two types of shocks across countries. From our previous observations, it is imminent that $\beta^{\tau}_{pc,\theta} = \beta^{\tau}_{p,\theta} - \beta^{\tau}_{c,\theta}$ and $\beta^{\tau}_{pc,r} = \beta^{\tau}_{p,r} - \beta^{\tau}_{c,r}$.

Therefore, when running the regressions of cross-country yield differences, we have the following predictions:

Proposition 3. *We have* $\lim_{\tau\to 0}\beta^{\tau}_{pc,r} = \lim_{\tau\to\infty}\beta^{\tau}_{pc,r} = 0$*, and there exists* $\bar{\tau}_{pc} > 0$ *such that* $d\beta^{\tau}_{pc,r}/d\tau > 0$ *for all* $\tau \in (0, \bar{\tau}_{p-c})$ *and* $d\beta^{\tau}_{pc,r}/d\tau < 0$ *for all* $\tau \in (\bar{\tau}_{pc}, \infty)$*. Thus,* $\beta^{\tau}_{pc,r}$ *is hump-shaped across maturities, in both univariate and multivariate regressions.*

Further, we have $\lim_{\tau\to 0}\beta^{\tau}_{pc,\theta} = \lim_{\tau\to\infty}\beta^{\tau}_{pc,\theta} = 0$*, and there exists* $0 < \bar{\tau}_{pc,1} < \bar{\tau}_{pc,2}$ *such that* $d\beta^{\tau}_{pc,\theta}/d\tau < 0$ *for all* $\tau \in (0, \bar{\tau}_{pc,1})$ *and* $d\beta^{\tau}_{pc,\theta}/d\tau > 0$ *for all* $\tau \in (\bar{\tau}_{pc,1}, \bar{\tau}_{pc,2})$*. Thus, for sufficiently small maturities* $\beta^{\tau}_{pc,\theta}$ *is negative and U-shaped: first decreases then increases, in both univariate and multivariate regressions.*

The heterogeneity across countries is driven by our assumption on heterogeneity in the bond-market participation of agents. In fact, yield-oriented investors are absent in core countries, hence the only effect of target rate and communication shocks on the yield curve is due to the expectation hypothesis as described above.[17] In peripheral countries, when the central bank announces changes to the current target rate or changes to the intended future path of monetary policy, there is also an indirect effectthat works through the risk premium channel: shocks, by influencing the demand of yield-oriented investors, effectively manifest as changes to the relative net supply of bonds that risk-averse arbitrageurs have to hold in equilibrium. A positive target rate shock that lifts short-term yields more than long-term yields implies that reaching-for-yield investors are less willing to hold long-term bonds against short-term bonds. As the former are riskier, risk-averse arbitrageurs, who have to hold more in equilibrium, demand a higher risk premium on them. Hence, the risk premium channel amplifies the direct effect of target rate shocks for all maturities. At the same time, a positive communication shock that lifts medium-term yields more than short or long yields via the expectation channel also shifts the relative demand of yield-oriented investors for medium-term bonds instead of long bonds. In turn, this change in relative net supplies translates to a decreasing equilibrium risk premium on medium-term bonds, but an increasing one on long bonds.

[17] Our results would remain qualitatively the same if we allowed for some yield-oriented investors to trade bonds in core countries, too, as long as their proportion remains higher among the peripheral country investors.

Therefore, the risk premium channel dampens the direct effect of a communication shocks on medium-term yields, while amplifies it for long yields: the hump shifts towards longer maturities. The difference in the proportion of yield-oriented investors across countries implies that the indirect effect is more prominent in peripheral countries than in core countries. Hence, our model provides an understanding of how target rate and communication shocks affect the term structure in equilibrium, both in the cross-section of maturities and across countries.

5 Conclusion

Much research has been devoted to the study of the impact of forward guidance on asset prices ever since interest rate around the globe have hit the zero lower bound. However, the precise measurement of forward guidance shocks in the US is complicated by the fact that target rate and communication about the future path of interest rates announcements coincide. In this paper, we propose a novel measure of target rate and communication shocks on days when the ECB announces its monetary policy. Using high-frequency data on a host of money market rates, we estimate these shocks separately and study their effect on Eurozone bond yields.

We document the following empirical findings. Target rate shocks have virtually no impact on Eurozone bond yields, whereas communication shocks have highly significant impact not just statistically but also economically. Moreover, we find the effect to be the strongest for bond yields at intermediate maturities between two and five years. As the maturity increases, the effect of the communication shocks dissipates. We also find that while monetary policy shocks had a homogeneous effect on bond yields of core and peripheral countries until 2008, we document large cross-sectional heterogeneity across core and peripheral countries during the most recent financial crisis. More specifically, we find that for the 2008 to 2014 period, target rate shocks significantly lowered the yield spread between peripheral and core countries for the shortest maturity bonds, however, communication shocks increased the yield spread. This finding shows that communication shocks dampened some of the effects of the ECB's unconventional monetary policy tools aiming at lowering the yield spread taken since May 2010.

We rationalize these findings in a parsimonious dynamic term structure model with heterogeneous investors and credit risk. Equilibrium yields are determined by risk-averse arbitrageurs who interact with reaching-for-yield investors who give rise to a monetary policy risk premium. When the central bank announces changes to the current target rate or changes to the intended future path of monetary policy, it has a direct effect on the yield curve through the expectation hypothesis, but also an indirect one, by influencing the demand of yield-oriented investors, effectively creating a shock to the net supply of bonds mean-variance investors have to hold in equilibrium.

A Appendix

A.1 Proofs and derivations

Proof of Theorem 1. Substituting (14) into (11), we obtain that the budget constraint of mean-variance investors is

$$dW_t = \left[r_t W_t + \sum_{i=1}^{I} \int_0^T x_{i,t}^\tau \left(\mu_{i,t}^\tau - r_t\right) d\tau\right] dt - \left[\sum_{i=1}^{I} \int_0^T x_{i,t}^\tau \sigma_{r,i,t}^\tau d\tau\right] dB_{r,t}$$
$$- \left[\sum_{i=1}^{I} \int_0^T x_{i,t}^\tau \sigma_{\theta,i,t}^\tau d\tau\right] dB_{\theta,t} - \sum_{i=1}^{I} \left[\int_0^T x_{i,t}^\tau \sigma_{\lambda,i,t}^\tau d\tau\right] dB_{\lambda,i,t} - \sum_{i=1}^{I} \left[\int_0^T x_{i,t}^\tau d\tau\right] dZ_{i,t}.$$

From here, using (9), we can express $\mathrm{E}_t\left[dW_t\right]$ and $\mathrm{Var}_t\left[dW_t\right]$. Substituting them into (12) results in (15). Point-wise maximization of (15) with respect to $x_{i,t}^\tau$ yields (16). Similarly, point-wise maximization of (17) with respect to $z_{i,t}^\tau$ for $i \in \mathcal{J}$ yields (18).

To solve for equilibrium bond prices and yields, we apply Ito's lemma to (20) and compair the result to (19). Collecting r_t, θ_t, λ_t, and constant terms, respectively, we obtain

$$B_i'(\tau) + B_i(\tau)\kappa_r - 1 = -\mathbf{1}_{i\in\mathcal{J}} \frac{\phi}{1-\phi}\left(B_i'(\tau) - 1\right) \tag{30}$$

and

$$C_i'(\tau) - B_i(\tau)\kappa_r + C_i(\tau)\kappa_\theta = -\mathbf{1}_{i\in\mathcal{J}} \frac{\phi}{1-\phi} C_i'(\tau) \tag{31}$$

and

$$D_i'(\tau) + D_i(\tau)\kappa_{\lambda,i} = \frac{1}{1-\phi}\alpha \int_0^T s_i^\tau d\tau - \mathbf{1}_{i\in\mathcal{J}} \frac{\phi}{1-\phi}\left(D_i'(\tau) - 1\right) + 1. \tag{32}$$

and

$$\begin{aligned} &A_i'(\tau) + \frac{1}{2}B_i^2(\tau)\sigma_r^2 + \frac{1}{2}C_i^2(\tau)\sigma_\theta^2 + \frac{1}{2}D_i^2(\tau)\sigma_{\lambda,i}^2 \\ &= \frac{1}{1-\phi}\alpha B_i(\tau)\sigma_r^2\left[\sum_{j=1}^{I}\int_0^T B_j(\tau) s_j^\tau d\tau\right] \\ &+ C_i(\tau)\left\{\kappa_\theta\bar{\theta} + \frac{1}{1-\phi}\alpha\sigma_\theta^2\left[\sum_{j=1}^{I}\int_0^T C_j(\tau) s_j^\tau d\tau\right]\right\} \\ &+ D_i(\tau)\left\{\kappa_{\lambda,i}\bar{\theta}_{\lambda,i} + \frac{1}{1-\phi}\alpha\sigma_{\lambda,i}^2\left[\int_0^T D_i(\tau) s_i^\tau d\tau\right]\right\} - \mathbf{1}_{i\in\mathcal{J}}\frac{\phi}{1-\phi}A_i'(\tau). \end{aligned} \tag{33}$$

From (30), (31), and (32), together with $B_i(0) = C_i(0) = D_i(0) = 0$, we get (22) for $i \notin \mathcal{J}$ countries, while we obtain (23) for $i \in \mathcal{J}$. Given those functions, we can solve for the functional forms of the A_is from (33). □

Proof of Propositions 2-3. As $\beta_{i,r}^\tau = \frac{B_i(\tau)}{\tau}\sigma_r$ and $\beta_{i,\theta}^\tau = \frac{C_i(\tau)}{\tau}\sigma_\theta$, and the $B_i(.)$ and $C_i(.)$ functions for $i \in \mathcal{J}$ and $i \notin \mathcal{J}$ only differ in the positive constants with and without asterisk (e.g. κ_θ and κ_θ^*), it is sufficient to prove our statements in Propositions 2-1 for the $i \notin \mathcal{J}$ case.

First, it is straightforward that

$$\lim_{\tau\to\infty} \beta_{i,r}^\tau = \lim_{\tau\to\infty} \frac{1-e^{-\kappa_r\tau}}{\kappa_r\tau}\sigma_r = 0 \text{ and } \lim_{\tau\to\infty} \beta_{i,\theta}^\tau = \lim_{\tau\to\infty} \left[\frac{1-e^{-\kappa_\theta\tau}}{\kappa_\theta\tau} + \frac{e^{-\kappa_\theta\tau}-e^{-\kappa_r\tau}}{(\kappa_\theta-\kappa_r)\,\tau}\right]\sigma_\theta = 0$$

as the numerators of all fractions remain finite, whereas the denominators diverge to plus or minus infinity. Second, L'Hospital's Rule implies that

$$\lim_{\tau\to 0} \beta_{i,r}^\tau = \lim_{\tau\to 0} \frac{1-e^{-\kappa_r\tau}}{\kappa_r\tau}\sigma_r = \lim_{\tau\to 0} e^{-\kappa_r\tau}\sigma_r = \sigma_r,$$

while

$$\lim_{\tau\to 0} \beta_{i,\theta}^\tau = \lim_{\tau\to 0} \left[\frac{1-e^{-\kappa_\theta\tau}}{\kappa_\theta\tau} + \frac{e^{-\kappa_\theta\tau}-e^{-\kappa_r\tau}}{(\kappa_\theta-\kappa_r)\,\tau}\right]\sigma_\theta = \lim_{\tau\to 0}\left[e^{-\kappa_\theta\tau} + \frac{-\kappa_\theta e^{-\kappa_\theta\tau}+\kappa_r e^{-\kappa_r\tau}}{(\kappa_\theta-\kappa_r)}\right]\sigma_\theta = 0.$$

Third, regarding slopes,

$$\frac{d\beta_{i,r}^\tau}{d\tau} = \frac{(\kappa_r e^{-\kappa_r\tau})(\kappa_r\tau) - (1-e^{-\kappa_r\tau})(\kappa_r)}{(\kappa_r\tau)^2} = -\frac{1-e^{-\kappa_r\tau}-\kappa_r\tau e^{-\kappa_r\tau}}{\kappa_r\tau^2},$$

which has the opposite sign as $F(\kappa_r\tau) \equiv 1-e^{-\kappa_r\tau}-\kappa_r\tau e^{-\kappa_r\tau}$. But $\lim_{x\to 0} F(x) = 0$ and $F'(x) = xe^{-x} > 0$ when $x > 0$. Hence, $F(\kappa_r\tau) \geq 0$ for all $\tau \geq 0$, and $\beta_{i,r}^\tau$ is downward sloping. Since $\lim_{\tau\to\infty} \beta_{i,r}^\tau = 0$, it is positive and downward sloping for all $\tau > 0$.

For $\beta_{i,\theta}^\tau$, notice that, after some algebra,

$$\frac{d\beta_{i,\theta}^\tau}{d\tau} = \frac{\kappa_r}{(\kappa_\theta-\kappa_r)}\left[\frac{F(\kappa_\theta\tau)}{\kappa_\theta\tau^2} - \frac{F(\kappa_r\tau)}{\kappa_r\tau^2}\right], \tag{34}$$

and for any $\kappa > 0$ we have

$$\lim_{\tau\to 0}\frac{F(\kappa\tau)}{\kappa\tau^2} = \lim_{\tau\to 0}\frac{\kappa e^{-\kappa\tau}}{2} = \frac{\kappa}{2} \text{ and } \lim_{\tau\to\infty}\frac{F(\kappa\tau)}{\kappa\tau^2} = 0$$

$$\frac{d}{d\tau}\frac{F(\kappa\tau)}{\kappa\tau^2} \equiv \frac{d}{d\tau}\frac{1-e^{-\kappa\tau}-\kappa\tau e^{-\kappa\tau}}{\kappa\tau^2} = -2\frac{e^{-\kappa\tau}}{\kappa\tau^3}\left[e^{\kappa\tau} - \left(1+\kappa\tau+\frac{\kappa^2\tau^2}{2}\right)\right] < 0.$$

But $1+\kappa\tau+\frac{\kappa^2\tau^2}{2}$ are the first three terms of the power series of $e^{\kappa\tau}$, and it is well-known that the difference can be approximated by $\frac{\kappa^3\tau^3}{6}$; therefore,

$$\frac{d}{d\tau}\left[\frac{F(\kappa_\theta\tau)}{\kappa_\theta\tau^2} - \frac{F(\kappa_r\tau)}{\kappa_r\tau^2}\right] \approx \frac{1}{3}\left[\kappa_r^2 e^{-\kappa_r\tau} - \kappa_\theta^2 e^{-\kappa_\theta\tau}\right]$$

Finally, it is easy to show that the function $\tau \mapsto \kappa_r^2 e^{-\kappa_r\tau} - \kappa_\theta^2 e^{-\kappa_\theta\tau}$ is first negative then positive if and only if $\kappa_\theta > \kappa_r$ (and vice versa for $\kappa_\theta < \kappa_r$).Therefore, the RHS of (34) is positive for small positive τ values and turns negative after a threshold $\bar{\tau}_i$. But this, together with the previous observations, implies that $\beta_{i,\theta}^\tau$ must be hump shaped.

Finally, notice that since

$$\beta_{p-c,r}^{\tau} = \beta_{p,r}^{\tau} - \beta_{c,r}^{\tau} = \left[\frac{1-e^{-\kappa_r \tau}}{\kappa_r \tau} - \frac{1-e^{-\kappa_r^* \tau}}{\kappa_r^* \tau}\right]\sigma_r,$$

we have

$$\frac{d\beta_{p-c,r}^{\tau}}{d\tau} = \left[\frac{1-e^{-\kappa_r \tau} - \kappa_r \tau e^{-\kappa_r \tau}}{\kappa_r \tau^2} - \frac{1-e^{-\kappa_r^* \tau} - \kappa_r^* \tau e^{-\kappa_r^* \tau}}{\kappa_r^* \tau^2}\right]\sigma_r = \left[\frac{F(\kappa_r \tau)}{\kappa_r \tau^2} - \frac{F(\kappa_r^* \tau)}{\kappa_r^* \tau^2}\right]\sigma_r.$$

Here we have that $\lim_{\tau\to 0}\beta_{p-c,r}^{\tau} = 0$ and $\lim_{\tau\to\infty}\beta_{p-c,r}^{\tau} = 0$, moreover, we have shown above that the sign of the term in brackets is positive for small positive τ and negative afterwards if and only if $\kappa_r > \kappa_r^* = \kappa_r(1-\phi)$. Therefore $\beta_{p-c,r}^{\tau}$ is positive and hump shaped. This concludes the proof of Propositions 2-3. □

A.2 Alternative continuous time specifications

Suppose that, unlike in (17), where we replace the instantaneous drift $\mu_{i,t}^{\tau}$ by the instantaneous forward rate $f_{i,t}^{\tau}$, we use the actual maturity-τ yield, $y_{i,t}^{\tau}$, in the yield-oriented investors' optimization problem to obtain

$$\max_{\{z_{i,t}^{\tau}\}_{\tau\in(0,T],i\in\mathcal{J}}} \sum_{i\in\mathcal{J}}\int_0^T z_{i,t}^{\tau}\left[y_{i,t}^{\tau} - r_t - \lambda_{i,t}\right]d\tau - \frac{\alpha}{2}\left[\sum_{i\in\mathcal{J}}\int_0^T z_{i,t}^{\tau}\sigma_{r,i,t}^{\tau}d\tau\right]^2 \tag{35}$$
$$- \frac{\alpha}{2}\left[\sum_{i\in\mathcal{J}}\int_0^T z_{i,t}^{\tau}\sigma_{\theta,i,t}^{\tau}d\tau\right]^2 - \frac{\alpha}{2}\sum_{i\in\mathcal{J}}\left[\int_0^T z_{i,t}^{\tau}\sigma_{\lambda,i,t}^{\tau}d\tau\right]^2 - \frac{\alpha}{2}\sum_{i\in\mathcal{J}}\lambda_{i,t}\left[\int_0^T z_{i,t}^{\tau}d\tau\right]^2,$$

The FOC w.r.t. $z_{i,t}^{\tau}$ then becomes

$$y_{i,t}^{\tau} - r_t - \lambda_{i,t} = \alpha\sigma_{r,i,t}^{\tau}\left[\sum_{j\in\mathcal{J}}\int_0^T z_{j,t}^{\tau}\sigma_{r,j,t}^{\tau}d\tau\right] + \alpha\sigma_{\theta,i,t}^{\tau}\left[\sum_{j\in\mathcal{J}}\int_0^T z_{j,t}^{\tau}\sigma_{\theta,j,t}^{\tau}d\tau\right] \tag{36}$$
$$+ \alpha\sigma_{\lambda,i,t}^{\tau}\left[\int_0^T z_{i,t}^{\tau}\sigma_{\lambda,i,t}^{\tau}d\tau\right] + \alpha\lambda_{i,t}\left[\int_0^T z_{i,t}^{\tau}d\tau\right],$$

and combining (13), (16), and (36) implies

$$\mu_{i,t}^{\tau} - r_t - \lambda_{i,t} = \frac{1}{1-\phi}\alpha\sigma_{r,i,t}^{\tau}\left[\sum_{j=1}^{I}\int_0^T s_j^{\tau}\sigma_{r,j,t}^{\tau}d\tau\right] + \frac{1}{1-\phi}\alpha\sigma_{\theta,i,t}^{\tau}\left[\sum_{j=1}^{I}\int_0^T s_j^{\tau}\sigma_{\theta,j,t}^{\tau}d\tau\right] \tag{37}$$
$$+ \frac{1}{1-\phi}\alpha\sigma_{\lambda,i,t}^{\tau}\left[\int_0^T s_j^{\tau}\sigma_{\lambda,i,t}^{\tau}d\tau\right] + \frac{1}{1-\phi}\alpha\lambda_{i,t}\int_0^T s_j^{\tau}d\tau - \mathbf{1}_{i\in\mathcal{J}}\frac{\phi}{1-\phi}\left(y_{i,t}^{\tau} - r_t - \lambda_{i,t}\right).$$

As before, we want to solve for equilibrium bond prices in an affine form. Conjecturing bond prices and yields to be as in (20) and (21), respectively, applying Ito's lemma and collecting r_t and θ_t terms, we obtain that the functions $B_i(\tau)$ and $C_i(\tau)$ for the core countries are the same as before, whereas for periphery countries, $i \in \mathcal{J}$,

$$B_i'(\tau) + B_i(\tau)\kappa_r - 1 = -\frac{\phi}{1-\phi}\left(\frac{B_i(\tau)}{\tau} - 1\right) \tag{38}$$

and

$$C_i'(\tau) - B_i(\tau)\kappa_r + C_i(\tau)\kappa_\theta = -\frac{\phi}{1-\phi}\frac{C_i(\tau)}{\tau} \tag{39}$$

for all $\tau > 0$, while $B_i(0) = C_i(0) = 0$. It turns out, however, that all solutions to (38) can be written in the form of

$$B_i(\tau) = \frac{1}{\kappa_r}\frac{1}{1-\phi} + e^{-\kappa_r\tau}\tau^{-\frac{\phi}{1-\phi}}\left[Z - \frac{\phi}{(1-\phi)^2}(-\kappa_r)^{-\frac{1}{1-\phi}}\Gamma\left(\frac{\phi}{1-\phi}, -\kappa_r\tau\right)\right], \tag{40}$$

where Z is an arbitrary constant and

$$\Gamma(a,z) \equiv \int_z^\infty t^{a-1}e^{-t}dt$$

denotes the incomplete gamma function. As $\lim_{\tau\to 0}\Gamma(a,z) = \Gamma(a)$, the gamma function, which is finite for all $a > 0$, we obtain that in (40) the term inside the bracket has a finite limit when $\tau \to 0$, whereas $\lim_{\tau\to 0}\tau^{-\frac{\phi}{1-\phi}} = \infty$. Hence, we cannot have $\lim_{\tau\to 0} B_i(\tau) = 0$ for any real Z, and we conclude that there exists no meaningful solution to the alternative model where the objective function of yield-oriented investors has y_t^τ instead of f_t^τ.

We also consider the case when the expected instantaneous excess return term, $\mu_{i,t}^\tau - r_t$, is replaced by $\tau(y_t^\tau - r_t)$ in (17), which simply follows the discrete-time specification of Hanson and Stein (2015). Writing down the FOC of reaching-for-yield investors, combining it with (13) and (16), then looking for equilibrium bond prices in an affine form, we obtain that the coefficients of r_t and θ_t have to solve

$$B_i'(\tau) + B_i(\tau)\kappa_r - 1 = -\frac{\phi}{1-\phi}(B_i(\tau) - \tau), \tag{41}$$

and

$$C_i'(\tau) - B_i(\tau)\kappa_r + C_i(\tau)\kappa_\theta = -\frac{\phi}{1-\phi}C_i(\tau). \tag{42}$$

Equation (41) then, together with $B_i(0) = 0$, implies

$$B_i(\tau) = \tau + \kappa_r\frac{1 - \left(\kappa_r + \frac{\phi}{1-\phi}\right)\tau - e^{-\left(\kappa_r + \frac{\phi}{1-\phi}\right)\tau}}{\left(\kappa_r + \frac{\phi}{1-\phi}\right)^2},$$

and this result, together with $C_i(0) = 0$ and (42), leads to

$$C_i(\tau) = \frac{\kappa_r}{(\kappa_\theta - \kappa_r)} \left[\kappa_r \frac{1 - \left(\kappa_r + \frac{\phi}{1-\phi}\right)\tau - e^{-\left(\kappa_r + \frac{\phi}{1-\phi}\right)\tau}}{\left(\kappa_r + \frac{\phi}{1-\phi}\right)^2} - \kappa_\theta \frac{1 - \left(\kappa_\theta + \frac{\phi}{1-\phi}\right)\tau - e^{-\left(\kappa_\theta + \frac{\phi}{1-\phi}\right)\tau}}{\left(\kappa_\theta + \frac{\phi}{1-\phi}\right)^2} \right].$$

Conducting our analysis of Propositions 2-3 with these functions leads to qualitatively similar predictions as our main specification.

References

Acharya, V. V., T. Eisert, C. Eufinger, and C. Hirsch (2015): "Whatever it takes: The Real Effects of Unconventional Monetary Policy," Working Paper, New York University.

Acharya, V. V., and S. Steffen (2015): "The "greatest" carry trade ever? Understanding euroeuro bank risks," *Journal of Financial Economics*, 115, 215–236.

Altavilla, C., D. Giannone, and M. Lenza (2014): "The Financial and Macroeconomic Effects of OMT Announcements," ECB Working Paper.

Barbu, A., C. Fricke, and E. Moench (2016): "Reach for Yield in Investment Funds," Working Paper, Deutsche Bundesbank.

Boyarchenko, N., V. Haddad, and M. C. Plosser (2015): "Market Confidence and Monetary Policy," Working Paper, Federal Reserve Bank of New York.

Brand, C., D. Buncic, and J. Turunen (2010): "The Impact of ECB Monetary Decisions and Communication on the Yield Curve," *Journal of the European Economic Association*, 8, 1266–1298.

Christiano, L. J., M. Eichenbaum, and C. L. Evans (1999): "Monetary Policy Shocks: What have we learned and to what end?," *Handbook of Macroeconomics*, 1, 65–148.

Cochrane, J. H., and M. Piazzesi (2002): "The Fed and Interest Rates - A High-Frequency Identification," *American Economic Review*, 92, 90–95.

DiMaggio, M., and M. Kacperczyk (2016): "The Unintended Consequences of the Zero-Lower-Bound Policy," *forthcoming, Journal of Financial Economics.*

Ehrmann, M., and M. Fratzscher (2005): "How should central banks communicate?," ECB working paper No. 557.

Falagiarda, M., and S. Reitz (2015): "Announcements of ECB unconventional programs: Implications for the sovereign spreads of stressed euro area countries," *Journal of International Money and Finance*, 53, 276–295.

Greenwood, R., and D. Vayanos (2014): "Bond Supply and Excess Bond Returns," *Review of Financial Studies*, 27, 663–713.

Gürkaynak, R. S., B. Sack, and E. Swanson (2005): "Do Actions speak louder than Words? The Response of Asset Prices to Monetary Policy Actions and Statements," *International Journal of Central Banking*, 1, 55–93.

Hanson, S. G. (2014): "Mortgage Convexity," *Journal of Financial Economics*, 113, 270–299.

Hanson, S. G., and J. C. Stein (2015): "Monetary Policy and Long-Term Real Rates," *Journal of Financial Economics*, 115, 429–448.

Kohn, D., and B. Sack (2004): "Central Bank Talk: Does it Matter and Why?," Macroeconomics, Monetary Policy, and Financial Stability.

Krishnamurthy, A., S. Nagel, and A. Vissing-Jorgensen (2015): "ECB Policies Involving Government Bond Purchases: Impact and Channels," Working Paper, Stanford University.

Kuttner, K. N. (2001): "Monetary Policy Surprises and Interest Rates: Evidence from the Fed Funds Futures Market," *Journal of Monetary Economics*, 47, 523–544.

Malkhozov, A., P. Mueller, A. Vedolin, and G. Venter (2016): "Mortgage Risk and the Yield Curve," *Review of Financial Studies*, 29, 1220–1253.

Nakamura, E., and J. Steinsson (2015): "High Frequency Identification of Monetary Non-Neutrality," NBER Working Paper No. 19260.

Newey, W. K., and K. D. West (1987): "A Simple, Positive Semi-definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix," *Econometrica*, 55, 703 – 708.

Romer, C. D., and D. H. Romer (2004): "A New Measure of Monetary Shocks: Derivation and Implications," *American Economic Review*, 94, 1055–1084.

Rosa, C., and G. Verga (2008): "The impact of central bank announcements on asset prices in real time," *International Journal of Central Banking*, 13, 175–217.

Svensson, L. E. O. (2004): "Challenges for Monetary Policy," Paper prepared for the Bellagio Group Meeting at the National Bank of Belgium, Brussels.

Swanson, E. (2016): "Measuring the Effects of Federal Reserve Forward Guidance and Asset Purchases on Financial Markets," Working paper, University of California.

Vayanos, D., and J.-L. Vila (2009): "A Preferred-Habitat Model of the Term Structure of Interest Rates," Working Paper, London School of Economics.

Woodford, M. (2003): "Interest and Prices: Foundations of a Theory of Monetary Policy," Princeton University Press.