Term Premia and Short-Rate Expectations in the Euro Area

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Abstract

Identifying the components of yields is a challenging task for monetary authorities. We use a stochastic volatility macro term structure model to estimate time-varying term premia and short-rate expectations for ten countries in the euro area. The model relies on country-specific factors and eurozone global factors and accounts for the effect of yield-related, volatility and macro variables on yield components. The empirical analysis includes yields with maturities up to 30 years and provides new evidence on the behavior of long-maturity term premia and expected short rates. We find significant cross-country interconnections for the yield components, with the size of the links that varies substantially over time and across countries.

Keywords: Term structure, Term premia, Expected short rates, Convexity, Euro sovereign bonds

JEL classification: G12, E43, E44, C58

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1 Introduction

The Global Financial Crisis (GFC), the eurozone sovereign debt crisis and, more recently, the pandemic shock have all posed considerable challenges to European institutions, monetary authorities and investors. The European Central Bank (ECB) has been forced to adopt unconventional monetary policy measures, such as negative interest rates and asset purchases, to stabilize financial markets and stimulate economic growth. After more than a decade of near-zero rates, policymakers are currently debating whether the conditions exist to reduce quantitative easing and normalize interest rates. A clear understanding of the forces underlying the movements in interest rates has thus become a timely and very relevant issue for central bankers. However, the decomposition of yields cannot be inferred directly from market prices, and identifying the drivers of yield curve movements in real time is a challenging task.

Bond yields are given by the sum of an expectation component that reflects the average of current and future expected short-term rates over the bond's maturity, and a risk premium component, defined as the term premium, which is the additional compensation required by the investors to hold a longer-term bond rather than a series of shorter-term bonds. The literature on the decomposition of yields into their expectation and risk premium components includes several empirical analyses for the US (Kim and Wright, 2005; Haubrich et al., 2012; Adrian et al., 2013; Abrahams et al., 2016), the UK (Joyce et al., 2010; Malik and Meldrum, 2016; Kaminska et al., 2018), the euro area (Hördahl and Tristani, 2014; Cohen et al., 2018; McCoy, 2019), Japan (Imakubo and Nakajima, 2015), and international comparisons (Jotikasthira et al., 2015; Moench, 2019; Berardi and Plazzi, 2022).

In this paper, we decompose the yields into their elements and provide new evidence for the euro area as a whole and separately for each country in a set of ten countries of the eurozone. We propose an affine term structure model that relies on five state variables, including both country-specific factors and global (eurozone-specific) macro factors. The dynamics of the factors is described by stochastic processes allowing for time-varying volatility, so that yields and their components are influenced by volatility shocks (see, for example, Cieslak and

Povala (2016), Feldhütter et al. (2018), and Berardi et al. (2022)). Moreover, we explicitly disentangle a convexity effect from the expectation and risk premium components, and we observe that the size of this effect increases with the maturity of the yield and varies over time as a function of yield volatility (see Brown and Schaefer (2000) and Balter et al. (2021)).

The estimation of the model allows us to analyze the components of the yield curve for ten countries in the euro area (Germany, France, the Netherlands, Austria, Finland, Belgium, Italy, Spain, Portugal and Ireland) and the euro area as a whole over the sample period January 2000 to September 2021. The empirical analysis is based on yields with maturities up to 30 years and thus studies the behavior of term premia and short-rate expectations at very long maturities. The model is also fitted to yield variances – calculated as the realized within-month variance of daily changes in yields – and macro expectations, which are proxied by the average 1-year-ahead survey forecasts of inflation and real GDP growth rates for the euro area.

The estimates show that the term structure of term premia is, on average, upward sloping for all countries and the volatility of term premia significantly increases with maturity. Yields, term premia and expected short rates all show a marked downward trend over the sample period, although there appear to be significant differences between countries with relatively low yields ("low-rate countries") and countries with higher yields ("high-rate countries") during turbulent times, such as the GFC, the European sovereign debt crisis of 2011–2012, and the outbreak of the pandemic in 2020.[1]

In crisis periods, we also observe substantial convexity effects on long-term yields. The time-varying convexity implied by our stochastic volatility model helps to explain the downward slope in the term structure of long-term forward rates that has been observed in previous empirical evidence for the euro area (see Balter et al. (2021)). Indeed, we find that, for sufficiently long maturities, convexity dominates the other components in forward rates and the estimated spread between two long-term forward rates is always significantly negative for all countries.

[1] The group of low-rate countries includes Germany, France, the Netherlands, Austria, Finland and Belgium, and the group of high-rate countries includes Italy, Spain, Portugal and Ireland.

A sensitivity analysis shows that expected short rates tend to increase in response to positive shocks in the eurozone's expected inflation rate and GDP growth rate. Conversely, term premia react negatively to shocks in expected inflation and output growth, and they are also highly sensitive to volatility shocks.

Although the model is estimated separately for each country, we provide a measure for the degree of connectedness in yield components among the ten countries by applying the variance decomposition technique of Diebold and Yilmaz (2012). This analysis is related to a large literature studying the interdependence across euro sovereign bonds and the contagion effects occurring at crisis times (see, among others, Metiu (2012), Claeys and Vašíček (2014) and Caporin et al. (2018)).

Different from previous evidence based on variance decomposition (see Claeys and Vašíček (2014)), our estimates show that total connectedness in expected short rates and term premia appears to be relatively strong in stable times and decrease during crisis periods. For example, in the 2007–2013 sub-period, characterized by the GFC and the sovereign debt crisis, there were only a few significant connections across low-rate and high-rate countries, while we observe stronger links within the two groups. This dichotomy is also evident in the 2014–2021 sub-period, which is highly influenced by the effects of the Asset Purchase Programme implemented by the ECB (see, for example, Andrade et al. (2016); Eser et al. (2019); De Santis and Holm-Hadulla (2020); Altavilla et al. (2021)). Overall, the evidence implies that there exist significant cross-country interconnections for both short-rate expectations and term premia, but the size of these links can vary substantially over time.

2 The Model

We assume that the economy is driven by five latent factors, three of which are country-specific factors and two of which are linked to eurozone global factors. In particular, the country-specific factors are the following: (i) a variance factor v, which accounts for the dynamics of the conditional volatility of the other two country-specific variables; (ii) a factor

ℓ, which the model's estimation will unveil to be a proxy for the level of yields; and (iii) a factor s, which will be shown to be a proxy for the slope of the yield curve. The latent global factors are represented by the eurozone instantaneous expected inflation rate π and expected output growth rate μ. The state variables are collected in the state vector $X = (X_1\ X_2)'$, where X_1 contains the three country-specific factors, $X_1 = (v\ \ell\ s)'$, and X_2 the two global factors, $X_2 = (\pi\ \mu)'$.

The state vector follows a $A_1(5)$ stochastic process of the Dai and Singleton (2000) type $dX_t = K(\Theta - X_t)dt + \Sigma\sqrt{\Xi_t}dZ_t$, which can also be written as follows:

$$\begin{pmatrix} dX_{1t} \\ dX_{2t} \end{pmatrix} = \begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix} \begin{pmatrix} \Theta_1 - X_{1t} \\ \Theta_2 - X_{2t} \end{pmatrix} dt + \begin{pmatrix} \Sigma_{11} & 0 \\ 0 & \Sigma_{22} \end{pmatrix} \begin{pmatrix} \Omega_t & 0 \\ 0 & \mathrm{I} \end{pmatrix} \begin{pmatrix} dZ_{1t} \\ dZ_{2t} \end{pmatrix}, \tag{1}$$

where K_{11}, K_{12}, K_{21} and K_{22} are full matrices, Θ_1 and Θ_2 are full vectors, Σ_{11} and Σ_{22} are diagonal matrices, Ω_t is a diagonal matrix with all elements equal to $\sqrt{v_t}$, I is an identity matrix, and dZ_{1t} and dZ_{2t} are vectors of independent Brownian motions.

In sum, we model the first factor v as a square-root process that enters the diffusion term of the other two country-specific, conditionally Gaussian factors, ℓ and s. Instead, the global factors π and μ in X_2 follow a Gaussian process and potentially interact with each other and with the country-specific factors through the drift term. We assume that they are linked to the exogenously given price level p and the real production output q through the following process:

$$dM_t = X_{2t}dt + \Sigma_M dZ_{Mt}, \tag{2}$$

where $dM_t' = \left(\frac{dp_t}{p_t}\ \frac{dq_t}{q_t}\right)$, Σ_M is a diagonal matrix and dZ_{Mt} a vector of independent Brownian motions.

We characterize the dynamics under the risk-adjusted probability measure $\mathbb{Q}$ by using an "essentially affine" specification of the instantaneous market price of risk of the Duffee

(2002) type $\Psi_t = \sqrt{\Xi_t^-}\,(\Lambda_0 + \Lambda_1 X_t)$, i.e.:

$$\begin{pmatrix} \Psi_{1t} \\ \Psi_{2t} \end{pmatrix} = \begin{pmatrix} \Omega_t^{-1} & 0 \\ 0 & \mathrm{I} \end{pmatrix} \left[\begin{pmatrix} \Lambda_{01} \\ 0 \end{pmatrix} + \begin{pmatrix} \Lambda_{11} & \Lambda_{12} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} X_{1t} \\ X_{2t} \end{pmatrix} \right], \tag{3}$$

where Λ_{01} is a full vector and Λ_{11} and Λ_{12} are full matrices.

We then impose the constraint that the global factors in X_2 are unspanned, i.e., they affect short-rate expectations and risk premia in an exactly offsetting way and, therefore, influence the dynamics of bond yields under the historical probability measure $\mathbb{P}$ but not under the measure $\mathbb{Q}$ (see, for example, Duffee (2011) and Joslin et al. (2014)). Such a constraint requires (i) that the instantaneous interest rate r does not depend on X_2:

$$r_t = \delta_0 + \begin{pmatrix} \delta_1' & 0 \end{pmatrix} \begin{pmatrix} X_{1t} \\ X_{2t} \end{pmatrix}, \tag{4}$$

where δ_0 is a constant and δ_1 is a full vector, and that (ii):

$$\Lambda_{12} = -\Sigma_{11}^{-1} K_{12}. \tag{5}$$

The second constraint implies that in the risk-adjusted process of the state vector X, i.e., $dX_t = (\widetilde{K}\widetilde{\Theta} - \widetilde{K} X_t)dt + \Sigma\sqrt{\Xi_t} d\widetilde{Z}_t$, where $d\widetilde{Z}_t = dZ_t + \Psi_t dt$, the drift of the country-specific factors in X_1 does not depend on the global factors in X_2:

$$\begin{pmatrix} dX_{1t} \\ dX_{2t} \end{pmatrix} = \left[\begin{pmatrix} K_{11}\Theta_1 + K_{12}\Theta_2 - \Sigma_{11}\Lambda_{01} \\ K_{21}\Theta_1 + K_{22}\Theta_2 \end{pmatrix} - \begin{pmatrix} K_{11} + \Sigma_{11}\Lambda_{11} & 0 \\ K_{21} & K_{22} \end{pmatrix} \begin{pmatrix} X_{1t} \\ X_{2t} \end{pmatrix} \right] dt + \begin{pmatrix} \Sigma_{11} & 0 \\ 0 & \Sigma_{22} \end{pmatrix} \begin{pmatrix} \Omega_t & 0 \\ 0 & \mathrm{I} \end{pmatrix} \begin{pmatrix} d\widetilde{Z}_{1t} \\ d\widetilde{Z}_{2t} \end{pmatrix} \tag{6}$$

The time-t equilibrium price of a unit discount bond with time to maturity τ, $P_t(\tau)$, has an exponentially affine closed-form solution:

$$P_t(\tau) = \exp\left\{A(\tau) - B'(\tau)X_t\right\}, \tag{7}$$

where $A(\tau)$ and $B(\tau)$ solve a system of ordinary differential equations (see, for example, Dai and Singleton (2000)) and, because of the unspanned nature of the global factors, $B'(\tau) = (B'_1(\tau), 0)$. The term structure of interest rates is thus affine in the country-specific factors:

$$Y_t(\tau) = a(\tau) + b'(\tau)X_t, \tag{8}$$

where $a(\tau) = -A(\tau)/\tau$ and $b'(\tau) = B'(\tau)/\tau = (b'_1(\tau), 0)$.

The diffusion term in the risk-adjusted dynamics of X is a function of v, which implies that yield volatilities are time-varying and are driven by that factor. In particular, the time-t instantaneous variance of changes in the τ-maturity yield, $V_t(\tau)$, is affine in v and is given by:

$$V_t(\tau) = b'(\tau)\left(\Sigma\, \Xi_t \Sigma'\right) b(\tau). \tag{9}$$

The solution of the model implies that the time-t instantaneous forward rate for date $t+\tau$, $f_t(\tau) = \frac{1}{P_t(\tau)} \frac{\partial P_t(\tau)}{\partial t}$, can be expressed as:

$$f_t(\tau) = r_t + B'(\tau)K(\Theta - X_t) - B'(\tau)\Sigma(\Lambda_0 + \Lambda_1\, X_t) - \frac{1}{2}B'(\tau)\left(\Sigma\, \Xi_t \Sigma'\right) B(\tau), \tag{10}$$

or, equivalently, as:

$$\begin{aligned} f_t(\tau) = {} & \left[r_t + G'(\tau)K(\Theta - X_t)\right] + \left[B'(\tau) - G'(\tau)\right] K(\Theta - X_t) \\ & - B'(\tau)\Sigma(\Lambda_0 + \Lambda_1\, X_t) - \frac{1}{2}B'(\tau)\left(\Sigma\, S_t \Sigma'\right) B(\tau), \end{aligned} \tag{11}$$

where $G'(\tau) = \delta' K^{-1}(\mathrm{I} - e^{-K\tau})$. The first term in brackets on the right-hand side of the equation is the time-t instantaneous expected short rate at $t+\tau$ under the $\mathbb{P}$ measure, $\mathrm{E}_t^{\mathbb{P}}\left[r_{t+\tau}\right] \equiv r_t + G'(\tau)K(\Theta - X_t)$.

Using a Gaussian framework, Dai and Singleton (2002) define the difference between $f_t(\tau)$ and $\mathrm{E}_t^{\mathbb{P}}[r_{t+\tau}]$ as the "forward term premium." However, in a stochastic volatility model, such as our model, there can be a significant and time-varying convexity effect, measured as $c_t(\tau) = -\frac{1}{2}B'(\tau)(\Sigma S_t \Sigma')B(\tau)$, that must be removed from this expression. Therefore, we use the following definition for the time-t forward term premium on a τ-maturity bond, $FTP_t(\tau)$:

$$FTP_t(\tau) = f_t(\tau) - \mathrm{E}_t^{\mathbb{P}}[r_{t+\tau}] - c_t(\tau). \tag{12}$$

Taking the integral of both sides of Equation (12) and dividing by τ, we obtain an expression for the yield term premium: $TP_t(\tau) = \frac{1}{\tau}\int_t^{t+\tau} FTP_t(u)du$. Similarly, we define the average expected short rate between t and $t+\tau$ as $ESR_t(\tau) = \frac{1}{\tau}\int_t^{t+\tau} \mathrm{E}_t^{\mathbb{P}}[r_{t+u}du]$ and the average convexity between t and $t+\tau$ as $CX_t(\tau) = \frac{1}{\tau}\int_t^{t+\tau} c_t(u)du$. Therefore, the yield on a τ-maturity zero coupon bond in Equation (8) can also be expressed as the sum of these three components:

$$Y_t(\tau) = ESR_t(\tau) + TP_t(\tau) + CX_t(\tau). \tag{13}$$

3 Data and Preliminary Analysis

The model is estimated using monthly data on country-specific yields and yield volatilities and data on eurozone macroeconomic expectations from January 2000 to September 2021. Ten countries of the euro area are considered: Germany, France, the Netherlands, Austria, Finland, Belgium, Italy, Spain, Portugal and Ireland. Moreover, we provide estimates for the euro area as a whole. For each country, we use yields with maturities from 2 to 10 years and 30 years (not available for Finland, Portugal and Ireland) and yield variances with maturities 5 and 10 years. Yield variances are obtained by calculating the realized within-month variance of daily changes in yields. The data source is Bloomberg for the ten countries and the ECB website for the euro area.[2] For macro expectations, we use the average 1-year-ahead forecasts of annual CPI growth and annual real GDP growth rates obtained from the

[2]As the ECB data start only in September 2004, for the period January 2000 to August 2004, the yield curve for the euro area is calculated as the simple average of the yield curves of the ten countries considered in our dataset.

ECB Survey of Professional Forecasters (SPF). As these data are available on a quarterly basis, we interpolate the series with a spline technique to derive monthly observations.

Summary statistics for the data are reported in **Table 1**. We can distinguish a group of countries with relatively low yields composed of Germany, France, the Netherlands, Austria, Finland, and Belgium. For these countries, average yields are below 1.6% at the 2-year maturity and below 3% at the 10-year maturity. The other group of countries, which includes Italy, Spain, Portugal, and Ireland, shows significantly higher average yields at any maturity. The average term structure of yields is upward sloping in all countries, with the difference between the 10-year and 2-year yield ranging from 100 bps for Germany to 156 bps for Italy. Yield volatilities for the 5- and 10-year maturities are comprised between 60 and 65 bps for the group of low-rate countries and between 78 and 130 bps for the group of high-rate countries. The average yield curve for the euro area as a whole increases from 1.7% at the 2-year maturity to 3.0% at the 10-year maturity, with a yield volatility around 60 bps.

The table also reports means and standard deviations for the 1-year-ahead SPF forecasts of the CPI inflation rate and real GDP growth rate in the euro area. The average inflation and GDP growth rates are both around 1.6%, while the predicted GDP growth rate is five times more volatile than the predicted inflation rate.

Panels A and B of **Table 2** contain the cross-country correlations between monthly changes in the 2-year and 10-year yields, respectively. We observe that correlations tend to be higher for the 10-year maturity (average correlation 0.63 versus 0.52 for the 2-year maturity) and correlations between low-rate countries are generally stronger than those between high-rate countries (average correlation at the 10-year maturity is 0.92 for low-rate and 0.56 for high-rate countries).

Panel C reports the result of a principal component analysis (PCA) applied to monthly changes in yields and yield variances. When we consider yields for all countries and all maturities – from 2 to 10 years and 30 years (when available), i.e., 97 series – the first principal component (PC) explains 59% of the total variability and the first three PCs together explain 81%. These percentages become significantly higher when we split the sample into low-rate countries (81% and 93%, respectively) and high-rate countries (62% and 88%, respectively).

Similarly, the first three PCs together explain 68% of the total variability when we run the PCA for yield variances of all countries and all maturities (from 2 to 10 years, i.e., 90 series), but more than 80% when we separately consider low-rate and high-rate countries.

Overall, this preliminary analysis of the data shows that yields and yield variances are highly correlated across countries, but the correlation is even stronger when we separate high-rate from low-rate countries.

4 Empirical Results

This section contains the main empirical results. First, we describe the methodology used for estimation and present the results for the goodness of fit and the estimated state variables and parameters. We then focus on the estimated yield components by analyzing their properties and sensitivities and, finally, their degree of connectedness.

4.1 Estimation Method

The parameters of the state-space representation of the model are estimated by the quasi-maximum likelihood method, with an approximate Kalman filter algorithm being used to calculate the values of the unobserved state variables. The use of approximate linear filtering is necessary in the cases in which the state vector has affine dynamics but is not Gaussian. In this scenario, an approximate transition equation can be obtained by exploiting the existence of an analytical expression of the first two conditional moments of the state vector (see, for example, Christoffersen et al. (2014)).

The estimation is performed in two steps. In the first step, we estimate the model for the euro area by fitting fourteen series, i.e., the 2- to 10-year and the 30-year yields, the 5- and 10-year realized yield variances, and the 1-year ahead forecasts of inflation and real GDP growth.

In the second step, we keep fixed the parameters estimated for the stochastic processes of the global factors, i.e., the eurozone instantaneous expected inflation rate π and expected output growth rate μ (Equation (1)) and the related price level p and real production output q (Equation (2)). We then fit separately for each country the twelve country-specific variables, i.e., the 2- to 10-year and 30-year (when available) yields and the 5- and 10-year realized yield variances.

4.2 Goodness of Fit

Table 3 reports statistics on the goodness of fit of the model, where errors are defined as the difference between model estimates and actual values. The average standard deviation of yield errors, across maturities from 2 to 10 years and 30 years, ranges from 5.2 bps (Finland) to 16.7 bps (Portugal). The range of the average standard deviation of estimation errors for yield volatilities across the 5- and 10-year maturities ranges between 4.0 (euro area) and 11.4 bps (Portugal). We observe a significant under-estimation of average yield volatility for Portugal and Ireland, especially with regard to the 10-year maturity, while for all the other variables, there is not a significant bias. The standard deviation of estimation errors for the 1-year-ahead inflation rate and GDP growth rate in the euro area is equal to 2.1 and 8.7 bps, respectively.

In addition, the table reports estimated values for the maximal attainable Sharpe ratio (see Duffee (2010)), computed as $\sqrt{\Psi_t' \Psi_t}$, which can be interpreted as a diagnostic on the specification of the stochastic discount factor. We obtain reasonable estimates for this statistic, with average values ranging from 1.0 (Portugal) to 3.1 (euro area).

4.3 State Variables and Parameters

The Kalman filter technique allows us to obtain an estimate for the latent state variables. We find that the factors ℓ and s behave as the "level" and the "slope" of the yield curve, respectively, with the "slope" defined as the difference between a short rate and a long rate. Indeed, Panel A of **Table 4** shows that the correlation between monthly changes in ℓ and the first principal component of monthly changes in yields is very high for each country (on average, 0.87), and so is the correlation between monthly changes in s and the second principal component of monthly changes in yields (on average, 0.88). The panel also shows that the estimated latent factor v is a good proxy for the level of yield variance since, for each country, the correlation between monthly changes in v and the first principal component of monthly changes in realized yield variances is close to one (0.98, on average). The estimated state variables π and μ are almost perfectly correlated with the observed 1-year-ahead expected inflation rate and GDP growth rate of the euro area (correlation coefficient 0.99).

Panel B contains the average value of each parameter, calculated across the ten countries and the euro area.[3] We find that the level factor ℓ is relatively persistent, while the slope factor s is mean-reverting (average mean reversion coefficients equal to 0.14 and 0.30, respectively). The average mean reversion coefficient of the variance factor v is 0.22, while the latent macro factors π and μ exhibit a substantially higher mean-reverting behavior, with coefficients equal to 0.43 and 0.64, respectively.

The estimated average coefficients in matrix Σ imply that ℓ and s are more sensitive to innovations in v than v itself, while the (Gaussian) volatility coefficient for μ is higher than that for π (159 vs 136 bps). The diagonal elements of matrix Λ_1 are all negative, with the coefficient on the level factor ℓ being about four times that on the slope factor s.

4.4 Yield Components

Table 5 collects the results for the decomposition of the τ-maturity yield into the expected short rate $ESR(\tau)$, term premium $TP(\tau)$ and convexity $CX(\tau)$ (see Equation (13)).

We find that the average term structure of ESR for low-rate countries is upward sloping with a spread between the 30- and 5-year maturities of about 100 bps, on average. In the cases of Italy and Spain, the only two high-rate countries with an observable 30-year yield, the term structure of ESR tends to become flat at long maturities and the average spread

[3]For brevity, we do not report a separate table of the estimated parameters for each country.

between the 30- and 5-year maturities is only about 40 bps. When we consider the euro area as a whole, the average 30–5 year spread for ESR is 78 bps. We also observe that, for all countries, the volatility of the 30-year ESR is only about one-third of the volatility at the 5-year maturity.

The average term structure of TP is, for all countries, upward sloping. In particular, average 5-year term premia are negative for low-rate countries (-28 bps) and around zero for high-rate countries, while average 30-year term premia are equal to 41 bps and 151 bps, respectively. Low-rate countries exhibit a slightly negative average 10-year TP (ranging from -22 (Finland) to 1 bps (Belgium)), while for high-rate countries, this value is moderately positive (from 23 (Spain) to 44 bps (Portugal)). We also observe that the volatility of estimated term premia increases substantially with maturity.

The term structure of CX is also strongly upward sloping, in absolute terms. The 10-year maturity average CX is equal to -7 bps for low-rate countries and -20 bps for high-rate countries and reaches -47 and -58 bps, respectively, at 30 years.

Figure 1 contains the time series estimates for the yield components at the 10-year maturity and shows a marked downward trend for both ESR and TP in the 2000–2021 sample period. Panel A shows that there are no significant differences between low-rate countries in ESR estimated for the period between 2000 and 2008. However, starting with the GFC and the subsequent ECB quantitative easing programme, the 10-year ESR for Germany becomes lower (by about 20 bps) than the one estimated for the other low-rate countries. The minimum level of the series is reached during the pandemic shock in spring 2020, with values around only 70 bps.

Panel C displays the time series estimates of the 10-year TP for low-rate countries. We find that TP averages around 100 bps in the first part of the sample, decreases to zero in the period 2005–2007, and then rebounds to 100 bps at the peak of the GFC. The subsequent downward movement is temporarily interrupted by the European sovereign bond crisis in 2011–2012, but after 2012, the 10-year TP in low-rate countries becomes persistently negative and, apart from a couple of episodes – such as, for example, the sharp increase in correspondence with "Brexit" in 2016 – follows a downward trend. The minimum level of about −200 bps experienced in the last quarter of 2020 is followed by a marked rebound towards the −100 bps level in 2021. This path is consistent with previous estimates for the 10-year TP in the euro area (see, for example, Cohen et al. (2018) and Berardi and Plazzi (2022)) and relatively similar to the time series estimates of the 10-year TP for the US (see, among others, Kim and Wright (2005) and Adrian et al. (2013))[4] and the UK (see Malik and Meldrum (2016) and Kaminska et al. (2018)).

Panels B and D contain estimates of the 10-year maturity ESR and TP, respectively, for high-rate countries. We notice that in the 2000–2008 period, ESR is similar for the four countries and fluctuates around 4%, while TP is not too dissimilar from those of the low-rate countries, as it is initially around 100 bps and then declines towards zero in 2005–2007. TP increases substantially during the peak of the European sovereign debt crisis between 2010 and 2012, with values close to 300 bps for Italy and Spain and above 400 bps for Portugal and Ireland. In the same period, ESR reaches almost 6% for Italy and Spain and more than 10% for Portugal and Ireland.

After the "whatever it takes" speech by ECB President Mario Draghi in July 2012 and with the implementation of the Asset Purchase Programme (APP), both ESR and TP sharply decrease for high-rate countries.[5] The 10-year TP becomes negative in 2015 and, with the exception of Portugal in 2017 and Italy in 2018, remains below zero and reaches a minimum of −150 bps for Spain in autumn 2020.

Panels E and F report estimates of the 10-year maturity CX for low-rate and high-rate countries, respectively. We find that CX in low-rate countries exceeds 20 bps only in correspondence with the three peaks of volatility in 2008 (GFC), 2012 (sovereign debt crisis) and 2020 (pandemic shock), while CX in high-rate countries is well above 100 bps on several occasions, and consistently during the debt crisis in 2011–2012, with peaks around 500 bps for Portugal and Ireland.

[4]Updated estimates of the term premium obtained from Kim and Wright (2005) and Adrian et al. (2013) can be downloaded from the websites of the Federal Reserve and the New York Fed, respectively.

[5]According to Eser et al. (2019), the APP has determined a persistent compression in the 10-year term premium of about 100 bps.

While the term structure of CX is, by definition, always (negatively) increasing with maturity, the slope of the term structure of ESR and TP changes significantly over the 2000–2021 sample period. This result is shown in Panels A and B of **Figure 2**, which report, respectively, the time series of ESR and TP at different maturities for the euro area as a whole.[6] We observe that the term structure of ESR is relatively flat, sometimes inverted, in the first part of the sample, becomes positively sloped since the GFC in 2008 and increases its slope in the last part of the sample. On the opposite, TP increases significantly with maturity between 2000 and 2013 and then, when it becomes negative, exhibits an almost flat term structure.

Panels C and D of **Figure 2** provide a different perspective on the analysis of the decomposition of yields in the euro area at the 10-year and 30-year maturities. We observe that, although both yields decrease sharply during the sample period (from about 6% to nearly zero), the 30-year ESR remains in a range between 2.5% and 4%, and most of the decline in the 30-year yield is explained by TP and CX. In particular, TP fluctuates between 100 and 200 bps before 2013, then decreases towards zero and remains negative since October 2014, with a negative peak around -150 bps in November 2020. Convexity effects are also significant throughout the sample period, with a peak corresponding to episodes of high volatility, such as the sovereign debt crisis in 2011–2012 and the outbreak of the pandemic in 2020. The impact of CX is much smaller at the 10-year maturity, for which we observe a marked decline in both ESR (from 5% to about 1%) and TP (from 1% to almost -2%) over the sample period.

As a robustness check, in Appendix A, we compare these estimates for expected short rates and term premia with those provided by a standard 5-factor Gaussian model. We find that, on average, the differences are small, but change significantly over time and become marked during crisis periods. We also notice that the Gaussian model produces expected short rates that are substantially less volatile than those of our model and, vice versa, term premia that are too volatile.

[6]For brevity, we do not report the equivalent graphs for each country, as the results are qualitatively very similar.

Convexity effects exert downward pressure on long-term yields, which offsets the positive impact of long-term bond risk premia. As a result, we find that, at long maturities, the term structure of yields becomes flat and the term structure of forward rates is downward sloping. This evidence is consistent with previous empirical results for the euro area (Balter et al. (2021)) and the US (Berardi et al. (2022)). Panel A of **Figure 3** shows that, for all countries, the estimated average term structure of instantaneous forward rates increases for maturities up to 15 years and then decreases substantially for longer maturities. This implies that, for sufficiently long maturities, convexity dominates the other components in forward rates (see Equation (11)). This is a very persistent effect, as it is shown in Panel B, where we observe that the spread between the 25- and 15-year instantaneous forward rates is always negative for all countries, with an average size that ranges from −57 bps (Italy) to −105 bps (the Netherlands). Panel C shows that at least 60% of the forward rate spread is explained by the convexity component, with such a percentage that reaches almost 90% in the cases of Italy and Austria.

As yield components are affine in the underlying state variables (see Equations (8) and (13)), we can use model estimates to derive a measure of the impact of shocks in these factors on ESR, TP and CX. Panel A of **Figure 4** reports the sensitivity of monthly changes in the yield components to orthogonalized and normalized changes in the five state variables (v, ℓ, s, π, μ) for the euro area as a whole.[7] We first observe that, at shorter maturities (i.e., less than 10 years), ESR is positively affected by shocks in all variables and, although the level factor ℓ and the slope factor s are predominant, the macro factors π and μ and the variance factor v play a significant role, with a peak at the 3-year maturity. At long maturities, only shocks to the level factor are significant for ESR, a result which is consistent with ℓ following a persistent process.

The sensitivity of TP with respect to shocks in the variance factor v increases substantially with maturity and, for maturities longer than 25 years, it overcomes the level factor ℓ. The slope factor s, defined as short rate minus long rate, has an impact on TP that is

[7] Normalized changes make the size of the sensitivities comparable. Again, for the sake of space, we do not include the graph for all countries. In general, we observe that the results for each country are qualitatively similar to those for the euro area, with the only significant difference being a higher sensitivity of TP to v for high-rate countries.

negative and increasing with maturity. Shocks to the macro factors π and μ have a significant negative effect on TP for maturities below 10 years, with the size of the response to an output growth shock being almost double that of a shock in inflation. The global macro variables π and μ are assumed to be "hidden" factors in the model, meaning that they influence risk premia and expected short rates in opposite directions and in a perfectly offsetting way, so that bond yields are unaffected (see Equations (4) and (5)). Our evidence suggests that a higher expected inflation in the eurozone pushes ESR up and TP down and, similarly, an expected improvement in the eurozone real economy contributes to increase ESR and decrease TP. Finally, we notice that, as expected, only shocks in v affect convexity, and the size of the effect increases (not linearly) with maturity.

In Panel B, we report the impulse-response function for the yield components at the 10-year maturity. This measures the reaction of the 10-year ESR, TP and CX to a positive one-standard-deviation shock to the five factors. We observe that only the shock to the level factor ℓ tends to be very persistent for both ESR and TP, while responses to shocks to the other variables converge faster towards zero. Volatility shocks last for about five years in the case of TP and CX.

4.5 Connectedness in Yield Components

In this section, we analyse the degree of connectedness between yields and yield components in the ten countries.

First, we analyze the contemporaneous cross-country correlation in the estimated components of the 10-year yield. Panels A and B of **Table 6** show that monthly changes in the 10-year ESR and TP are highly correlated within low-rate countries (average correlation around 90%), while the correlation within high-rate countries is much lower, with the only exception being the correlation between Italy and Spain. Panel C contains the corresponding cross-correlation for monthly changes in the convexity component of the 10-year yield and shows values around 70%, on average, within low-rate countries and relatively low within high-rate countries, with the exception of the Spain–Italy and Spain–Portugal correlations (around 50%).

Next, we consider the lead-lag dimension of the relation between yield components in the ten countries by calculating different measures of connectedness based on the Diebold and Yilmaz (2012 and 2014) variance decomposition methodology (see Appendix B for a brief description).

We first apply a static full-sample analysis and compute the pairwise directional connectedness for monthly changes in the 10-year yield and each of its components (ESR, TP and CX) over the 2000–2021 period. These are the coefficients $d_{ij}, i = 1, ..., 10, i \neq j$, in Equation (B.2), which are then used to obtain the total directional connectedness *to* other countries *from* the i-th country ($D_{\cdot i}, i = 1, ..., 10$, in Equation (B.3)) and the total directional connectedness *from* other countries *to* the i-country ($D_{i\cdot}, i = 1, ..., 10$, in equation (B.4)). Finally, we take the difference between these two values and derive the *net* total directional connectedness for each country ($D_i^*, i = 1, ..., 10$, in Equation (B.5)).

Table 7 (rows 1 to 10) shows that low-rate countries appear to be "exporters" of shocks with regard to yield, ESR and TP, with France, Austria and Belgium being the main transmitters. On the opposite, high-rate countries – in particular, Portugal and Ireland – are mainly "importers" of shocks. The evidence for CX is mixed, although France and Austria remain the main exporters and Portugal the main importer.

The last row of the table reports the total connectedness measure for monthly changes in the 10-year yield and its components ($D_i, i = 1, ..., 10$, in Equation (B.6)) over the full-sample period. We find a total connectedness between 75% and 80% for yield, ESR and TP, which means that about three-fourths of the variation in these variables in a country can be explained by shocks from other countries and only about one-fourth of the variation by domestic factors. This result is consistent with previous evidence at the international level (see Longstaff et al. (2011) and Moench (2019)) and, more specifically, for the euro area (see Claeys and Vašíček (2014)). Total connectedness for CX is also relatively strong, with a value of 66%.

The static full-sample analysis provides a picture of the links between countries. However, the degree of connectedness may change significantly over time and, to study its evolution, we run a dynamic rolling-sample analysis. Panel A of **Figure 5** reports rolling estimates of the total connectedness measure for monthly changes in the 10-year yield and its estimated components. The rolling window comprises 36 months, which means that the first estimation window ranges from February 2000 to January 2003 and the last window from October 2018 to September 2021. The estimated degree of connectedness is high (about 90%) for all components in the first part of the sample and then decreases sharply, as a consequence of both the GFC and the European sovereign debt crisis. In Panel B, we observe that the first period corresponds to a phase of low and stable spreads between the average 10-year yield in high-rate countries and in low-rate countries. These spreads increase substantially in 2009 and explode at the peak of the sovereign debt crisis in 2011–2012, with values above 500 bps. Since 2015, we observe a rebound of total connectedness above 80% for ESR and TP, another drop around 2018, and a constant increase in the final part of the sample. Again, we notice that these movements are reflected by the behavior of the spreads, which implies that total connectedness in yields and yield components tends to be relatively high during stable periods and to decrease during crisis periods. This result is in contrast with Claeys and Vašíček (2014) reporting a total spillover index that rises after 2008, while it is consistent with the evidence in Caporin et al. (2018), which shows a divergent path of sovereign yields in the eurozone as a consequence of the GFC.[8]

To study the evolution of the cross-country relationships for ESR and TP,[9] in **Figure 6**, we report the pairwise directional connectedness for the 10-year ESR (Panel A) and TP (Panel B) computed for three non-overlapping sub-periods: (i) 2000–2006, (ii) 2007–2013 and (iii) 2014–2021. In the 2000–2006 sub-period, which is characterized by relatively stable spreads between yields and yield components in high-rate and low-rate countries (as described in Panel B of **Figure 5** above), we observe statistically significant pairwise directional connectedness for ESR and TP within low-rate countries (upper-left panel) and between low-rate countries and Italy and Spain (upper-right and lower-left panels). Italy

[8] A similar result is observed by Moench (2019) for expected short rates and term premia calculated from a large panel of both developed and emerging market sovereign bonds.

[9] For brevity, we do not include the results for CX.

and Spain are also mutually connected (lower-right panel), while Portugal and Ireland do not affect other countries and rather receive shocks from them (Portugal for TP and Ireland for ESR).

The 2007–2013 sub-period, which includes both the GFC and the European debt crisis, shows a clear dichotomy between low-rate and high-rate countries (see upper-right and lower-left panels), as there seem to be only a few significant connections across the two groups for both ESR and TP. A notable exception is the link between Belgium and high-rate countries for both ESR and TP and, in particular, the mutual dependence between Belgium, Italy and Spain. Claeys and Vašíček (2014) find an analogous result and explain it as an effect of the large exposures that the banks of those countries have towards the sovereign debt of the other two countries.[10] Finally, we observe a relatively strong interdependence between Italy, Spain, Portugal and Ireland (lower-right panel), a result that is consistent with some studies on the presence of contagion effects in that period (see, for example, Metiu (2012)).

In the 2014–2021 period, where yields and their components are highly influenced by the APP and the ECB expansionary monetary policy (see, for example, Altavilla et al. (2019) and Eser et al. (2019)), the pairwise connectedness from high-rate to low-rate countries (upper-right panel) is totally absent, while Spain and Ireland are significantly affected by ESR and TP in low-rate countries (lower-left panels). As regards the connectedness within high-rate countries (lower-right panel), we observe that Spain impacts all other countries both for ESR and TP.

To sum up, we observe that expected short rates and term premia in the euro area exhibit strong cross-country interrelation. However, the degree of connectedness varies substantially over time, can be very different for low-rate and high-rate countries, and tends to weaken during crisis periods.

[10]Similarly, Ang and Longstaff (2013) consider Belgium, Italy and Spain as systemic bond markets.

5 Concluding Remarks

Separating the expectation and risk premium components of yields is crucial for monetary authorities. We address this issue using a term structure model with stochastic volatility and macro information and estimate time-varying term premia and short-rate expectations for ten countries in the euro area.

The empirical analysis shows that term premia and expected short rates decrease sharply over the 2000–2021 sample period, but there are significant differences in the dynamics across countries, especially during turbulent times, such as the GFC, the sovereign debt crisis and the outbreak of the pandemic. In all countries, term premia increase with maturity and are highly influenced by time-varying volatility. Moreover, they are negatively related to shocks in the expected inflation and output growth of the eurozone. Conversely, expected short rates tend to increase in response to shocks in the two macro variables.

The model separates convexity effects from term premia. We observe that these effects are relevant for long-term maturity (up to 30 years) yields and determine a downward slope in the forward rate curve of all countries.

The study of the cross-country connectedness between the yield components of the ten countries, carried out by means of a variance decomposition technique, reveals the existence of significant interconnections for both term premia and short-rate expectations. The size of these links varies substantially over time and, departing from previous empirical evidence on the euro area, we observe that total connectedness in expected short rates and term premia is relatively strong in stable times and decreases in high volatility periods.

Appendix

A Comparison with Estimates From a Gaussian Model

In this appendix, we report the estimates of short-rate expectations and term premia for the euro area obtained from a standard 5-factor Gaussian model (see Dai and Singleton (2000)) . The model assumes, as in Adrian et al. (2013), that the state variables are the first five principal components of yields and it is estimated using the two-step approach proposed by Joslin et al. (2011) (see also Wright (2011)). In particular, we first run a principal components analysis on yields, take the first five principal components as state variables, and estimate a vector autoregression (VAR) for the dynamics of the five factors to obtain the coefficients of their processes under the physical measure. We then keep these coefficients fixed and estimate the remaining parameters – i.e., those that determine the market price of risk – by imposing the cross-sectional no-arbitrage restrictions implied by the model. The estimation method is based on maximum likelihood, assuming that the differences between the observed yields and the corresponding model-implied values are i.i.d. measurement errors. The empirical analysis is for the euro area as a whole, and the sample period is January 2000 to September 2021.

Panel A of **Figure A.1** reports the time series of the difference between the 10-year and 30-year expected short rates estimated by the Gaussian model and those estimated by our model. We notice that the average difference for the 10-year expected short rate (ESR) is zero. However, there is a significant over-estimation (about 50 bps) of the Gaussian model in the period preceding the GFC and under-estimation (about -50 bps) during the European sovereign debt crisis. Again, in the final part of the sample, we can observe a substantial over-estimation from the Gaussian model. The path of the differences in ESR for the 30-year maturity is similar, but the values are almost always negative, which means that the Gaussian model tends to significantly under-estimate the long-term ESR with respect to our model. The average difference is -37 bps.

Panel B shows the time series of the differences for the term premia. Here, we find that, on average, both the differences are close to zero: -9 and 1 bps for the 10- and 30-year maturity, respectively. The behavior of the difference for the 10-year term premium (TP) is symmetric to that for ESR, as the Gaussian model estimates of TP are significantly lower than those of our model before the GFC, higher during the sovereign debt crisis, and much lower (i.e., even more negative) in the final part of the sample. Interestingly, the term premia estimated by the two models for the 30-year maturity are relatively close, with significant differences only at the beginning of the sovereign debt crisis and in correspondence with the pandemic shock in 2020.

Overall, by comparing the estimates for ESR and TP obtained by our model with those provided by the estimation of the Gaussian model, we observe that the differences range in the $-50/+50$ bps interval and, apart from the very long-maturity ESR, are on average close to zero.

However, when we consider the volatility of the original series of ESR and TP generated by the two models, a relevant difference emerges. Indeed, the standard deviation of ESR estimated by the Gaussian model is substantially lower than that of the corresponding estimates provided by our model, and vice versa for TP. In particular, the volatility of the 10-year (30-year) TP is 38% (15%) higher than that of our model, a result which is consistent with previous evidence on the excessive volatility of TP estimated by Gaussian models (see, for example, Bauer et al. (2014)). This result might be explained by the fact that constant volatility Gaussian models do not explicitly separate the convexity component, which is relevant at long maturities, and is thus mainly incorporated in the TP component of yields.

B Connectedness Measures

We calculate different measures of connectedness using the variance decomposition methodology of Diebold and Yilmaz (2012 and 2014).

For the 10-year yields and for the corresponding estimated components, we estimate a covariance stationary VAR(1) of the form $x_t = \Phi x_{t-1} + \varepsilon_t$, where x_t is a vector that contains the 10-year yields of the ten countries or one of the yield components, i.e., the 10-year expected short rates, term premia, and convexities, and $\varepsilon_t \sim (0, \Gamma)$ is a vector of independently and identically distributed disturbances. The moving average representation is $x_t = \sum_{h=0}^{\infty} Q_h \varepsilon_{t-h}$, where the 10×10 matrices Q_h follow the recursion $Q_h = \Phi Q_{h-1}$, with Q_0 being the identity matrix and $Q_h = 0$ for $h < 0$.

The fraction of the H-step-ahead error variances in forecasting the variable x for the i-th country that are due to shocks to the variable x for the j-th country, $i, j = 1, ..., 10, i \neq j$, is computed as

$$\widetilde{d}_{ij}(H) = \frac{\gamma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i' Q_h \Gamma e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_i' Q_h \Gamma Q_h' e_i\right)}, \tag{B.1}$$

where γ_{jj} is the standard deviation of the error term for the j-th equation, e_i (e_j) is a vector with one as the i-th (j-th) element and zeros otherwise, and the denominator is the variance of the H-step-ahead forecast error. Since the variables are not orthogonalized, the sum of the entries of the variance decomposition, $\widetilde{d}_{ij}(H)$, might be different from one. Therefore, we normalize each element by the sum of the elements:

$$d_{ij}(H) = \frac{\widetilde{d}_{ij}(H)}{\sum_{j=1}^{N} \widetilde{d}_{ij}(H)}. \tag{B.2}$$

The fractions $d_{ij}(H)$, $i \neq j$, define the "pairwise directional connectedness *from* the j-th country *to* the i-th country" and, similarly, $d_{ji}(H)$, $j \neq i$, the "pairwise directional connectedness *from* the i-th country *to* the j-th country." Therefore, the sum

$$D_{\cdot i}(H) = \sum_{j=1, j \neq i}^{N} d_{ji}(H) \tag{B.3}$$

indicates the "total directional connectedness *to* other countries *from* the i-th country", and the sum

$$D_{i \cdot}(H) = \sum_{j=1, j \neq i}^{N} d_{ij}(H) \tag{B.4}$$

the "total directional connectedness *from* other countries *to* the i-th country." The difference between $D_{\cdot i}(H)$ and $D_{i \cdot}(H)$, i.e., the difference between the shocks transmitted to and the shocks received from all other countries, gives the "*net* total directional connectedness for the i-th country":

$$D_i^*(H) = D_{\cdot i}(H) - D_{i \cdot}(H). \tag{B.5}$$

The "total connectedness" measure is obtained as the average of the *from* values $D_{i \cdot}(H)$ or the *to* values $D_{\cdot i}(H)$, $i = 1, ..., N$:

$$D(H) = \frac{1}{N} \sum_{i=1}^{N} D_{i \cdot}(H) = \frac{1}{N} \sum_{i=1}^{N} D_{\cdot i}(H). \tag{B.6}$$

In the empirical analysis, we set $H = 1$, i.e., a one-month forecast horizon. However, estimates obtained using a higher value for H produce very similar results.

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Table 1
Summary Statistics

This table reports mean and standard deviation for the time series of yields, yield volatility and macro survey expectations. Data on yields are end-of-month observations with maturities from 2 to 10 years and 30 years (not available for Finland, Portugal and Ireland), while data on 5- and 10-year yield volatilities are annualised monthly realized volatilities calculated from daily changes in yields with corresponding maturities. Data on macro expectations refer to the median of the ECB Survey of Professional Forecasters expectations of 1-year-ahead inflation and real GDP growth rates in the euro area. These data are available on a quarterly basis and we interpolate the data with a spline technique to derive monthly observations. The average value (Avg) is computed from the level of the variables. The standard deviation (S.D.) of yields and yield volatility is the annualised standard deviation of monthly changes in the variables, while the standard deviation of macro expectations is calculated from the level. All values are expressed in basis points. The sample period is January 2000 to September 2021.

	Maturity	Germany		France		Netherlands		Austria		Finland	
	Years	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Yields	2	1.382	0.637	1.487	0.646	1.418	0.636	1.490	0.674	1.412	0.650
	3	1.500	0.669	1.626	0.680	1.582	0.637	1.667	0.647	1.575	0.649
	4	1.649	0.679	1.814	0.680	1.744	0.662	1.839	0.656	1.737	0.664
	5	1.802	0.669	1.991	0.689	1.902	0.674	2.001	0.673	1.898	0.660
	6	1.935	0.670	2.135	0.684	2.054	0.663	2.150	0.687	2.055	0.659
	7	2.067	0.659	2.270	0.674	2.198	0.654	2.288	0.696	2.201	0.663
	8	2.186	0.647	2.417	0.664	2.330	0.649	2.420	0.683	2.327	0.653
	9	2.287	0.640	2.549	0.667	2.442	0.657	2.540	0.670	2.445	0.658
	10	2.377	0.634	2.670	0.657	2.548	0.650	2.648	0.662	2.557	0.660
	30	2.961	0.651	3.331	0.662	3.032	0.667	3.236	0.643		
Yield Vol.	5	0.608	0.520	0.612	0.564	0.602	0.531	0.610	0.590	0.595	0.550
	10	0.608	0.428	0.600	0.413	0.596	0.377	0.592	0.392	0.596	0.394

	Maturity	Belgium		Italy		Spain		Portugal		Ireland	
	Years	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Yields	2	1.567	0.810	2.060	1.283	1.963	1.201	2.760	2.963	2.246	2.345
	3	1.765	0.759	2.360	1.261	2.218	1.164	3.097	3.000	2.423	2.159
	4	1.956	0.756	2.588	1.225	2.405	1.102	3.311	2.722	2.613	1.944
	5	2.135	0.758	2.814	1.146	2.611	1.065	3.573	2.750	2.784	1.779
	6	2.294	0.764	3.008	1.102	2.792	0.999	3.778	2.606	2.961	1.628
	7	2.432	0.746	3.172	1.076	2.965	0.969	3.954	2.316	3.118	1.484
	8	2.570	0.730	3.324	1.034	3.117	0.943	4.096	2.071	3.279	1.349
	9	2.699	0.727	3.472	0.971	3.252	0.912	4.180	1.845	3.399	1.309
	10	2.813	0.722	3.618	0.922	3.380	0.875	4.223	1.636	3.510	1.237
	30	3.462	0.685	4.358	0.709	4.091	0.771				
Yield Vol.	5	0.643	0.725	0.920	1.415	0.829	1.217	1.285	3.285	0.894	2.083
	10	0.617	0.533	0.817	0.982	0.776	0.968	1.071	2.243	0.786	1.231

	Maturity	Euro Area	
	Years	Avg	S.D.
Yields	2	1.721	0.727
	3	1.911	0.693
	4	2.103	0.674
	5	2.287	0.669
	6	2.462	0.662
	7	2.621	0.650
	8	2.763	0.640
	9	2.885	0.633
	10	2.992	0.627
	30	3.710	0.710
Yield Vol.	5	0.591	0.453
	10	0.581	0.295
Inflation	1	1.583	0.314
GDP Growth	1	1.612	1.522

Table 2
Cross-Country Correlation in Yields

This table reports statistics on the cross-country correlation in yields. Panel A and Panel B contain the cross-correlation in monthly changes in 2-year yields and 10-year yields, respectively. Panel C shows the cumulative percentage contribution of the first three principal components to the total variability of monthly changes in yields with maturities from 2 to 10 years and 30 years (when available), and yield variances with maturities from 2 to 10 years. Columns "All" refer to data for the ten countries; columns "Low-rate" to the low-rate countries, i.e., Germany, France, the Netherlands, Austria, Finland, and Belgium; columns "High-rate" to the high-rate countries i.e., Italy, Spain, Portugal, and Ireland. All values are expressed in percentage terms. The sample period is January 2000 to September 2021.

Panel A: 2-year yield

	Fra	Net	Aus	Fin	Bel	Ita	Spa	Por	Ire
Ger	91.5	94.0	86.4	90.9	69.5	27.4	32.1	16.4	24.0
Fra		89.7	87.5	85.9	78.6	38.6	41.3	21.9	24.4
Net			87.6	89.2	68.5	29.3	34.1	21.9	27.7
Aus				80.2	81.7	41.8	43.4	20.1	28.3
Fin					65.7	27.7	32.4	19.6	27.1
Bel						59.6	58.0	18.8	34.5
Ita							83.1	45.5	52.5
Spa								41.2	52.6
Por									43.8

Panel B: 10-year yield

	Fra	Net	Aus	Fin	Bel	Ita	Spa	Por	Ire
Ger	93.3	96.2	92.9	96.0	84.2	41.6	50.6	20.6	47.6
Fra		94.5	94.2	94.0	90.2	54.9	57.7	25.3	52.9
Net			95.1	96.1	86.4	45.6	53.7	19.2	50.9
Aus				94.8	89.5	51.0	58.6	30.2	55.3
Fin					87.3	44.7	52.4	23.5	49.8
Bel						62.1	70.1	33.6	65.8
Ita							76.2	39.9	57.2
Spa								46.4	72.2
Por									46.0

Panel C: Principal Components Analysis

	Yields			Yield Variances		
	All	Low-rate	High-rate	All	Low-rate	High-rate
First PC	58.7	81.0	62.4	40.7	58.0	44.7
Second PC	74.8	89.3	77.7	56.6	74.0	75.1
Third PC	81.3	92.8	87.5	68.0	81.1	86.0

Table 3
Fitting Errors

This table reports mean (Avg) and standard deviation (S.D.) for the estimation errors of (i) yields with maturities from 2 to 10 years and 30 years (for all countries except Finland, Portugal and Ireland), (ii) yield volatilities with maturities 5 and 10 years, and, only for the euro area, (iii) 1-year-ahead inflation and real GDP growth rates. The table also reports the maximal Sharpe ratio (MSR) calculated as $\sqrt{\Psi_t' \Psi_t}$. All values are expressed in basis points. The sample period is January 2000 to September 2021.

	Germany		France		Netherlands		Austria		Finland	
	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Yields	0.6	6.3	0.0	6.1	0.3	5.7	0.4	6.5	0.4	5.2
Yield Volatility	0.2	5.1	1.6	5.6	0.0	5.8	0.4	5.6	0.2	6.0
MSR	2.7	1.4	1.8	2.5	2.1	1.1	1.1	0.7	2.3	0.6
	Belgium		Italy		Spain		Portugal		Ireland	
	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
Yields	0.9	7.2	0.5	7.6	0.6	7.8	0.1	16.7	0.2	10.8
Yield Volatility	0.2	4.9	-2.2	7.1	-0.5	6.8	-5.7	11.4	-10.7	7.6
MSR	2.7	1.2	2.0	1.0	2.5	1.5	1.0	0.4	1.3	0.5

	Euro Area	
	Avg	S.D.
Yields	2.5	6.1
Yield Vol.	0.4	4.0
Inflation	2.2	2.1
GDP Growth	2.7	8.7
MSR	3.1	1.0

Table 4
State Variables and Parameters

This table reports the correlation between estimated state variables and principal components of yields and yield variances and the average value of estimated parameters. In Panel A, a principal components analysis is applied, for each country, to monthly changes in yields (with maturities from 2 to 10 years and 30 years, when available) and monthly changes in yield variances (with maturities from 2 to 10 years). Then the correlation between the following variables is calculated: (i) monthly changes in the estimated state variable ℓ and the first principal component of yield changes (a proxy for the level of yields); (ii) monthly changes in the estimated state variable s and the second principal component of yield changes (a proxy for the slope of the yield curve); and (iii) monthly changes in the estimated state variable v and the first principal component of yield variance changes (a proxy for the level of yield variance). All values are expressed in percentage terms. The sample period is January 2000 to September 2021. Panel B shows, for each parameter, the average value calculated across the ten countries and the euro area, and the corresponding standard error (in parenthesis). No standard error is computed for those parameters that are estimated only for the euro area as a whole, i.e., the fourth and the fifth rows of matrices K and Σ and vector Θ and the elements of matrix Σ_M.

Panel A: Correlation between state variables and principal components

	Ger	Fra	Net	Aus	Fin	Bel	Ita	Spa	Por	Ire	E.A.
ℓ – first PC yields	87.9	87.0	91.8	92.9	63.0	90.2	95.8	97.6	79.9	71.9	94.8
s – second PC yields	92.7	91.4	95.2	87.4	97.7	83.6	81.2	93.9	51.0	92.4	96.8
v – first PC yield variances	98.3	97.3	97.4	98.0	96.0	99.2	99.3	99.3	98.7	99.6	98.8

Panel B: Average estimated parameters

K					Θ	$\Sigma_{(ii)}$	$\Sigma_{M(ii)}$
0.2163	0.0114	0.0210	-0.1079	0.0767	0.0088	0.0845	0.0018
(0.0301)	(0.0110)	(0.0132)	(0.0263)	(0.0218)	(0.0059)	(0.0185)	–
0.0162	0.1415	0.1215	-0.0946	-0.0424	-0.0054	0.2062	0.0059
(0.0287)	(0.0112)	(0.0246)	(0.0175)	(0.0099)	(0.0074)	(0.0163)	–
0.0436	-0.0091	0.2963	-0.1243	-0.0838	0.0213	0.1429	
(0.0161)	(0.0236)	(0.0339)	(0.0171)	(0.0217)	(0.0065)	(0.0350)	
0.0031	0.0623	0.0993	0.4302	0.0485	0.0182	0.0136	
–	–	–	–	–	–	–	
0.0078	0.0250	0.1716	0.0348	0.6358	0.0178	0.0159	
–	–	–	–	–	–	–	

Λ_1					Λ_0	δ_0	δ_1
-0.0679	0.0320	-0.1845	1.7711	-1.0443	-0.0372	0.0176	0.0199
(0.0117)	(0.0142)	(0.0683)	(0.6295)	(0.3639)	(0.0092)	(0.0034)	(0.0089)
0.0058	-0.3925	0.0441	0.4831	0.2310	-0.0288		0.9257
(0.0128)	(0.0245)	(0.0260)	(0.1106)	(0.0555)	(0.0034)		(0.0162)
-0.1944	-0.0941	-0.1012	1.1993	0.7184	0.0216		0.9877
(0.1208)	(0.0210)	(0.0118)	(0.2436)	(0.2240)	(0.0055)		(0.0465)
0	0	0	0	0	0		
–	–	–	–	–	–		
0	0	0	0	0	0		
–	–	–	–	–	–		

Table 5
Yield Components

This table reports mean and standard deviation for the time series of estimated components of yields, i.e., expected short rate (ESR), term premium (TP) and convexity (CX) with maturities 5, 10 and 30 years (when available). The average value (Avg) is computed from the level of the variables, while the standard deviation (S.D.) is the annualised standard deviation of monthly changes in the variables. All values are expressed in basis points. The sample period is January 2000 to September 2021.

	Maturity	Germany		France		Netherlands		Austria		Finland	
	Years	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
ESR	5	217	56	209	52	233	56	226	53	221	53
	10	261	41	274	42	273	41	286	44	282	42
	30	312	20	356	22	299	19	340	21		
TP	5	-35	30	-11	18	-41	32	-25	22	-30	24
	10	-17	34	-3	35	-13	34	-16	36	-22	33
	30	28	86	32	90	50	87	29	92		
CX	5	-2	3	-2	3	-2	3	-2	3	-2	3
	10	-7	11	-7	11	-6	10	-6	12	-6	10
	30	-45	74	-55	90	-47	71	-47	89		

	Maturity	Belgium		Italy		Spain		Portugal		Ireland	
	Years	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.	Avg	S.D.
ESR	5	245	63	291	91	281	82	348	345	292	186
	10	286	48	337	69	326	58	413	358	323	164
	30	321	22	336	33	318	31				
TP	5	-29	33	-5	48	-14	37	28	113	-5	50
	10	1	43	35	72	23	58	44	151	39	94
	30	65	135	153	241	150	242				
CX	5	-2	8	-6	27	-5	21	-19	218	-9	113
	10	-7	23	-14	67	-13	60	-37	429	-14	181
	30	-41	132	-55	262	-61	273				

	Maturity	Euro Area	
	Years	Avg	S.D.
ESR	5	256	56
	10	297	42
	30	335	20
TP	5	-24	29
	10	9	32
	30	73	66
CX	5	-2	3
	10	-6	8
	30	-38	53

Table 6
Correlation in Yield Components

This table reports the cross-country correlation in the estimated components of the 10-year yield. Panel A contains the cross-correlation in monthly changes of the 10-year expected short rate. Panels B and C show the same correlation for monthly changes in the 10-year term premium and convexity, respectively. All values are expressed in percentage terms. The sample period is January 2000 to September 2021.

Panel A: Expected short rate

	Fra	Net	Aus	Fin	Bel	Ita	Spa	Por	Ire
Ger	93.1	95.4	88.7	95.8	81.8	33.9	46.3	6.1	21.3
Fra		94.9	94.3	95.0	89.5	48.2	57.1	11.3	25.5
Net			92.0	95.5	83.6	40.2	51.5	4.0	22.9
Aus				91.3	89.4	51.8	57.3	18.0	26.2
Fin					85.7	42.4	51.0	7.6	23.6
Bel						60.6	68.5	17.1	43.2
Ita							78.8	23.6	49.2
Spa								25.3	61.0
Por									41.9

Panel B: Term premium

	Fra	Net	Aus	Fin	Bel	Ita	Spa	Por	Ire
Ger	92.9	96.6	88.5	94.4	80.0	39.0	51.3	12.7	28.0
Fra		93.0	93.7	94.2	89.2	49.8	54.8	19.6	29.4
Net			89.1	94.4	79.9	40.9	52.6	9.7	27.9
Aus				91.6	90.3	50.8	46.8	28.1	28.8
Fin					83.2	44.2	50.0	15.3	27.7
Bel						59.2	54.7	29.9	42.1
Ita							67.4	24.1	42.2
Spa								22.4	55.0
Por									48.4

Panel C: Convexity

	Fra	Net	Aus	Fin	Bel	Ita	Spa	Por	Ire
Ger	61.5	69.4	61.5	63.5	58.1	49.3	59.4	44.4	32.6
Fra		66.5	86.4	54.1	83.6	31.8	39.8	39.6	9.9
Net			72.3	87.0	68.2	81.0	53.6	32.2	13.7
Aus				61.2	78.9	37.3	42.8	36.8	1.1
Fin					56.6	82.0	53.4	21.1	29.5
Bel						34.5	37.3	30.8	8.9
Ita							52.2	15.0	22.9
Spa								51.6	10.1
Por									11.6

Table 7
Net Directional Connectedness in Yield Components

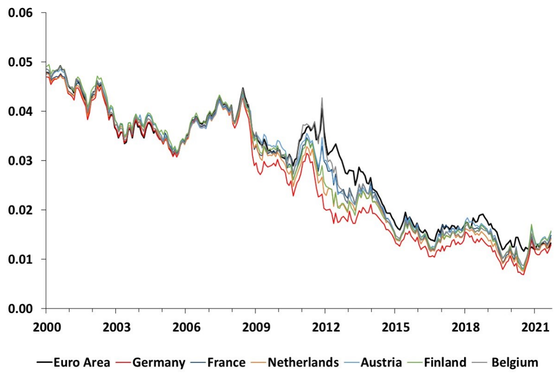
This table shows the net total directional connectedness in the 10-year expected short rate, term premium and convexity. The "net" total directional connectedness is calculated as the difference between the total directional connectedness "to" others and the total directional connectedness "from" others. Therefore, positive values of net connectedness indicate that the country is a net exporter of shocks in the yield, or yield component, for the other countries, while negative values mean that the country is a net importer of shocks from the other countries. The total connectedness measure at the bottom of the table is obtained as the average of all the "to" others (or "from" others) total directional connectedness values. All values are expressed in percentage terms and refer to the period January 2000 to September 2021.

	Yield	Exp. Short Rate	Term Premium	Convexity
Germany	3.17	3.65	6.83	-4.81
France	15.62	14.52	15.44	22.21
Netherlands	8.01	8.80	8.86	1.27
Austria	15.70	14.19	11.33	20.03
Finland	9.57	9.48	9.19	-9.08
Belgium	16.18	17.05	14.34	7.87
Italy	-17.03	-15.27	-16.34	-2.81
Spain	-4.07	-3.86	-7.30	-13.35
Portugal	-31.47	-21.39	-23.66	-17.49
Ireland	-15.67	-27.17	-18.68	-3.84
Total Connectedness	80.50	74.63	74.58	65.75

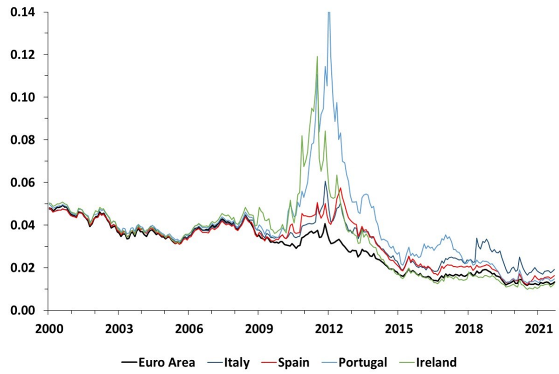
Figure 1
Time Series of Yield Components

This figure shows the time series of the estimated 10-year maturity expected short rate, term premium and convexity for the sample period January 2000 to September 2021. Panel A reports the expected short rate for the euro area and the six low-rate countries (i.e., Germany, France, the Netherlands, Austria, Finland and Belgium) and Panel B for the euro area and the four high-rate countries (i.e., Italy, Spain, Portugal and Ireland). Panels C and D report the corresponding time series for the term premium, while Panels E and F the time series for convexity.

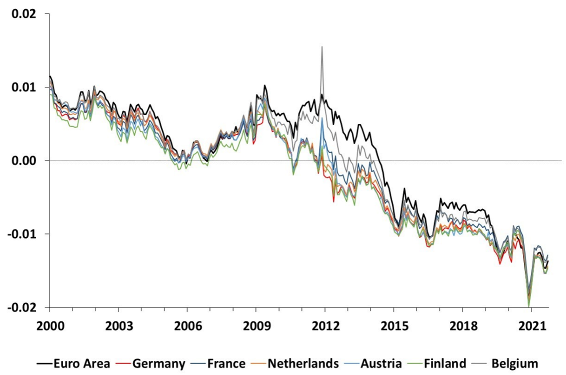
Panel A: Expected short rate in low-rate countries



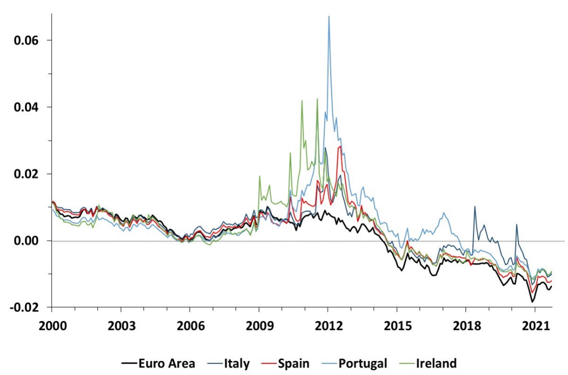
Panel B: Expected short rate in high-rate countries



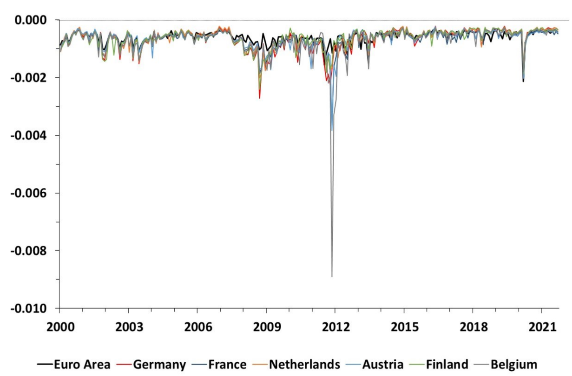
Panel C: Term premia in low-rate countries



Panel D: Term premia in high-rate countries



Panel E: Convexity in low-rate countries



Panel F: Convexity in high-rate countries

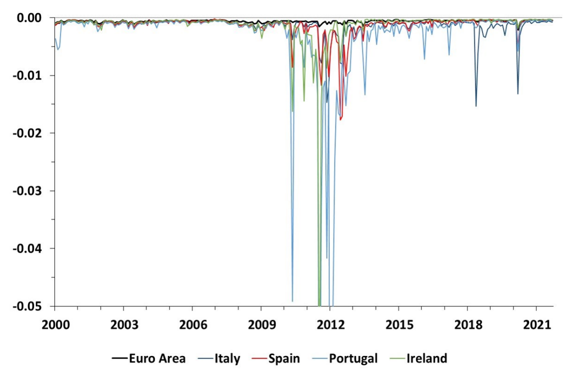


Figure 2
Decomposition of Yields in the euro area

This figure shows evidence on the decomposition of yields for the euro area as a whole. Panels A and B contain the time series of expected short rates and term premia at the 5-, 10-, and 30-year maturities. Panels C and D report the time series of the yield components for the 10-year yield and 30-year yield, respectively. The sample period is January 2000 to September 2021.

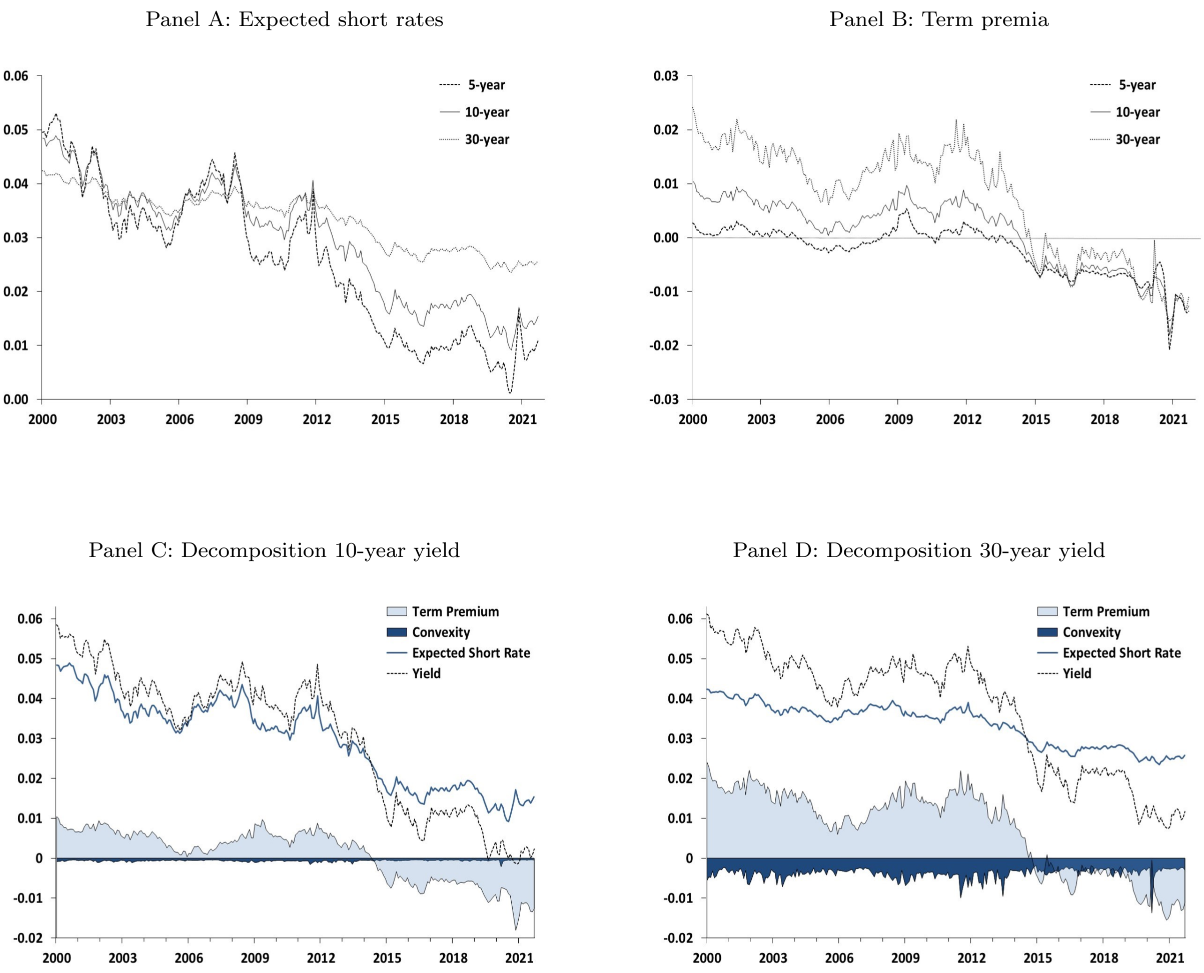
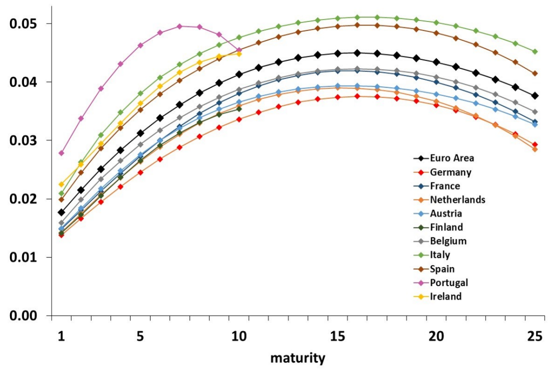


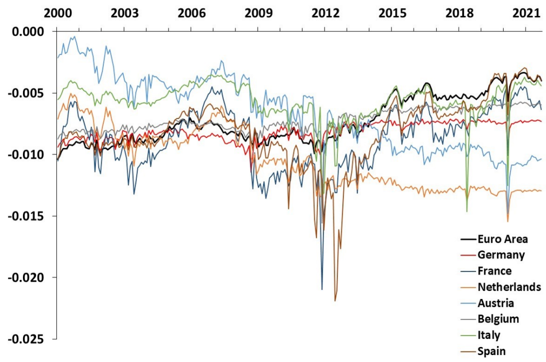
Figure 3
Forward Rates

This figure shows evidence on estimated instantaneous forward rates, for each country, over the sample period January 2000 to September 2021. Panel A reports the average term structure of instantaneous forward rates, while Panel B contains the time series of the spread between the 25-year and the 15-year instantaneous forward rates. This difference can be calculated only for those countries which include the 30-year yield in estimation (i.e., all countries except Finland, Portugal and Ireland). Panel C shows the average size of convexity and the sum of the other components (see equation (11)) in the 25- minus 15-year forward rate spread.

Panel A: Average term structure of forward rates



Panel B: 25- minus 15-year forward rate spread



Panel C: Size of convexity in 25- minus 15-year forward rate spread

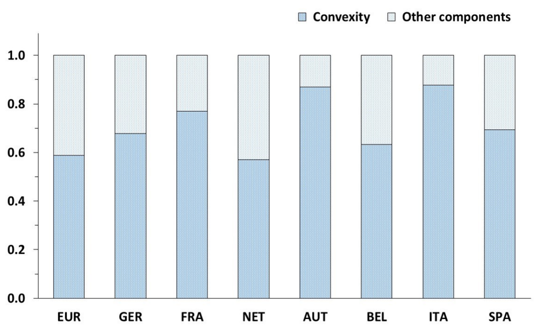
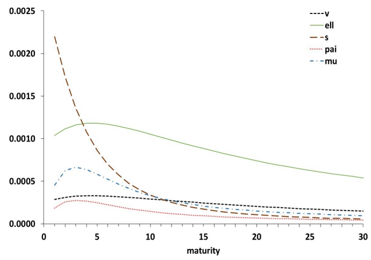


Figure 4
Sensitivity of Yield Components to Factors

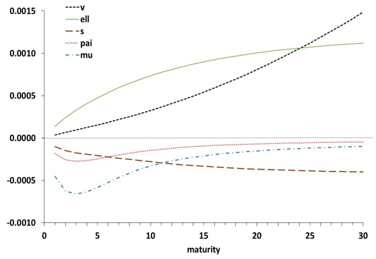
This figure shows the relation between the yield components and the five factors (i.e., the variance factor v, the level factor ℓ, the slope factor s, the expected inflation rate π, and the expected output growth rate μ) for the euro area as a whole. Panel A reports the sensitivity of changes in τ-maturity expected short rates, term premia and convexities, with $\tau = 1, ..., 30$ years, to orthogonalized and standardized changes in the five state variables. Panel B shows the impulse-response function for the 10-year expected short rate, term premium and convexity following a one-standard-deviation shock to each standardized state variable.

Panel A: Sensitivity of yield components to shocks in the factors

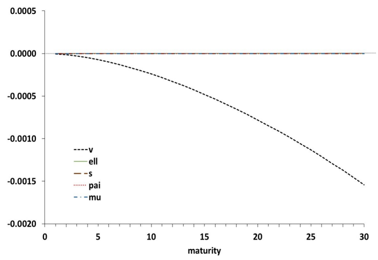
Expected short rate



Term premium

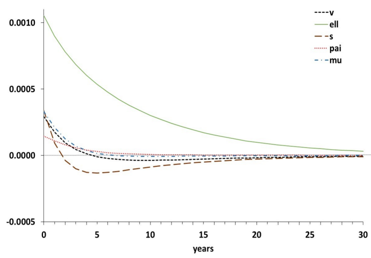


Convexity

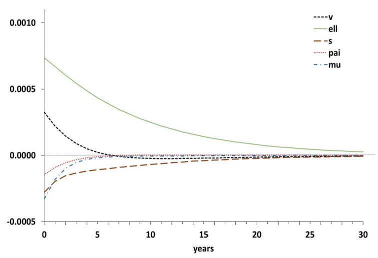


Panel B: Impulse-response function for 10-year yield components

Expected short rate



Term premium



Convexity

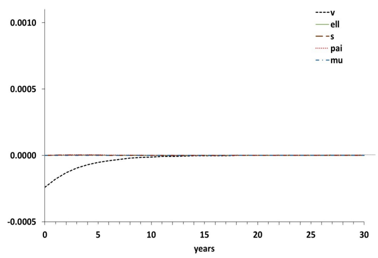
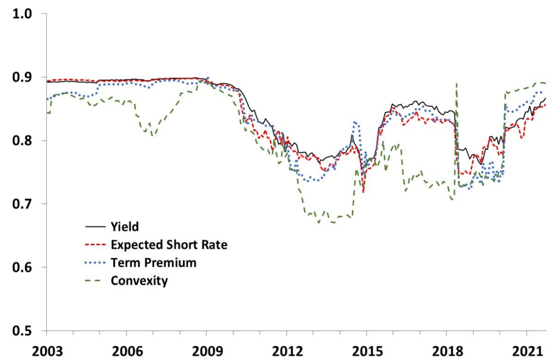


Figure 5
Total Connectedness

This figure contains evidence on the total connectedness in yields and their components and the spreads between these variables in high-rate and low-rate countries. Panel A reports rolling estimates of the total connectedness measure – defined as the average of all the "to" others (or "from" others) total directional connectedness values – for monthly changes in the 10-year yield and its estimated components. The size of the rolling window is 36 months, which means that the first estimation window ranges from February 2000 to January 2003 and the last window ranges from October 2018 to September 2021. Panel B shows the difference between the average value of the 10-year yield and its components (i.e., expected short rate, term premium and convexity) for high-rate countries and the average value of the equivalent variables for low-rate countries. The sample period is January 2000 to September 2021.

Panel A: Rolling total connectedness



Panel B: Spreads between high-rate and low-rate countries

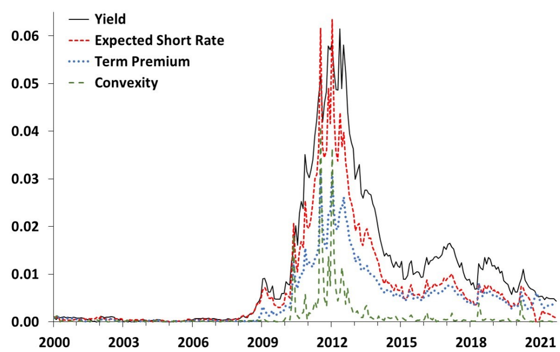


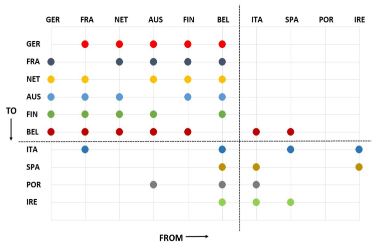
Figure 6
Pairwise Directional Connectedness for Yield Components

This figure shows the network structure for monthly changes in the estimated components of the 10-year yield. Panel A reports the pairwise directional connectedness for the 10-year expected short rate calculated over three separate sub-sample periods: (i) January 2000 to December 2006, (ii) January 2007 to December 2013, and (iii) January 2014 to September 2021. Panel B contains the equivalent measure for the 10-year term premium. The coloured nodes in the figures indicate that the corresponding link is in the fiftieth percentile of all pairwise directional connectedness.

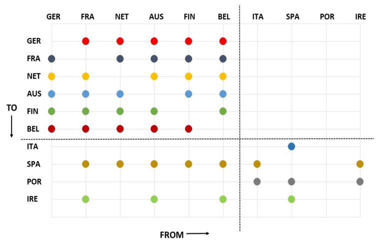
Panel A: Sub-samples pairwise directional connectedness for expected short rate

2000 – 2006

2007 – 2013

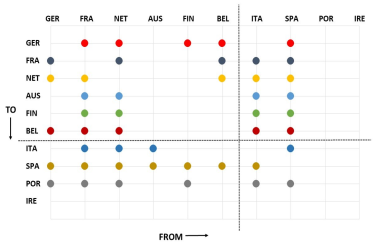


2014 – 2021

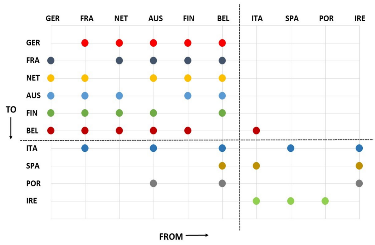


Panel B: Sub-samples pairwise directional connectedness for term premium

2000 – 2006



2007 – 2013

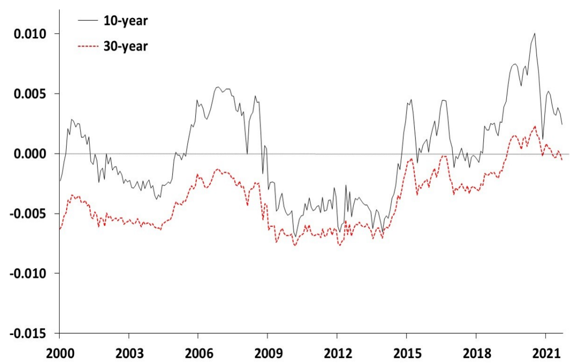


2014 – 2021

Figure A.1
Difference Between Gaussian and Model Estimates

This figure reports the difference between the expected short rates and term premia in the euro area estimated by a 5-factor Gaussian model and by our model. Panel A shows the time series of the differences for the 10-year and 30-year expected short rates, calculated as values from the Gaussian model minus values from our model. Panel B shows the same differences for term premia. The sample period is January 2000 to September 2021.

Panel A: Difference for expected short rates



Panel B: Difference for term premia