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EXPLAINING THE FAILURE OF THE EXPECTATIONS HYPOTHESIS WITH SHORT-TERM RATES

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This paper provides the first systematic study of the temporal and cross-sectional variation in the risk premium of the expectations hypothesis (EH) at very short end of the term structure. Using a unique and comprehensive dataset of European repurchase (repo) rates, we explain the sources and time variation affecting the risk premium. Our results show that the EH cannot be rejected when loans are secured by safe collateral and that unconventional monetary policy can substantially reduce risk premiums. By contrast, the EH is violated when interest rates are affected by funding risk and collateral risk.

Keywords: Expectations hypothesis, interest rates, risk premium, monetary policy, repo

JEL Codes: D01, E43, E52, G10, G21

The expectations hypothesis (EH) of the term structure of interest rates postulates that the long-term rate is purely determined by the current and expected future short-term rates plus a constant risk premium. Since Fisher (1896), this has been a pivotal theory for interest rates and bond asset pricing. However, the EH has typically been rejected using a wide variety of econometric methods and data. Why does the EH fail? Would it hold in absence of time-varying risk premiums? By comparing assets with different risk characteristics, can we explain the failure of the EH?

In this paper, we empirically address these important questions by conducting a comprehensive analysis of European repurchase agreements or "repos". These are short-term loans secured with collateral securities that are characterized by different degrees of risk. Using unique transaction-level data, we analyze whether temporal and cross-sectional variation in repo rates help explain the failure of the EH at the very short-end of the term structure. We find that the EH holds when repos are collateralized by relatively safe securities, market risk is low, and (unconventional) monetary policy structurally reduces funding and collateral risk.

The EH is important to policy makers and investors for at least three reasons. First, investment decisions and economic output are determined by short-term market expectations, which are commonly retrieved from the yield curve and require a separation of the effects coming from risk premiums (Keynes, 1936). Second, an effective and timely implementation of economic policies needs a thorough understanding and accurate interpretation of interest rates, agents' expectations, and risk premiums. This holds for conventional monetary policy, whose transmission channels critically depend on interest rate expectations, as well as for unconventional policies aiming at alleviating risk premiums. Third, among the first symptoms of a financial crisis are a sudden increase in risk premiums and quantity rationing of money market liquidity that can generate bank runs, rollover risk, and system-wide financial contagion. Thus, a better understanding of money market risk premiums and factors contributing to funding strains is crucial for market regulators (e.g., Financial Stability Board, 2012).

European repos are ideal for testing the EH due to their contract design and institutional setting. A repo is a collateralized loan, or equivalently, a sell and repurchase agreement of the underlying security, including collateral ownership and margin requirements ("haircuts"), which give the cash lender strong protection against risk. In addition, repos are mostly traded on very short-term maturities, which reduces term premiums and uncertainty over longer horizons (Hicks, 1946). Importantly, European repos are secured by a variety of collateral, ranging from extremely safe to riskier securities, thereby providing cross-sectional heterogeneity.

The institutional setting is characterized by risk mitigation and facilitates the identification of risk premiums. European repos are mostly traded on anonymous, transparent, and liquid platforms cleared by central counterparties (Mancini, Ranaldo, and Wrampelmeyer, 2016), which reduces counterparty credit risk (e.g., Duffie and Zhu, 2011; Acharya and Bisin, 2014), possible arbitrage opportunities, and frictions such as credit risk, search costs, and market illiquidity that can bias the EH analysis (Longstaff, 2000a). Moreover, collateral securities in the interbank market are typically eligible for refinancing operations at the ECB that uses repos as its main operational tool. This important institutional feature further reduces funding risk by facilitating the substitution between "private" and "public" liquidity.

In this paper, we perform various tests of the EH across time and collateral securities. Econometrically, we employ the vector autoregression (VAR) framework proposed by Bekaert and Hodrick (2001), and test the unbiasedness hypothesis using overnight repo spot and forward rates. This analysis provides the first test of the predictability of the repo overnight rate, i.e., the market's actual short rate and target rate of ECB conventional monetary policy. Specifically, we examine whether today's forward premium is an efficient predictor of tomorrow's spot spread, and test the resulting restrictions imposed by the EH on the VAR parameters using a recursive iterative procedure developed by Bekaert and Hodrick (2001), whose size and power properties have also been investigated by Sarno, Thornton, and Valente (2007).

We use a unique and comprehensive data set representing the vast majority of the European repo market. Our data set spans from 2006 to 2015, including pre-crises as well as crises periods. We access every trade executed on the three main automated trading systems: BrokerTec, Eurex Repo, and MTS Repo, which together represent more than 67% of the entire European repo market in 2014 (ECB, 2014), covering a total trading volume of EUR 540 trillion, i.e., on average more than 50 trillion per year. These numbers give an idea about the importance and the size of the European repo market, which is larger than the estimated size of the repo market in the United States.[1] Our data set consists of general collateral (GC) repos, whose collateral includes a wide range of securities with similar characteristics, and specific repos ("specials", SC), whose collateral is limited to a specific security. GC repos benefit from risk diversification, while special repos inherit idiosyncratic risk from the collateral security (Duffie, 1996). Given the information granularity of our data, we provide the first systematic study of the temporal and cross-sectional variation in repo

[1]Estimates of the size of the U.S. repo market range from USD 5.5 trillion (Copeland et al., 2012) to USD 10 trillion (Gorton and Metrick, 2012).

rates during different monetary regimes, market conditions, and across heterogeneous collateral securities.

We perform extensive unconditional and conditional tests of the EH. The unconditional analysis aims at identifying the major sources impacting the repo risk premium, which are funding and collateral risk.[2] The ECB's implementation of unconventional monetary policies (UMP) in mid-October 2008, designed to alleviate money market tensions and funding risk (González-Páramo, 2011), serves as a quasi-experiment to analyze this source of the risk premium. Specifically, one of the major changes is the substitution of the variable-rate (VR) tender format with the fixed-rate full-allotment (FA) regime. In the FA regime, banks pledging eligible collateral have full access to central bank liquidity at no punitive rates. Representing an unambiguous transformation of the institutional environment, we test whether the EH tends to hold more (less) after (before) the ECB's implementation of UMP measures in October 2008. To shed light on collateral risk, we compare repo contracts with different collateral securities. We test whether the violation of the EH is likely to arise for repo rates bearing larger collateral risk stemming from idiosyncratic risk (as for specials) or sovereign risk as for some government bonds more affected by the European sovereign debt crisis.

The conditional tests aim at investigating the time variation of the risk premium. We employ two methods for the conditional analyses. First, we condition the EH tests on risk variables, such as the 3-month Euribor-Eonia spread (i.e., the Euro counterpart of the 3-month Libor-OIS spread), representing a broad measure of money market risk premiums. Second, we condition the

[2]Throughout this paper, funding risk broadly refers to the inability to fulfill short-term obligations or liquidity needs. Collateral risk refers to value losses of the collateral security or the difficulty to repurchase it.

EH tests on weekdays, analyzing the timing of the weekly main refinancing operations (MRO) in the Eurosystem. As documented in Garcia-de-Andoain et al. (2016), banks apply for new reserves on Tuesdays, which they receive from the ECB on Wednesdays. This schedule naturally implies lower funding risk right after Wednesdays than on the weekdays before.

Several clear results emerge from our study. On the one hand, the EH holds when repo rates are unaffected by risk suggesting that agents tend to form correct expectations about very short-term rates. This generally applies from mid-October 2008 on, suggesting that the new ECB monetary regime is effective in removing funding and collateral risk. On the other hand, the EH is typically rejected in presence of risk. This holds true in our time-series and cross-sectional analyses. We find that test results co-move with well-known risk variables, displaying less support in high-risk periods and vice versa. Cross-sectionally, the rejection of the EH is more evident when collateral securities bear sovereign risk premiums, such as for Italian and Spanish government bonds, or idiosyncratic risks as for specials. The EH analysis throughout the MRO weekdays reveals the dependence of the EH on deterministic patterns in funding risk, showing higher support on reserve-rich days than outside. Overall, we provide statistical support that the validity of the EH moves inversely with funding risk and collateral risk, and that central bank policies can counteract these risks, leading to a better alignment of expectations and interest rates.

Our paper contributes to two strands of the literature. First, as a simple but general theory, the EH has attracted an enormous deal of attention in the literature.[3] The most important contributions closest to our paper are Longstaff (2000b) and Della Corte, Sarno, and Thornton (2008),

[3]An exhaustive survey goes beyond the scope of this paper. Former studies on the EH include, e.g., Roll (1970), Fama (1984a), Fama and Bliss (1987), Frankel and Froot (1987), Stambaugh (1988), Froot (1989) Campbell and Shiller (1991), Bekaert, Hodrick, and Marshall (1997), and Bekaert and Hodrick (2001).

both providing a thorough empirical analysis of the EH using U.S. repo data. Contrary to prior research, Longstaff (2000b) shows that the EH holds for very short maturities, from overnight up to several weeks. Della Corte, Sarno, and Thornton (2008) provide evidence against the EH, but their rejection is insignificant from an economic point of view. Our paper reconciles this mixed evidence by explaining *why* the EH can fail, that is, the fundamental role of the time-varying risk premium that essentially stems from funding and collateral risk. While the time-series approach has dominated prior research on the EH, none of the previous papers provides a comparative analysis over different repo collateral securities and rates. From an economic point of view, our cross-sectional analysis also reveals that the EH tends to hold for the largest share of the European repo market after October 2008. From an informational point of view, our results are in line with the idea that loans secured by high-quality securities are inherently informationally insensitive (Holmstrom, 2015), whereas informationally-sensitive securities bear (time-varying) risk premiums.

Second, we contribute to the growing empirical literature on repo markets. Gorton and Metrick (2012), Krishnamurthy, Nagel, and Orlov (2014), and Copeland, Martin, and Walker (2014) analyze the effects of the recent financial crisis on U.S. repos. Mancini, Ranaldo, and Wrampelmeyer (2016) document the overall resilience of the European repo market during the recent financial crisis, while Boissel et al. (2016) show that repo rates collateralized by government bonds of GIIPS countries were affected by sovereign risk. Focusing on specials, Jordan and Jordan (1997) and Buraschi and Menini (2002) provide evidence that (liquidity) risk premiums affect repo rates. We contribute to the extant literature by examining whether and how time-varying risk and central bank policies affect expectations on the pricing of GC and special repo rates. To do this, we analyze the largest and most comprehensive transaction-based data set of the European repo market studied so far.

The paper proceeds as follows. The next section describes the data set and provides summary statistics. Section 2 presents the EH and its theoretical test predictions, and the econometric procedure is described in Section 3. Our unconditional results are presented in Section 4, and the conditional test results in Section 5. In Section 6, we present several robustness checks, including term structure tests. Section 7 concludes.

1. Data

Our data set contains every repo transaction executed on the three major European electronic trading platforms from 2006 to 2015: BrokerTec, Eurex Repo, and MTS Repo, which together represent more than 67% of the entire European repo market in 2014 (ECB, 2014).[4] There are two important distinguishing characteristics across European repos: First, the geographical origin of the collateral securities, which can be a country or a pool of countries: Austria, Belgium, France, Germany, Italy, Netherlands, and Spain, or GC Pooling ECB basket (henceforth "GCP") and GC Pooling ECB Extended basket ("GCPx"). Second, a repo can be collateralized either more generally by a pre-specified basket of collateral securities (e.g., the same country issuing the collateral securities, or certain eligibility criteria as required for GCP vs. GCPx), or limited to only a specific security (i.e., an unique ISIN). The former is called "general collateral" (GC) and the latter is a "special". The motives to enter a GC or special differ, in that GC repos are generally

[4]Other platforms exist (e.g., SENAF/MEFF Repo, TulletPrebon), but their volumes for CCP-based repo transactions are much smaller. For instance, the total repo volume on MEFF Repo between 2011 and 2014 is less than EUR 4.5 trillion (MEFF, 2014).

meant to be cash- or funding-driven, while specials can be used for trading purposes.[5]

Every trading platform is important for some segments of the European repo market. For instance, BrokerTec operates a large panel of specials and GC of various countries including Austria, Belgium, France, Germany, Netherlands, and Spain. Eurex Repo exclusively provides the GCP, in which only very safe collateral securities are eligible, and the sibling basket GCPx, which extends the list of eligible assets to some riskier securities.[6] An important share of German GC is also traded on Eurex. MTS Repo is the predominant trading platform for Italian repos and runs a non-negligible share of specials.[7]

In total, our database includes 19'267'850 transactions and about EUR 539'981'171 million of (one-sided) traded volume. These data offer at least three improvements to the data used in previous tests of the EH. First, our sample is very large and economically relevant. It comprises various collateral securities providing cross-sectional heterogeneity in our analysis. Moreover, the sample period spans from January 2006 to December 2015, including pre-crises and crises periods. Second, risks in the repo market crucially depend on the market structure (Martin, Skeie, and von Thadden, 2014). In contrast to bilateral or triparty repos that proved to be fragile[8], all repos in our sample are traded anonymously via a central counterparty (CCP), which protects lenders from

[5]For example, a bank in need of cash will pledge its government securities as collateral to obtain a repo loan, for which it pays the GC repo rate. Since the motive is funding, the type of collateral security makes no difference as long as it belongs to the pre-specified basket. In contrast, a specific repo is often used for trading, in particular for short-selling, so that the delivery of a specific collateral security is required.

[6]The GCP ECB basket consists of the safest, very high quality collateral securities, including those securities admitted for collateralization of open market operations by the ECB that have been rated at least A-/A3. The GCP ECB Extended basket consists of a larger subset of the securities admitted at the ECB, i.e., potentially riskier, but still safe securities (Mancini, Ranaldo, and Wrampelmeyer, 2016).

[7]MTS Repo provides transaction data starting only from 2010.

[8]Prior empirical research provides evidence on the fragility of U.S. bilateral repos (Gorton and Metrick, 2012) and triparty repos (Krishnamurthy, Nagel, and Orlov, 2014; Copeland, Martin, and Walker, 2014) and Euro bilateral repos (Mancini, Ranaldo, and Wrampelmeyer, 2016). A resilient part of the U.S. triparty repo market is the GCF segment based on a CCP and an anonymous electronic order book (Agueci et al., 2014).

counterparty credit risk. Moreover, the collateral assets used in the European CCP-based repo market are likewise eligible for refinancing operations at the central bank, making the ECB the (repo) lender of last resort. Due to this risk mitigation, some of our repo data are effectively riskless interest rates and thus particularly suitable for testing the EH at the extreme short-end of the term structure. Third, we construct daily volume-weighted average interest rates, which provide a more representative measure of the actual funding costs in the market, as opposed to daily U.S. closing repo rates used in Longstaff (2000b) and Della Corte, Sarno, and Thornton (2008).

Table 1A summarizes the descriptive statistics of European repo rates. The data comprise overnight (ON) and "tomorrow-next" (TN) repos, both constituting overnight loans with interest rates agreed upon the same day, but differing with respect to their execution date. While ON transactions are spot trades, TN transactions are executed one business day later.[9] Thus, a TN repo is a forward contract, and TN repo rates represent forward rates for next day's ON transactions.

[Table 1A about here.]

Summary statistics for GC overnight repo rates are shown in Panel A of Table 1A. All rates are expressed in percentage points per annum. Mean and standard deviations of GC ON and TN rates are fairly close to one another, differing only by a few basis points (bps), and displaying cross-sectional differences. For example, the mean French GC ON rate of 0.9303 is less than 1 bp smaller than the mean French GC TN rate of 0.9381, while the spread between the mean GC ON and GC TN for Italian securities is approximately 3 bps. In general, spreads between TN and ON rates are positive across all assets, indicating a *risk premium* inherent in the forward rates. To give an

[9] Analogously, "spot-next" (SN) trades are overnight transactions initiated two business days later.

idea about this premium from an investor's perspective, we report the annualized volatility $\sigma(a)$ for an annual holding period and the spread μ, measured as the difference between the products of the unconditional means and $\sigma(a)$ for the full sample period and from 2010 to compare with Italy and Spain.[10] The variation of these spreads is economically meaningful: Albeit quantitatively small, the daily overnight spread varies between 1 and 2 basis points between 2006 and 2015, but becomes miniscule when only considering the period from 2010 onwards. The latter observation is particularly surprising given the European sovereign debt crisis amidst this period, with Italian and Spanish assets being among the collateral securities perceived as riskier.

Panel B of Table 1A reports the descriptive statistics of overnight special rates, for which the differences in means and standard deviations are much larger than for GC rates. More precisely, the average risk premium between the French ON and TN special rates is almost 11 bps, while for Spanish ON and TN specials the difference is more than 25 bps – and thus comparable to the bond term premiums found in long-maturity forward rates (e.g., Fama, 1984b; Fama and Bliss, 1987). Similarly, annualized risk premiums are as high as 16 basis points. Dissecting the time periods, the reduction of the spreads between 2010 and 2015 is even more pronounced for specials than for GC rates, revealing fairly large cross-sectional differences. Taking into account the different starting dates of GC repos in our sample, the observed differences in the risk premiums in Table 1A serve as a *prima facie* indicator that the test results of the EH may vary across time, assets, and repo

[10]Following Lo (2002) and Della Corte, Sarno, and Thornton (2008), we compute the annualized volatility as $\sigma(a) = \sqrt{Var(i_t(a))}$, where a refers to the average number of trading days, $i_t(a) = \sum_{k=0}^{a-1} i_{t-k}(d)$ is the sum of daily returns, and $i_t(d) = \frac{i_t}{360 \times 100}$ is the daily return for a given raw repo rate i_t. Annualized rates are computed as "Mean$\times\sigma(a)$" (i.e., Black's volatility), and μ denotes the spread between annualized TN and ON rates.

type.[11]

[Table 1B about here.]

Table 1B provides an overview of the traded volume across collateral securities. With a total volume of EUR 182 and 119 trillion (13 trillion), repos secured with German and Italian (Austrian and GCPx) securities are among the most (least) traded over the entire sample period. Table 1B also shows that specials constitute a market share of around 72% in our data, that are almost exclusively traded overnight (ON, TN, SN). European GC repos are also traded predominantly overnight, with only a small fraction (between 1.39% and 15.43%) traded on longer maturities.[12] Within GC, TN and ON represent the largest market shares, whereas SN and TN are predominant within specials.[13] Given a cumulative trading volume of around EUR 540 trillion, our forward-rate based tests of the EH using GC and special overnight repo rates thus cover the by far most traded contract-type in the repo market.

2. The Expectations Hypothesis

Under rational expectations, the forward rate on a n-period repo loan equals the expected future n-period spot rate plus a constant risk premium, which is expressed by the EH as

$$f_t^n = \mathbb{E}_t(i_{t+h}^n) + c^n, \tag{1}$$

[11] The number of observations can differ across assets due to matching TN and corresponding ON transactions. Specifically, the number of observations reported in Table 1A includes only those days, for which there is a coherent TN/ON pair. In total, our sample represents the vast majority of trades, which are distributed very evenly across time.

[12] So-called "term" repos include maturities from one week to 12 months. We analyze term repos for GCP in Section 6.2.

[13] While our analysis is based on ON/TN, we also perform tests using specific SN repos to address the large share of SN trades for specials. See the Internet Appendix for results.

where f_t^n denotes the forward rate, i_{t+h}^n the spot rate at time $t+h$, and c^n the risk premium. Intuitively, Equation (1) states that an investor in the repo market can borrow funds locking in today's forward rate, or wait and borrow at the future spot rate. As we look at overnight repos only, we drop subscript n and set $h=1$, such that the forward rate f_t refers to an overnight repo loan traded "tomorrow-next", and i_t is the overnight spot rate.[14] Under the EH, both repo rates should only differ by a constant risk premium, or even be the same under the pure form of the EH, i.e., $c=0$.

Thus, the spread-based test of the EH is written as

$$\Delta i_{t+1} = \alpha_1 + \beta_1 s_t + \varepsilon_{t+1}, \tag{2}$$

where ε_{t+1} is the rational expectations error term, and the null hypothesis in Equation (2) is $\alpha_1 = 0$, $\beta_1 = 1$, i.e., the forward premium $s_t = f_t - i_t$ is an unbiased predictor of the future spot spread, Δi_{t+1} (Froot, 1989).

3. Methodology

Since tests of Equation (2) in single line equations using ordinary least squares (OLS) have been shown to perform poorly in small samples producing biased coefficients (e.g., Schotman, 1997; Bekaert, Hodrick, and Marshall, 1997, 2001), we rely on a linear VAR testing framework developed by Bekaert and Hodrick (2001), in which we test a set of nonlinear restrictions derived from Equation (1) that would make the VAR model consistent with the EH (e.g., Sarno, Thornton, and Valente,

[14] Accordingly, the SN repo rate is the 2-day ahead forward rate, i.e., $h=2$.

2007; Della Corte, Sarno, and Thornton, 2008).[15] That is, we constrain the coefficients of the VAR model such that the forward premium is the sole predictor of the future spot spread, estimate this constrained VAR system by the generalized methods of moments (GMM), and test the validity of these highly nonlinear restrictions with the Lagrange Multiplier (LM) and Distance Metric (DM) tests.[16]

3.1. The VAR Framework

Reconsider Equation (2) with demeaned spot and forward spreads Δi_t and s_t, respectively, and form a bivariate VAR system according to

$$\Delta i_t = a(L)\Delta i_{t-1} + b(L)s_{t-1} + u_{1,t} \tag{3}$$

$$s_t = c(L)\Delta i_{t-1} + d(L)s_{t-1} + u_{2,t}, \tag{4}$$

with polynomials $a(L)$, $b(L)$, $c(L)$, and $d(L)$ of lag order p and error terms $u_{1,t}$ and $u_{2,t}$. This setting allows us to concentrate on testing the time-variation of the risk premium without discriminating between the standard and pure form of the EH by using demeaned data. Intuitively, Equation (3) determines the future spot spread, and Equation (4) generates the current forward premium. As thoroughly documented, the simultaneous estimation of the VAR equations improves efficiency by considering contemporaneous cross-correlations in the error terms (Mishkin, 1982; Pagan, 1984).

[15] For a discussion of the validity of the assumptions underlying a linear VAR model, in particular with respect to the literature on affine specifications (e.g., Duffie and Singleton, 1999; Dai and Singleton, 1999; Collin-Dufresne and Goldstein, 2002; Clarida et al., 2006), see Della Corte, Sarno, and Thornton (2008).

[16] Bekaert and Hodrick (2001) find that the LM test has the most desirable properties in the presence of nonlinear restrictions, whereas the Wald test as well as the DM test have by far the worst properties in small samples. Thus, while reporting LM and DM test statistics, we base our interpretations on the LM test results.

Following Bekaert and Hodrick (2001), the lag length p is chosen by the Schwartz Criterion (BIC).

To derive the set of nonlinear restrictions, we translate Equations (3) and (4) into a first-order VAR companion form,

$$\begin{bmatrix} \Delta i_t \\ s_t \\ \Delta i_{t-1} \\ s_{t-1} \\ \vdots \\ \Delta i_{t-p+1} \\ s_{t-p+1} \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & \dots & a_{p-1} & b_{p-1} & a_p & b_p \\ c_1 & d_1 & \dots & c_{p-1} & d_{p-1} & c_p & d_p \\ 1 & & & & & & \\ & 1 & & & & & \\ & & \ddots & & & & \\ & & & 1 & & & \\ & & & & 1 & & \end{bmatrix} \begin{bmatrix} \Delta i_{t-1} \\ s_{t-1} \\ \Delta i_{t-2} \\ s_{t-2} \\ \vdots \\ \Delta i_{t-p} \\ s_{t-p} \end{bmatrix} + \begin{bmatrix} u_{1,t} \\ u_{2,t} \\ \\ \\ \\ \\ \end{bmatrix}, \tag{5}$$

where blank elements are zeros. The companion VAR can be written in compact form as

$$Y_t = \Theta Y_{t-1} + \nu_t, \tag{6}$$

where Y_t is a 2p-elements vector of variables, Θ is a 2p square companion matrix, and $\nu_t = [u_t', 0, \dots, 0]'$ is an innovation vector orthogonal to the time t information set, with zero mean and covariance matrix Σ_ν. Based on the information in the VAR at time t, the one-period forecast of the spot spread and forward premium is given by

$$E_t[Y_{t+1}] = \Theta Y_t. \tag{7}$$

Consistent with the EH in Equation (1), the vector of restrictions can thus be expressed as

$$e_1'\Theta = e_2', \tag{8}$$

where $e_1 = (1, 0, \ldots, 0)'$ and $e_2 = (0, 1, 0, \ldots, 0)'$ are 2p-dimensional indicator vectors. The left-hand side of Equation (8) is the expected future spot spread from Equation (7), whereas the right-hand side yields the current forward premium. When estimated, the restrictions force the coefficients in the VAR to yield the theoretical relation postulated by the EH. In fact, the coefficient of the forward premium in Equation (3) compares directly with the OLS coefficient in Equation (2),

$$\beta_1 = \frac{e_1' \Theta \Psi e_2}{e_2' \Psi e_2}, \tag{9}$$

where Ψ is the unconditional variance of Y_t, computed from $vec(\Psi) = (I - \Theta \otimes \Theta')^{-1} vec(\Sigma_\nu)$. The numerator of the slope coefficient yields the covariance between the forward premium and spot spread, and the denominator represents the variance of the forward premium. Stacking all relevant parameters from the companion matrix into vector $\theta = (a_1, \ldots, a_p, \ldots, d_1, \ldots, d_p)'$ and rewriting Equation (8) as

$$a(\theta) = e_1' \Theta - e_2', \tag{10}$$

we can define the null hypothesis of rational expectations and a constant risk premium as

$$H_0 : a(\theta) = 0. \tag{11}$$

Next, we estimate the VAR model based on the GMM method proposed by Bekaert and Hodrick (2001) under the null hypothesis that the EH holds, and test the significance of the cross-equation restrictions using the LM and DM tests.

3.2. The VAR Tests

To estimate the parameters, θ, subject to the nonlinear restrictions, we first establish the GMM criterion function by defining the moment conditions. From the VAR system, let $y_t \equiv [\Delta i_t, s_t]$ be the vector of data available at time t, u_t be the vector of orthogonal errors, and x_{t-1} be the vector of instruments available at time $t-1$, constructed by stacking lagged values of y_t (and a constant term). Define $z_t \equiv (y_t', x_{t-1}')'$, and let $g(z_t, \theta) \equiv u_t \otimes x_{t-1}$ be the vector-valued function of data and parameters to form the set of orthogonality conditions given by $\mathbb{E}_t[g(z_t, \theta)] \equiv 0$. For a sample of size T and corresponding sample moment conditions $g_T(\theta) \equiv T^{-1}\sum_{t=1}^{T} g(z_t, \theta)$, the parameters θ are estimated by maximizing the Lagrangian

$$\mathcal{L}(\theta, \gamma) = -\frac{1}{2} g_T(\theta)' \Omega_T^{-1} g_T(\theta) - a_T(\theta)'\gamma, \tag{12}$$

where the first term of Equation (12) is the GMM criterion function with positive semidefinite weighting matrix Ω_T^{-1} (Hansen, 1982), and the second term is the constraint, given by the sample restrictions $a_T(\theta)$ and the vector of Lagrange multipliers, γ.[17] As the parameters are estimated, the Lagrange multipliers will be different from zero if the imposition of the restrictions has a significant impact on the value of the objective function. The null hypothesis, that the Lagrange multipliers are jointly zero, can thus be tested using the LM statistic

$$T\overline{\gamma}'(A_T B_T^{-1} A_T')\overline{\gamma} \to \chi^2_{(2p)}, \tag{13}$$

[17]The Lagrangian is maximized indirectly through a recursive mechanism due to the nonlinearity of the constraints, extending the estimator proposed by Newey and McFadden (1994) (Bekaert and Hodrick, 2001). See the appendix for technical details on the constrained GMM maximization problem.

which follows a chi-square distribution with 2p degrees of freedom resulting from the number of restrictions imposed by the EH. Finally, the DM statistic is

$$Tg_T(\overline{\theta})'\Omega_T^{-1}g_T(\overline{\theta}) \rightarrow \chi^2_{(2p)}, \tag{14}$$

where $\overline{\theta}$ denotes the constrained parameter estimates.

3.3. Small Sample Bias Correction

Tests of the EH are likely to suffer from finite sample bias estimation errors, as the sample distribution may differ significantly from the asymptotic distribution (e.g., Bekaert, Hodrick, and Marshall, 1997). In line with Longstaff (2000b) and Della Corte, Sarno, and Thornton (2008), we deal with small sample properties by simulating bias-corrected data sets of 70,000 observations via residual bootstrap from the original data series using homoskedastic and GARCH innovations, and use these simulated data sets for our analysis.[18]

4. Unconditional Tests of the EH

In our empirical tests of the EH, we analyze the risk premium in two dimensions: First, we divide our sample period into two sub-samples before and after the major change of the monetary regime introduced by the ECB on October 15, 2008.[19] The new monetary regime put in force unprecedented unconventional monetary policies (UMP), including the substitution of a variable-rate (VR) tender format with a fixed-rate full allotment (FA) policy for all refinancing operations and matu-

[18]See the appendix for technical details on the data simulation process.
[19]Thereafter, period (1) and (2) refer to the time before and after mid-October 2008, respectively.

rities.[20] Second, we analyze the collateral and security-specific risks affecting the cross-section of European repo securities and types.

The FA policy is arguably the most significant non-standard measure implemented by the ECB to reduce funding risk faced by the banking system during the crisis that began in mid-2007 (González-Páramo, 2011). In the VR regime, costs and volume at which central bank liquidity is available are *ex ante* uncertain at individual and aggregate levels. Specifically, a bank does not know whether at all it will receive the needed liquidity, and if it does, at which interest rate and to what extent other banks' liquidity needs affect its own one. As a result, in times of uncertainty and elevated risk, banks severely overbid, pushing up the MRO rate (i.e., the interest rate of the ECB's main refinancing operations) and thus all money market rates (ECB, 2000; Cassola, Hortaçsu, and Kastl, 2013).

In contrast, under the FA regime, all information including the MRO rate is pre-established and banks know *ex ante* that their bids will be fully satisfied against eligible collateral, thereby eliminating idiosyncratic and aggregate uncertainty. As a result, the FA mechanism automatically stabilizes money markets and reduces (money market) risk premiums as ECB liquidity supply dynamically matches banks' liquidity demand. Accordingly, our first testing hypothesis relates to the underlying monetary regime, claiming that after (before) the ECB's inception of UMP on October 15, 2008, the EH should hold more (less).

In the cross-section, sovereign and idiosyncratic risks are key determinants of collateral risk. Regarding the former, our sample includes repos secured by several high-grade sovereigns with at

[20] Other measures introduced in October 2008 were the USD swap lines, Long-Term Refinancing Operations (LTRO), and an expansion of the list of assets eligible as collateral in Eurosystem credit operations.

least AA rating[21], namely Germany, Netherlands, Austria, France, and Belgium, and by riskier government bonds, i.e., Spain and Italy, whose ratings have substantially deteriorated during the European sovereign debt crisis.[22] Hence, our second testing hypothesis covers the effect of collateral risk on the risk premium, stating that the EH should hold more (less) for repos collateralized by safe (riskier) GC securities. Regarding idiosyncratic risks, GC repos benefit from some diversification effects and are mostly affected by the supply of and demand for cash, whereas special repo rates are also affected by security-driven issues creating idiosyncratic security risk. Hence, our third hypothesis is that the EH should hold more (less) for GC (special) repos.

4.1. VAR Dynamics

We test the EH before and after the inception of the UMP measures, taking the introduction of the FA regime on October 15, 2008, as the cutoff date.[23] To illustrate the VAR dynamics, we report the VAR-GARCH coefficients of the UMP period estimations for German and Italian GC repo rates in Table 2.[24] Panel A presents the unconstrained VAR parameter estimates including their bias-corrected counterparts, $\tilde{\theta}$, and Panel B shows the constrained coefficients, $\overline{\theta}$, satisfying the EH.

[Table 2 about here.]

[21] Throughout this paper, we use credit ratings from Standard & Poor's.

[22] Specifically, Spain's credit rating decreased from AAA to BBB, and Italy's rating from AA- to BBB-.

[23] We also try other definitions of the pre-UMP period. For instance, the change in the ECB tender procedure was announced on October 8, 2008. Taking the announcement time as our cutoff date leaves our results unchanged. The same holds when removing the days on which the ECB changed the official target rates.

[24] VAR dynamics for all other repos and time periods are available upon request.

In the unconstrained VAR, the slope coefficients of the lagged forward premium, s_{t-1}, for GC Germany and GC Italy are 1.0657 and 0.8429, respectively, and thus somewhat close to one. This is in line with former studies of U.S. data finding β_1 to be between zero and one in the very short-run (Froot, 1989). In contrast, the constrained coefficients in Panel B yield the relation imposed by the EH, as can immediately be seen from the lagged coefficients, which are all zero except for the coefficient of the forward premium at time $t-1$. The distance to the constrained estimate appears smaller for the German forward premium, and the dispersion of the slope coefficient is generally larger for Italy, while the other coefficients measuring the response of the spot spread are comparable in size.[25]. In particular, the standard error of the constrained slope coefficient is much larger for Italy (1.2767) than the corresponding value for Germany (0.1630). With regard to our first two hypotheses, the VAR dynamics indicate potentially different results with respect to the formal EH tests, which we present in the next section.

4.2. Test Results

Our main results are shown in Table 3, where we report the p-values of the LM and DM tests under the null hypothesis that the EH holds.[26] Panel A reports the test results for GC repos, Panel B for specific repos, and periods (1) and (2) denote the time before and after the ECB's inception of UMP, respectively.

[Table 3 about here.]

[25]Standard errors in the constrained estimations are generally larger than in the unconstrained estimations (see Della Corte, Sarno, and Thornton, 2008).
[26]We also report Hansen's (1982) J-Test for overidentifying moment conditions, validating the GMM approach as corresponding p-values are well above critical values.

The results fully support the three hypotheses stated above. First, before the regime change the EH is rejected no matter which collateral. This result is consistent with the presence of funding risk in a liquidity-deficit regime and more in general, with the common evidence from the previous literature against the EH. By contrast, the EH cannot be rejected in period (2) for the majority of our repo panel, suggesting that the UMP measures introduced in October 2008 were effective in reducing funding risk.[27] Second, the EH finds stronger support for safer GC repos such as those secured by German, Dutch, French, and Belgian securities, and weaker support for GC repos collateralized by riskier sovereigns such as Spanish and Italian collateral. The comparison between the GCP and GCPx baskets provides a *ceteris paribus* analysis, showing that when riskier securities are included into the pool of safe securities as for the GCPx basket, the p-value is "biased" downwards and the EH is close to being rejected. Third, the comparison between Panel A and Panel B of Table 3 shows that the EH holds more for GC and less for special repos, providing evidence for the presence of idiosyncratic security risks.

The results of our unconditional analysis can also be related to the opportunity costs of holding money, represented by the central bank's deposit rate (e.g., Nagel, 2016; Lagos and Zhang, 2016): From January 2006 to October 2008, the ECB's deposit rate increased from 1.25% to 3.25%, decreased sharply therafter to 0.25% within only a few months, and was even set negative in 2014, residing at -0.3% towards the end of 2015. Effectively, the rapid reduction in policy rates at the end of 2008 can be seen as a *structural break*, i.e., opportunity costs were high before and low after. From a lender's perspective, when opportunity costs of holding money are high and

[27] We also test all repos from 2010 onwards to address biases arising from different starting dates. Results are quantitatively alike.

speculative investments risky, lenders demand a higher compensation for holding and lending cash. In contrast, when outside opportunities yield low returns, liquidity provision in the repo market also comes at a lower premium. The transmission of monetary policy to the repo market thus materializes in lower money market risk premiums, lending support to the validity of the EH.

Overall, our findings corroborate the EH for seemingly riskless, very short-term repos in line with Longstaff (2000b), and point to its rejection (Della Corte, Sarno, and Thornton, 2008) in presence of time-varying risk premiums associated with funding risk, and collateral risk related to sovereign (Mancini, Ranaldo, and Wrampelmeyer, 2016; Boissel et al., 2016) and idiosyncratic risk (Jordan and Jordan, 1997; Buraschi and Menini, 2002). From an economic point of view, the EH cannot be rejected for the largest share of European repos including German and French collateral, and for an extensive period from October 2008 to the end of 2015. In the next section, we analyze the time variation more deliberately by conditioning the EH tests on time-varying risk factors.

5. Conditional Tests of the EH

In this section, we highlight the dependence of the risk premium on the time variation of risk by performing two conditional analyses: First, we condition our tests on various risk variables, and second, we explore day-of-the week patterns in the ECB's main refinancing operations.

5.1. Risk Factors

We condition our tests of the EH on some well-accepted risk variables. As our main variable, we use the 3-month Euribor-Eonia spread, i.e., the difference between the unsecured Euribor rate and overnight Eonia swap rate with 3-month maturity. This spread is a common measure of money market risk premiums (e.g., Taylor and Williams, 2009). Our conditioning approach works as follows: First, we order our sample periods (1) and (2) according to the risk factor, i.e., from the highest to the lowest value of the Euribor-Eonia spread.[28] Then, we determine the samples' quartiles (i.e., the 25%-quantiles), which now serve as the time series for our conditional tests. Specifically, we bias-correct each quartile as described in Section 3.3 and test the EH for each sample, denoting the quartile with the highest values of the risk variable *high-risk*, and the lowest quartile *low-risk*. Thus, if time variation of risk matters for the failure of the EH, the test results should reveal that the EH is violated more in the high-risk than in the low-risk quartile. Table 4 reports the p-values of the EH tests conditional on the 3-month Euribor-Eonia spread.[29]

[Table 4 about here.]

Overall, p-values for GC (Panel A) and specials rates (Panel B) are lowest when risk is highest, and vice versa. Moreover, p-values are consistent across quartiles, indicating that the risk premium varies with general (money market) risk as represented by the 3-month Euribor-Eonia spread.[30] While the EH seems to have more support in the low-risk quartile in period (1), the EH cannot be rejected for the safe GC repos in any of the quartiles in period (2). From sorting the data, we find that the high-risk quartile in period (1) consistently captures the time of the U.S. subprime crisis, while the low-risk period refers to pre-crisis and calmer phases in 2006 and early 2007. In period (2), the high-risk quartile fully captures the core time of the European sovereign debt crisis around 2011-2012, whereas the low-risk quartile contains all data past 2013. In fact, the results of period

[28] All panels in period (2) starting in 2008 are standardized to compare with panels starting in 2010.

[29] Reported values are all for homoskedastic innovations as Engle's ARCH test for (no) conditional heteroskedasticity cannot be rejected.

[30] See the Internet Appendix for test results of all four quartiles.

(2) in Table 4 show that the EH cannot be rejected for any of the securities and collateral types when risk was at its lowest level with the slight exception of Italian specific repos. These findings suggest that the unprecedented UMP measures including asset purchases of distressed sovereign bonds in the secondary market and the ECB's intention to "do whatever it takes" to resolve the crisis (announced in late July 2012) were (at least partially) effective in reducing funding and collateral risk.

In the next section, we look more closely into the practice of ECB refinancing operations and their effect on the EH test results.

5.2. MRO Weekday Effects

Another way to validate the time variation of the risk premium is to condition the analysis on the calendar effects created by monetary policy itself. As explained in Garcia-de-Andoain et al. (2016), the *modus operandi* of the ECB's main refinancing operations provides a quasi-experiment to analyze deterministic patterns of liquidity provision on interest rates. MROs are conducted every Wednesday, and banks apply to the ECB on Tuesdays posting their liquidity needs. This produces day-of-the-week effects on banks' reserve availabilities. Specifically, banks are more certain about their ability to fulfill their liquidity needs on Wednesdays and Thursdays, whereas funding risk is more of a concern on Mondays and Tuesdays when reserves may be running short. To test these patterns, we construct the respective time series for GC rates matching Monday (TN) and Tuesday (ON), Tuesday (TN) and Wednesday (ON), Wednesday (TN) and Thursday (ON), and Thursday (TN) and Friday (ON). Thus, our testing hypothesis is that the EH should hold more (less) when forming expectations on Wednesdays and Thursdays (Mondays and Tuesdays) for the spot GC repo rates on Thursdays and Fridays (Tuesdays and Wednesdays), respectively. Test results are reported in Table 5.

[Table 5 about here.]

Overall, the p-values are in line with our previous results, showing that the EH is predominantly rejected in period (1), and generally not rejected in period (2). Under the VR liquidity-deficit regime, the uncertainty regarding banks' liquidity needs leads to a rejection of the EH from Monday to Wednesday (Panels A and B), whereas expectations formed on Thursdays seem to better predict GC spot rates on Fridays (Panel D). Among day pairs, the reported p-values suggest that the difference is highest between Mondays and Thursdays, emphasizing the importance of funding risk for the failure of the EH.

Table 5 also shows that the MRO effects disappeared after mid-October 2008. The p-values in period (2) indicate that the EH cannot be rejected for any of the day pairs. Moreover, the p-values of the different day combinations in period (2) differ much less than those in period (1). These results are fully consistent with the aimed effects of the UMP introduced in October 2008, including the central bank's elastic supply of reserves via the FA mechanism and the longer-term refinancing operations (LTRO) that override the MRO's weekly effects.

In sum, both unconditional and conditional analyses suggest that the failure of the EH is related to the time variation of the risk premium. Although it is impossible to unambiguously disentangle the various sources of risk, our findings provide statistical support that the validity of the EH moves inversely with funding and collateral risk, and that central bank policies can counteract them, leading to a better alignment of expectations and interest rates. Well-collateralized repos appear informationally insensitive, whereas repos affected by funding and collateral risk might be informationally sensitive (Holmstrom, 2015).

6. Additional Results

We substantiate the previous findings performing various robustness checks and additional analyses. First, we replicate our conditional analysis using other risk variables in addition to the 3-month Euribor-Eonia spread. Second, we perform a simple extension of the VAR framework of Bekaert and Hodrick (2001) adding the risk variable used in the conditional approach as a third endogenous variable to the VAR system. Third, we conduct additional tests of the EH considering other maturities up to one year. And last, we replicate our unconditional EH tests using end-of-day rates rather than volume-weighted averages. This is an important exercise given that prior research on the EH has consistently used closing rates or low-frequency data.

6.1. Further Conditional Tests

We conduct three layers of robustness checks for our conditional analyses. First, we repeat our conditional tests using three additional risk variables. The first one is the 3-month Libor-OIS spread, which is the USD counterpart of the 3-month Euribor-Eonia spread. Both spreads capture market-wide risk by measuring funding strains in the interbank market. Due to the collateralization of repo loans with sovereign bonds, we also construct a sovereign risk variable by computing the spread between 10-year government bond yields of "core" European countries (i.e., Austria, Belgium, France, Germany, and Netherlands) and the Euro-zone "periphery" (i.e., Greece, Ireland, Italy, Portgual, and Spain, "GIIPS"). This spread widened substantially during the European sovereign debt crisis and narrowed back down towards the end of our sample. And third, we use the composite indicator of systemic stress (CISS), which is an aggregate risk index including several market-specific risk proxies (Holló, Kremer, and Lo Duca, 2012) that captures funding strains in the European repo market (Mancini, Ranaldo, and Wrampelmeyer, 2016).[31] In particular, the CISS combines elements of the individual risk variables we use, and thus provides a comprehensive financial risk variable for our conditional analysis.

Second, we extend the bivariate VAR model shown in Section 2 to a 3-variable VAR including the risk variable. That is, we include risk as an endogenous regressor into the VAR framework instead of conditioning our sample beforehand, and test the EH under the additional restriction that risk cannot predict the future spot spread (and thus the current forward premium remains the sole predictor). Qualitatively different results from our unconditional analysis in Table 3 would suggest that the coefficients in the VAR suffered from omitted variable bias, and the EH was actually rejected. Given our conditional results in Table 4, however, we nonetheless expect similar results. Table 6 presents the results of both robustness analyses for GC repos using the CISS as the risk variable.[32]

[Table 6 about here.]

As shown in Panel A of Table 6, conditioning the EH tests on the CISS (as well as on the 3-month Libor-OIS and 10-year government bond spreads) delivers highly similar results to the 3-month Euribor-Eonia spread for both periods (1) and (2). Moreover, the same finding holds for specific

[31] Specifically, the CISS contains 15 financial stress measures grouped into 5 sub-indices representing the bond, equity, money, foreign exchange (FX), and derivatives markets.

[32] In the Internet Appendix, we provide all test results of the conditional analyses for GC and special repos including all four risk variables and quartiles. Results for the 3-month Libor-OIS and 10-year government bonds spreads are highly consistent with those of the 3-month Euribor-Eonia spread and the CISS.

repo rates, and thus our results from the conditional analyses highlight that the failure of the EH is closely related to the time variation of risk. This finding is further supported by our endogenizing approach in Panel B of Table 6. The corresponding p-values for the cross-section of GC repos are quantitatively lower, but qualitatively the same as the results of the unconditional analysis in Table 3. In fact, the p-values of the GARCH-DGP are fairly close to the p-values of the first quartiles in the conditional analyses, suggesting that even after controlling for risk, the EH remains valid for the safe GC repos in the UMP period at the very short-end of the term structure.

Finally, we augment our analysis of calendar effects in Section 5.2 by addressing two further deterministic effects on GC repo rates, arising from (a) the ECB's reserve maintenance periods and (b) banks' quarterly reporting of their leverage ratio.[33] As explained in Beaupain and Durré (2012), funding risk increases towards the end of each maintenance period as banks are required to balance their liquidity needs. With maintenance periods typically lasting around one month, we construct two samples for each subperiod: One that contains only the last week of each maintenance period, starting from the last MRO to the end of the maintenance period, which is usually a Tuesday. The second sample includes all remaining days. In line with our results of the day-of-the-week effects in Table 5, we find that the EH is thoroughly rejected in the last week of the maintenance periods in period (1), emphasizing the role of funding risk for the violation of the EH. Furthermore, the EH cannot be rejected throughout period (2), thus supporting the stabilizing effect of UMP measures for the validity of the EH.[34]

[33] Results are provided in the Internet Appendix.

[34] Additionally, we also test the hypothesis that the daily patterns should be more prominent in times of risk by performing a *double conditioning* analysis, in which we further condition the weekday combinations on risk variables as explained in Section 5.1. See the Internet Appendix for results. Conditional on the 3-month Euribor-Eonia spread, p-values show that prior to the FA regime, the EH is almost generally rejected, while in period (2), the EH is more likely to hold even when risk is high.

As European regulatory standards oblige banks to report their end-of-quarter leverage ratios (as opposed to within-quarter averages in the U.S.) and repos generally induce leverage, repo trading activity decreases towards quarter end exposing banks to funding risk (Munyan, 2015). Hence, as with maintenance periods, we construct one subsample containing only the last week of each quarter and another subsample with all remaining days. In line with our previous results, we find that the EH tends to hold less at the end of each quarter, i.e., when repo trading volume is lower and funding risk higher. These results hold true before and after the UMP inception.

6.2. Term-Structure Tests

We now test the EH for the term structure of the GCP index using daily ON, 1-week (1W), 2-week (2W), 1-month (1M), 3-month (3M), 6-month (6M), and 12-month (12M) repo rates. We focus on the GC ECB basket (GCP) because it covers the longest and most complete data set, with maturities ranging from overnight to one-year tenor. The limited data availability for longer than overnight maturities naturally defines the sample period from October 2013 to December 2015, which coincides with the low-risk quartile of period (2) in the conditional analysis. With all the UMP measures in place and given our previous results, the EH for longer tenors up to one year is more likely to hold in this specific period than elsewhere.

For the term-structure tests, we need to adjust the econometric procedure. As shown in Della Corte, Sarno, and Thornton (2008), the EH for the term structure states that a long-term interest rate, i_t^n, should be equal to the average of the current and expected future short-term rates, i_t^m, plus a constant term premium. Hence, the theoretical relation imposed by the EH in Equation

(1) is restated as

$$i_t^n = \frac{1}{k}\sum_{q=0}^{k-1} \mathbb{E}_t \left[i_{t+mq}^m\right] + c^{n,m}. \tag{15}$$

Correspondingly, the variables in the bivariate VAR system in Equations (3) and (4) are now the short- and long-term repo rates, respectively. For instance, i_t^{ON} refers to the ON repo rate and the first line in the VAR, and i_t^{1M} is the one-month rate replacing the forward premium in Equation (4). Given these adjustments, the EH tests follow the same econometric procedure described in Section 3, and the corresponding restrictions implied by Equation (15) are[35]

$$e_2' = e_1' k^{-1}(I - \Omega^m)^{-1}(I - \Omega^n). \tag{16}$$

Table 7 presents the results for each pairwise combination of GCP repos.[36]

[Table 7 about here.]

The first line of Table 7 reports all combinations of term repos and overnight rate, including the forward rate i_t^{TN}/i_t^{ON} for completeness. The p-values indicate that the EH cannot be rejected up until two weeks, and is rejected for all longer horizons. The second line of Table 7 reports the remaining combinations, from one-week/two-week to the two longest tenors. Despite the limited number of observations, the results of our term structure tests overall suggest that the EH has more support at the short-end and towards the long-end of the yield curve. In contrast, intermediate-term repos have the lowest p-values. Yet, these findings partially differ from Della Corte, Sarno, and Thornton (2008), who generally reject the EH for all maturities, and strengthen the idea that

[35] See the appendix for technical details.

[36] As for the conditional tests, the null hypothesis of no heterskedasticity cannot be rejected for the period analyzed.

the EH is more supported in a low-risk market environment.

6.3. Closing Rates

Since former studies of the EH have used closing rates and almost always reject the EH, we repeat the unconditional EH tests in Table 3 using end-of-day repo rates. This additional analysis should reveal if the noise in lower-frequency data snapped at the closing time can potentially bias the EH. Table 8 shows the corresponding test results.

[Table 8 about here.]

Most strikingly, the EH is rejected for almost all repos and time periods using end-of-day rates. In particular, p-values are much lower for the safe repos in period (2) than their counterparts in Table 3, especially for GC repos. Our findings are consistent with the simple idea that (volume-weighted) prices capture better average market prices and, as in this setting, expectations. In contrast, end-of-day or point-in-time rates can deliver nosier values, especially if affected by intraday biases, which appear for money market rates (e.g., Baglioni and Monticini, 2008) and increase in crises periods (e.g., Jurgilas and Žikeš, 2014).

7. Conclusion

Despite its long history and central importance in economics and finance, the EH has found very little empirical support so far. In this paper, we explain why, and under which conditions the EH for very short-term rates holds or is violated. To do this, we analyze a unique and comprehensive data set of European repurchase agreements (repos) that are ideal for highlighting the role of time-varying risk. In fact, some important characteristics such as collateralization, anonymous CCP-based trading, and a close connection with central bank liquidity essentially narrow down the sources of risk to funding and collateral risk.

We perform extensive analyses in various dimensions, including unconditional, conditional, time-series as well as cross-sectional tests. We find compelling evidence that the time-varying risk premium is responsible for the rejection of the EH. This was generally the case before the ECB's unconventional monetary policies were introduced in October 2008, which highlights the impact of funding risk on market expectations. The prominent role of the time-varying risk premium clearly emerges in two other conditional analyses: First, when common risk variables such as the Euribor-Eonia or Libor-OIS spreads are high; second, when banks systematically need more reserves, i.e., before drawing from the weekly main refinancing operations (MRO) in the Eurosystem. In contrast, the EH cannot be rejected in low-risk and liquidity-rich environments.

Another original contribution in this paper is the cross-sectional analysis, in which we compare repo contracts with different collateral securities. Our results clearly show that the violation of the EH is likely to arise for repos bearing collateral risk, that is, collateral securities more affected by sovereign risk (e.g., Italian and Spanish government bonds) or idiosyncratic risk (i.e., "specials").

Several policy implications can be drawn from this study. Overall, we show that it is possible to make a neater distinction between expectations and risk premiums, at least for very short-term maturities. This should improve the analysis and decision making of important aspects of the social welfare system that needs accurate interpretation of agents' expectations and risk premiums, including investment, regulatory, and monetary policies.

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Appendix: Econometric Procedures

GMM Iterative Procedure

The constrained GMM maximization problem is solved via an iterative procedure. Optimizing the Lagrangian in Equation (12), the first-order condition is given by

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -G_T' \Omega_T^{-1} \sqrt{T} g_T(\overline{\theta}) - A_T' \sqrt{T} \overline{\gamma} \\ -\sqrt{T} a_T(\overline{\theta}) \end{bmatrix}, \tag{A.1}$$

where $A_T \equiv \nabla_\theta \alpha_T(\theta)$ and $G_T \equiv \nabla_\theta g_T(\theta)$. While the first-order conditions are nonlinear in the parameters, Bekaert and Hodrick (2001) derive an approximate asymptotic solution using the law of large numbers and a Taylor's series expansion of $g_T(\theta)$ and $a_T(\theta)$ around the true parameter value θ_0. Note that

$$\sqrt{T} g_T(\theta_0) \to \mathbb{N}(0, \Omega), \tag{A.2}$$

$$\sqrt{T} g_T(\overline{\theta}) \approx \sqrt{T} g_T(\theta_0) + G_T \sqrt{T} (\overline{\theta} - \theta_0), \tag{A.3}$$

and

$$\sqrt{T} a_T(\overline{\theta}) \approx \sqrt{T} a_T(\theta_0) + A_T \sqrt{T} (\overline{\theta} - \theta_0). \tag{A.4}$$

Under the null hypothesis, $a_T = 0$, and substituting Equations (A.3) and (A.4) into Equation (A.1), we have

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -G_T' \Omega_T^{-1} \sqrt{T} g_T(\theta_0) \\ 0 \end{bmatrix} - \begin{bmatrix} B_T & A_T' \\ A_T & 0 \end{bmatrix} \begin{bmatrix} \sqrt{T} (\overline{\theta} - \theta_0) \\ \sqrt{T} \overline{\gamma} \end{bmatrix}. \tag{A.5}$$

The formula for a partitioned inverse implies that

$$\begin{bmatrix} B_T & A_T' \\ A_T & 0 \end{bmatrix}^{-1} = \begin{bmatrix} B_T^{-1/2} M_T B_T^{-1/2} & B_T^{-1} A_T' (A_T B_T^{-1} A_T')^{-1} \\ (A_T B_T^{-1} A_T')^{-1} A_T B_T^{-1} & -(A_T B_T^{-1} A_T')^{-1} \end{bmatrix}, \tag{A.6}$$

where $M_T \equiv I - B_T^{-1/2} A_T' (A_T B_T^{-1} A_T')^{-1} A_T B_T^{-1/2}$ is an idempotent matrix, and $B_T \equiv G_T' \Omega_T^{-1} G_T$. Thus, the asymptotic distribution of the constrained estimator and Lagrange multiplier becomes $\sqrt{T}(\overline{\theta} - \theta_0) \to \mathbb{N}(0, B_T^{-1/2} M_T B_T^{-1/2})$ and $\sqrt{T}(\overline{\gamma}) \to \mathbb{N}(0, (A_T B_T^{-1} A_T')^{-1})$, respectively. Since direct maximization of the Lagrangian in Equation (A.1) is considered as computationally difficult (e.g., Melino, 2001), Bekaert and Hodrick (2001) propose an iterative scheme, extending the approach in Newey and McFadden (1994). Starting with an initial unconstrained estimate $\tilde{\theta}$, we derive $g_T(\overline{\theta}) = g_T(\tilde{\theta}) + G_T(\overline{\theta} - \tilde{\theta})$ and $a_T(\overline{\theta}) = a_T(\tilde{\theta}) + A_T(\overline{\theta} - \tilde{\theta})$, substitute into the first-order condition, and solve

$$\overline{\theta} \approx \tilde{\theta} - B_T^{-1/2} M_T B_T^{-1/2} G_T' \Omega_T^{-1} g_T(\tilde{\theta}) - B_T^{-1} A_T' (A_T B_T^{-1} A_T')^{-1} a_T(\tilde{\theta}), \tag{A.7}$$

$$\overline{\gamma} \approx -(A_T B_T^{-1} A_T')^{-1} A_T B_T^{-1} G_T' \Omega_T^{-1} g_T(\tilde{\theta}) + (A_T B_T^{-1} A_T')^{-1} a_T(\tilde{\theta}). \tag{A.8}$$

To obtain the constrained parameters $\overline{\theta}$, we iterate on Equations (A.7) and (A.8), substituting the first constrained estimate for the initial consistent unconstrained estimate to derive a second constrained estimate and so forth. The iterative process stops when the constrained estimate satisfies the constraints, that is, when $a_T(\overline{\theta}) = 0$.

Small Sample Bias Correction

Let $Z_t = [i_t, s_t]'$ be the set of our initial data, where $s_t = f_t - i_t$ is the spread between the overnight forward rate f_t ("tomorrow-next") and the overnight spot rate i_t, and assume VAR(p) dynamics analogous to Equations (3) and (4) in the text.

For the first data generating process (DGP), we estimate an unconstrained VAR and use the parameter estimates to generate 100,000 artificial data sets containing T observations, using an i.i.d. bootstrap of the residuals. We reestimate the VAR for each replication, compute the average of the parameter estimates of all artificial data sets, and determine bias as the difference between the parameter estimates of the initial data and the average of the estimates of the artificial data sets. Next, we correct the initial parameter estimates by adding the bias, simulate 70,000 observations (plus 1,000 starting values that are discarded to avoid any dependence on the initial values), and add each simulated i_t to each simulated spread s_t. As a result, we obtain a series of 70,000 spot and forward overnight repo rates, which we use for the iterative procedure.

The second DGP is constructed by using GARCH innovations, η_t, to capture the effects of temporal heteroskedasticity. While Bekaert and Hodrick (2001) as well as Longstaff (2000b) and Della Corte, Sarno, and Thornton (2008) use an augmented Factor-GARCH(1,1) model, with the short- and long-term rates as the factors, we employ a simple GARCH(1,1) structure, modelling volatility as $h_t = \omega + \beta h_{t-1} + \alpha \eta_{t-1}^2$, as both our repo rates are (short-term) overnight rates. Then, analogous to the i.i.d. bootstrap, we construct 100,000 artificial data sets with T observations, reestimate each replication and bias-correct the unconstrained parameter estimates. Finally, we estimate the GARCH parameters via quasi-maximum likelihood, and simulate a second bias-corrected data set of 70,000 (plus 1,000 starting values that are discarded) observations of i_t and f_t as described above.

Term Structure: Restrictions Implied by the EH

The set of restrictions implied by the EH in Equation (15) is derived as shown in Della Corte, Sarno, and Thornton (2008). Let the indicator vectors be $e_1 = (1, 0, \ldots, 0)'$ and $e_2 = (0, 1, \ldots, 0)'$, and use them to select the long-term and expected future short-term rate from the companion VAR in Equation (5) as $i_t^n = e_2' Y_t$ and $\mathbb{E}_t[i_{t+q}^m] = e_1' \Omega^q Y_t$, respectively. Then, Equation (15) can be rewritten as

$$e_2' Y_t = e_1' k^{-1} [I + \Omega^m + \Omega^{2m} + \ldots + \Omega^{m(k-1)}] Y_t, \tag{A.9}$$

which gives us the set of nonlinear restrictions if the eigenvalues λ^q of Ω are such that $|\lambda^q| < 1$, so that Equation (A.9) converges to the compact form

$$e_2' = e_1' k^{-1} (I - \Omega^m)^{-1} (I - \Omega^n). \tag{A.10}$$

Intuitively, the left-hand side of Equation (A.10) is the current long-term rate, and the right-hand side is the expected future short-term rate implied by the VAR system. Analogous to the forward test of the EH, this set of restrictions is subject to the GMM maximization and solved by the iterative procedure described above.

Table 1A

Descriptive Statistics for Daily European Overnight Repo Rates

This table summarizes the descriptive statistics for daily volume-weighted average repo rates of European government collateral securities from 2006 to 2015. Panel A presents repo rates for general collateral (GC) and Panel B for specific (SC) securities. ON rates are spot trades and TN rates are forward trades executed next day. Annualized volatility is given by $\sigma(a) = \sqrt{Var(i_t(a))}$, where a refers to the average number of trading days, $i_t(a) = \sum_{k=0}^{a-1} i_{t-k}(d)$ is the sum of daily returns, and $i_t(d) = \frac{i_t}{360\times100}$ is the daily return for a given raw repo rate i_t. Annualized rates are computed as "Mean$\times\sigma(a)$", and μ denotes the spread between annualized TN and ON rates. All statistics are measured in percentage points per annum.

Panel A: GC Repo Rates

	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
GC ON Repo Rates									
Mean	1.0484	0.9303	0.8906	0.2911	0.3326	0.1726	0.2724	1.1944	0.2813
Std Dev	1.5164	1.4195	1.4064	0.5778	0.6132	0.3481	0.3926	1.5431	0.4298
Min	−2.0000	−0.5170	−0.7500	−0.8000	−0.3627	−0.3067	−0.2919	−0.2980	−0.2920
Max	4.4015	4.6762	4.4567	3.3148	3.3707	1.9833	2.1451	5.0857	2.9020
GC TN Repo Rates									
Mean	1.0568	0.9381	0.9076	0.3040	0.3476	0.1905	0.3026	1.2149	0.3016
Std Dev	1.5214	1.4220	1.4135	0.5787	0.6131	0.3451	0.4100	1.5425	0.4366
Min	−1.0644	−0.3980	−0.7056	−0.8000	−0.3800	−0.2733	−0.2730	−0.2990	−0.3040
Max	4.4537	4.6642	4.5000	3.3563	3.3500	1.8500	2.0293	4.9550	3.0500
$\sigma_{ON}(a)$	0.8476	0.8029	0.7043	0.3837	0.1971	0.0835	0.1454	1.0113	0.2019
$\sigma_{TN}(a)$	0.8513	0.8046	0.7081	0.3846	0.1965	0.0813	0.1530	1.0111	0.2084
μ (bps)	1.10	0.80	1.54	0.52	0.28	0.11	0.67	2.05	0.60
$\mu_{'10-'15}$ (bps)	0.12	0.15	0.30	0.27	0.17	0.11	0.67	0.55	0.60
Obs	2,130	2,221	2,070	1,473	1,036	1,052	1,537	2,464	1,617
Start	2006	2006	2006	2008	2008	2010	2010	2006	2008

Table 1A

Descriptive Statistics for Daily European Overnight Repo Rates – Continued

Panel B: Specific Repo Rates

	DE	FR	BE	NL	ES	IT
SC ON Repo Rates						
Mean	0.8546	1.0215	0.8505	0.5213	0.2515	0.2710
Std Dev	1.4752	1.5967	1.4827	1.2536	1.2228	1.0106
Min	−1.7967	−2.3569	−3.4942	−2.0000	−5.6324	−2.4589
Max	4.2991	4.5325	4.3500	4.4005	4.3000	4.1000
SC TN Repo Rates						
Mean	0.9770	1.1306	0.9695	0.6428	0.5088	0.4498
Std Dev	1.5159	1.5821	1.5118	1.2734	1.1460	0.9915
Min	−1.5040	−2.4831	−1.3000	−1.3064	−1.2732	−0.6955
Max	4.3231	4.5631	4.3474	4.3884	4.2951	4.1000
$\sigma_{ON}(a)$	0.9348	1.0767	0.8876	0.5551	0.5416	0.3198
$\sigma_{TN}(a)$	0.9816	1.0700	0.9123	0.5736	0.5255	0.3171
μ (bps)	16.01	11.34	12.95	7.93	13.11	5.60
$\mu_{'10-'15}$ (bps)	1.28	2.01	1.51	1.37	6.03	3.11
Obs	2,442	2,556	2,300	1,874	2,017	1,802
Start	2006	2006	2006	2006	2006	2006

Table 1B

Descriptive Statistics for Daily European Repo Trading Volumes

This table provides descriptive statistics of daily trading activity in European government general collateral (GC) and specific (SC) securities from 2006 to 2015. Trading volumes are noted in EUR trillions and transactions refer to the sum of all repos traded on BrokerTec, Eurex Repo, and MTS Repo jointly. Maturity shares report the percentage of total volume traded overnight (ON, TN, SN) and longer terms (other). Repo shares measure the relative trading volume between GC and special repos. Countries are listed in columns and GCP and GCPx refer to two pooling baskets of GC securities as described in the text.

	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx	All
Total Volume (tn)	182	88	29	27	13	28	119	41	13	540
Transactions ('000)	5,690	3,516	1,356	1,267	787	1,632	4,825	138	58	19,268
Maturity Shares (%)										
ON	1.65	9.73	8.64	4.09	4.45	5.53	8.72	47.46	42.57	9.77
TN	14.14	22.73	20.86	17.35	14.12	16.71	20.57	21.89	26.17	18.49
SN	79.87	64.38	68.68	77.12	80.03	72.30	64.02	15.22	19.41	66.34
Other	4.34	3.17	1.82	1.44	1.39	5.46	6.69	15.43	11.85	5.40
Repo Shares (%)										
GC	11.03	17.28	18.74	11.80	11.70	12.50	37.94	100	100	27.45
SC	88.97	82.72	81.26	88.20	88.30	87.50	62.06	0	0	72.55
GC Maturity Shares (%)										
ON	12.16	45.38	42.20	30.98	34.89	35.35	20.99	47.46	42.57	33.03
TN	72.17	49.52	54.27	65.83	60.34	41.61	32.62	21.89	26.17	38.16
SN	6.63	4.00	2.02	1.86	2.67	12.07	36.35	15.22	19.41	18.72
Other	9.04	1.11	1.51	1.34	2.11	10.97	10.05	15.43	11.85	10.09
SC Maturity Shares (%)										
ON	0.34	2.28	0.90	0.50	0.42	1.27	1.22			0.97
TN	6.94	17.13	13.15	10.86	7.99	13.16	13.21			11.04
SN	88.95	77.00	84.05	87.19	90.28	80.90	80.93			84.36
Other	3.76	3.60	1.90	1.45	1.30	4.67	4.64			3.63

Table 2

VAR Dynamics: GC Germany and Italy

This table shows the unconstrained (Panel A) and constrained (Panel B) VAR parameter estimates for the period between October 15, 2008, and December 31, 2015, and the coefficients adjusted for small-sample bias via residual bootstrap assuming generalized autoregressive conditional heteroskedaticity (GARCH) innovations. The lag order is chosen by the Schwarz criterion (BIC). Standard errors are reported in parantheses, (s.e.), and are heteroskedasticity consistent. Credit ratings are from Standard & Poor's.

Panel A: Unconstrained VAR Dynamics

	GC Germany (AAA)						GC Italy (A+) - (BBB-)					
	Δi_{t-1} b.-corr. (s.e.)	s_{t-1} b.-corr. (s.e.)	Δi_{t-2} b.-corr. (s.e.)	s_{t-2} b.-corr. (s.e.)	Δi_{t-3} b.-corr. (s.e.)	s_{t-3} b.-corr. (s.e.)	Δi_{t-1} b.-corr. (s.e.)	s_{t-1} b.-corr. (s.e.)	Δi_{t-2} b.-corr. (s.e.)	s_{t-2} b.-corr. (s.e.)	Δi_{t-3} b.-corr. (s.e.)	s_{t-3} b.-corr. (s.e.)
Δi_t	0.2986	1.0692	−0.0269	−0.3008	0.0138	−0.0007	0.2130	0.8470	−0.0314	−0.3066	−0.0711	−0.0985
	0.6049	1.0657	0.0310	−0.6324	0.0044	−0.0770	0.3025	0.8429	−0.0716	−0.3917	−0.0470	−0.0596
	(0.0036)	(0.0001)	(0.0028)	(0.0039)	(0.0002)	(0.0030)	(0.0038)	(0.0026)	(0.0038)	(0.0041)	(0.0024)	(0.0042)
s_t	−0.2427	−0.2148	−0.1561	0.1788	−0.0999	0.1279	−0.3043	−0.1987	−0.1953	0.2187	−0.0619	0.1775
	0.1448	−0.3853	1.6280	−0.4271	−0.1072	−1.9852	−0.2923	−0.1475	−0.1886	0.2605	0.0148	0.1969
	(0.1550)	(0.0038)	(0.1204)	(0.1652)	(0.0076)	(0.1279)	(0.0054)	(0.0038)	(0.0055)	(0.0059)	(0.0034)	(0.0061)

Panel B: Constrained VAR Dynamics

	GC Germany (AAA)						GC Italy (A+) - (BBB-)					
	Δi_{t-1} (s.e.)	s_{t-1} (s.e.)	Δi_{t-2} (s.e.)	s_{t-2} (s.e.)	Δi_{t-3} (s.e.)	s_{t-3} (s.e.)	Δi_{t-1} (s.e.)	s_{t-1} (s.e.)	Δi_{t-2} (s.e.)	s_{t-2} (s.e.)	Δi_{t-3} (s.e.)	s_{t-3} (s.e.)
Δi_t	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
	(0.7323)	(0.1630)	(0.5803)	(0.7983)	(0.0325)	(0.6225)	(0.4443)	(1.2767)	(0.4821)	(0.6849)	(0.1749)	(0.6020)
s_t	1.8080	0.9224	−1.0878	−2.7656	0.1298	1.2772	0.1515	1.0336	−0.3142	−0.7679	0.0975	0.8322
	(2.7490)	(0.6380)	(2.9978)	(2.8775)	(0.1398)	(3.2227)	(0.6570)	(0.6653)	(0.2404)	(0.7219)	(0.0830)	(0.4505)

Table 3

Unconditional Tests of the EH

This table shows the results of the Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panel A reports the test results for general collateral (GC) repo rates, and Panel B for specific repo rates. Results in each panel are shown for when the data generating process (DGP) for bias-correction assumes homoskedastic (H-DGP) and generalized autoregressive conditional heteroskedasticity (GARCH-DGP) innovations. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: GC Repo Rates

	Before UMP (1)				After UMP (2)								
H-DGP	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0599	0.0442	0.0428	0.0460	0.3913	0.3353	0.4756	0.3354	0.3421	0.1635	0.2088	0.3455	0.2648
DM	0.0007	0.0039	0.0017	0.0118	0.0930	0.0308	0.1416	0.0872	0.0060	0.0050	0.0062	0.0150	0.0386
J-Test	0.4170	0.6561	0.3841	0.3533	0.9499	0.5411	0.9387	0.8828	0.4164	0.7991	0.5859	0.5796	0.7542
GARCH-DGP	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0259	0.0162	0.0172	0.0199	0.1898	0.1860	0.1900	0.1881	0.1631	0.0654	0.0418	0.1618	0.1076
DM	0.0006	0.0025	0.0001	0.0045	0.1159	0.0458	0.0080	0.0544	0.0240	0.0014	0.0053	0.0719	0.0021
J-Test	0.3926	0.5898	0.1340	0.2132	0.9641	0.6286	0.4658	0.8125	0.6671	0.6387	0.5601	0.8558	0.2645

Panel B: Specific Repo Rates

	Before UMP (1)						After UMP (2)					
H-DGP	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0294	0.0067	0.0407	0.0210	0.0254	0.0264	0.3319	0.2484	0.2446	0.2568	0.0989	0.1208
DM	0.0056	0.0001	0.0034	0.0002	0.0005	0.0094	0.0514	0.0562	0.0516	0.1131	0.0001	0.0365
J-Test	0.4061	0.2790	0.3298	0.4019	0.4833	0.4943	0.6542	0.6743	0.6553	0.8233	0.3395	0.7443
GARCH-DGP	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0105	0.0009	0.0061	0.0082	0.0143	0.0101	0.1092	0.0524	0.0793	0.0945	0.0404	0.0247
DM	0.0022	0.0000	0.0007	0.0000	0.0019	0.0031	0.0157	0.0178	0.0034	0.0201	0.0000	0.0037
J-Test	0.2724	0.2211	0.1587	0.2152	0.6779	0.3194	0.4041	0.4279	0.1805	0.4514	0.1841	0.3412

Table 4

Conditional Tests of the EH: 3-Month Euribor-Eonia

This table shows the results of the conditional tests of the EH. Repo rates are sorted according to the 3-month Euribor-Eonia spread, divided into quartiles, and only the first (high-risk) and fourth (low-risk) quartiles are reported. Each quartile is tested using the LM and DM tests, and all values reported are p-values and calculated as described in the text. Panel A reports the test results for general collateral (GC) rates, and Panel B for specific repo rates. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: GC Repo Rates

	Before UMP (1)				After UMP (2)								
High-Risk Quartile	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0081	0.0007	0.0055	0.0058	0.1291	0.1023	0.1125	0.1244	0.1028	0.0310	0.0434	0.1283	0.0890
DM	0.0000	0.0001	0.0001	0.0036	0.0045	0.0002	0.0106	0.0892	0.0184	0.0002	0.0059	0.0143	0.0076
J-Test	0.2026	0.1509	0.2390	0.1878	0.3729	0.2533	0.5150	0.7752	0.4348	0.2489	0.4146	0.5707	0.4577
Low-Risk Quartile	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.2056	0.1242	0.0671	0.1767	0.2504	0.2036	0.2232	0.2854	0.1795	0.1012	0.1051	0.2232	0.1665
DM	0.0150	0.0314	0.0030	0.0072	0.1128	0.0182	0.0514	0.0099	0.0022	0.0008	0.0004	0.0061	0.0082
J-Test	0.5789	0.5449	0.1697	0.4472	0.8229	0.7605	0.6542	0.5030	0.2698	0.5593	0.4781	0.5832	0.4697

Panel B: Specific Repo Rates

	Before UMP (1)						After UMP (2)					
High-Risk Quartile	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0094	0.0070	0.0073	0.0074	0.0068	0.0074	0.0743	0.0410	0.0574	0.0671	0.0159	0.0087
DM	0.0010	0.0011	0.0001	0.0006	0.0007	0.0004	0.0007	0.0288	0.0104	0.0009	0.0001	0.0013
J-Test	0.1865	0.1934	0.3307	0.3866	0.2730	0.3437	0.2762	0.5266	0.3307	0.2978	0.2767	0.2117
Low-Risk Quartile	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0783	0.0587	0.0319	0.0581	0.0482	0.0409	0.1834	0.1229	0.1714	0.1653	0.1182	0.0957
DM	0.0021	0.0134	0.0006	0.0041	0.0003	0.0216	0.0867	0.0051	0.0081	0.0091	0.0301	0.0134
J-Test	0.4189	0.3754	0.5299	0.3571	0.1800	0.4666	0.7692	0.3915	0.4667	0.7745	0.5357	0.7124

Table 5

Conditional Tests of the EH: MRO Weekday Effects

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests for day-of-the-week combinations. The first day of each pairwise combination denotes the forward premium (s_t), and the second day the overnight spot spread (Δi_t). All values reported are p-values and calculated as described in the text. The ECB main refinancing operations are conducted once a week on every Wednesday. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: Monday (s_t) - Tuesday (Δi_t)

	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.0158	0.0104	0.0081	0.0391	0.1167	0.1126	0.1108	0.1116
DM	0.0038	0.0009	0.0017	0.0013	0.0615	0.0425	0.0234	0.0023
J-Test	0.3463	0.1770	0.2418	0.6275	0.6945	0.6116	0.5014	0.4300

Panel B: Tuesday (s_t) - Wednesday (Δi_t)

	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.0358	0.0130	0.0282	0.0414	0.1640	0.1708	0.1364	0.1606
DM	0.0032	0.0042	0.0094	0.0016	0.0256	0.0122	0.0049	0.0305
J-Test	0.1747	0.3621	0.3156	0.2359	0.5014	0.3585	0.2228	0.7112

Panel C: Wednesday (s_t) - Thursday (Δi_t)

	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.0471	0.0517	0.0345	0.0610	0.1731	0.1380	0.1562	0.1751
DM	0.0035	0.0137	0.0005	0.0252	0.0024	0.0155	0.0017	0.0774
J-Test	0.1850	0.5623	0.2450	0.4983	0.2843	0.5853	0.1221	0.8664

Panel D: Thursday (s_t) - Friday (Δi_t)

	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.1344	0.1663	0.1360	0.2045	0.1284	0.1520	0.1123	0.1348
DM	0.0213	0.0378	0.1022	0.0255	0.0457	0.0151	0.0123	0.0001
J-Test	0.4638	0.5858	0.8033	0.5003	0.6279	0.3966	0.3595	0.2154

Table 6

Additional Tests of GC Repo Rates: Conditional Tests – CISS

This table shows additional results of the conditional tests of the EH. In Panel A, GC repo rates are sorted according to the composite indicator of systemic stress (CISS), divided into quartiles, and only the first (high-risk) and fourth (low-risk) quartiles are reported. Each quartile is tested using the LM and DM tests, and all values reported are p-values and calculated as described in the text. Panel B reports the test results when the risk variable (CISS) is included as an additional endogenous regressor into the VAR system in Equations (3) and (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: Conditional Tests (CISS)

	Before UMP (1)				After UMP (2)								
High-Risk Quartile	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0072	0.0011	0.0007	0.0065	0.0864	0.1161	0.1278	0.1155	0.0844	0.0016	0.0200	0.1199	0.0928
DM	0.0003	0.0001	0.0001	0.0001	0.0696	0.0072	0.0372	0.0239	0.0096	0.0001	0.0020	0.0176	0.0020
J-Test	0.3038	0.2072	0.1850	0.1832	0.7218	0.2747	0.5825	0.4872	0.3190	0.1897	0.2598	0.6088	0.4062
Low-Risk Quartile	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.1111	0.0944	0.0329	0.1726	0.2269	0.2385	0.2684	0.2241	0.1584	0.1099	0.1507	0.2253	0.2305
DM	0.0168	0.0046	0.0239	0.0109	0.0262	0.0278	0.0038	0.0024	0.0223	0.0353	0.0094	0.0124	0.1332
J-Test	0.4169	0.3748	0.6666	0.3391	0.5063	0.5191	0.6521	0.1471	0.4727	0.7379	0.6550	0.3614	0.8543

Panel B: Endogenizing Risk (CISS)

	Before UMP (1)				After UMP (2)								
H-DGP	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0229	0.0195	0.0182	0.0185	0.2761	0.3163	0.3711	0.3687	0.3647	0.0799	0.0907	0.3156	0.1462
DM	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0003	0.0004	0.0000	0.0011	0.0000	0.0000
J-Test	0.7606	0.7233	0.2587	0.6537	0.9873	0.3259	0.4375	0.9910	0.8018	0.7806	0.8838	0.9280	0.2897
GARCH-DGP	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0020	0.0001	0.0001	0.0008	0.1126	0.1067	0.1464	0.1434	0.1394	0.0273	0.0163	0.1296	0.0494
DM	0.0000	0.0000	0.0000	0.0005	0.0000	0.0002	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0004
J-Test	0.2960	0.4294	0.4350	0.9952	0.3943	0.7246	0.8046	0.6814	0.6750	0.1178	0.4670	0.9229	0.7834

Table 7

GCP Term Structure Tests of the EH

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The data are the GCP index repos of the following maturities: overnight (ON), tomorrow-next (TN), 1-week (1W), 2-week (2W), 1-month (1M), 3-month (3M), 6-month (6M), and 12-month (12M). The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. Each pairwise combination of short-term rate, i_t^m, and long-term rate, i_t^n, are such that $k = n/m$ is an integer. All values reported are p-values and calculated as described in the text, and the time period spans from October 16, 2013, to December 31, 2015.

i_t^n/i_t^m	i_t^{TN}/i_t^{ON}	i_t^{1W}/i_t^{ON}	i_t^{2W}/i_t^{ON}	i_t^{1M}/i_t^{ON}	i_t^{3M}/i_t^{ON}	i_t^{6M}/i_t^{ON}	i_t^{12M}/i_t^{ON}
LM	0.1628	0.1515	0.1529	0.0654	0.0008	0.0103	0.0180
DM	0.0016	0.0108	0.0074	0.0006	0.0008	0.0029	0.0006
J-Test	0.2336	0.6780	0.2785	0.2587	0.1696	0.3084	0.2584

i_t^m/i_t^n	i_t^{2W}/i_t^{1W}	i_t^{3M}/i_t^{1M}	i_t^{6M}/i_t^{1M}	i_t^{12M}/i_t^{1M}	i_t^{6M}/i_t^{3M}	i_t^{12M}/i_t^{3M}	i_t^{12M}/i_t^{6M}
LM	0.0880	0.0503	0.0326	0.0836	0.0922	0.1212	0.0627
DM	0.0019	0.0078	0.0062	0.0067	0.0265	0.0137	0.0018
J-Test	0.5472	0.2864	0.2529	0.2647	0.5088	0.3793	0.1255

Table 8

Unconditional Tests of the EH: Closing Repo Rates

This table shows the results of the Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. Closing rates represent the repo rate traded on the last transaction of each day. Panel A reports the test results for GC closing rates, and Panel B for specific closing rates. Results in each panel are shown for when the data generating process (DGP) for bias-correction assumes homoskedastic (H-DGP) and generalized autoregressive conditional heteroskedasticity (GARCH-DGP) innovations. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: GC Repo Closing Rates

	Before UMP (1)				After UMP (2)								
H-DGP	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0295	0.0420	0.0175	0.0444	0.1980	0.1535	0.1559	0.1665	0.1307	0.0749	0.0647	0.2314	0.1690
DM	0.0003	0.0002	0.0002	0.0000	0.0195	0.0764	0.0048	0.0219	0.0034	0.0000	0.0010	0.0257	0.0362
J-Test	0.4296	0.3626	0.4045	0.1278	0.7709	0.7421	0.3828	0.6496	0.4915	0.1658	0.4500	0.8954	0.9243
GARCH-DGP	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
LM	0.0120	0.0183	0.0007	0.0060	0.0913	0.0594	0.0654	0.0626	0.0551	0.0171	0.0290	0.0633	0.0966
DM	0.0001	0.0003	0.0000	0.0001	0.0027	0.0162	0.0455	0.0135	0.0010	0.0000	0.0016	0.0004	0.0059
J-Test	0.2698	0.4169	0.1186	0.1640	0.4561	0.4099	0.7825	0.5594	0.3154	0.1595	0.5246	0.3284	0.7155

Panel B: Specific Repo Closing Rates

	Before UMP (1)						After UMP (2)					
H-DGP	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0935	0.0263	0.0349	0.1041	0.0298	0.0203	0.1370	0.0625	0.1066	0.1404	0.0490	0.0559
DM	0.0009	0.0008	0.0013	0.0047	0.0008	0.0016	0.0812	0.0177	0.0307	0.0040	0.0242	0.0027
J-Test	0.3064	0.5575	0.6254	0.5400	0.2839	0.3818	0.8732	0.4269	0.8350	0.7715	0.8025	0.4563
GARCH-DGP	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0190	0.0055	0.0123	0.0154	0.0093	0.0094	0.0530	0.0300	0.0379	0.0488	0.0037	0.0096
DM	0.0001	0.0001	0.0000	0.0142	0.0013	0.0025	0.0127	0.0201	0.0127	0.0008	0.0002	0.0012
J-Test	0.1209	0.2637	0.1591	0.7216	0.3475	0.4428	0.5482	0.4521	0.7040	0.5627	0.1588	0.3412

Internet Appendix for "Explaining the Failure of the Expectations Hypothesis with Short-Term Rates"

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Abstract

This supplemental appendix extends the main paper by presenting additional tables.

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Contents

List of Tables

A. Additional Tables

Table IA.1
Unconditional Tests of the EH: Specific Repo Rates Spot-Next (SN)

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panel A reports the test results when the data generating process (DGP) used for small sample bias correction assumes homoskedastic innovations. Panel B reports the results when the DGP used for bias-correction assumes generalized autoregressive conditional heteroskedasticity (GARCH) innovations. On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

Panel A: Homoskedastic Innovations												
	Before UMP (1)						After UMP (2)					
	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0604	0.0030	0.0983	0.0426	0.0058	0.0161	0.2577	0.1072	0.2740	0.1443	0.0045	0.0325
DM	0.0001	0.0012	0.0126	0.0027	0.0000	0.0011	0.0024	0.0013	0.0016	0.0001	0.0001	0.0010
J-Test	0.2886	0.6119	0.8924	0.7210	0.2320	0.6021	0.7056	0.6242	0.6564	0.2703	0.2539	0.5933
Panel B: GARCH Innovations												
	Before UMP (1)						After UMP (2)					
	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
LM	0.0372	0.0007	0.0136	0.0116	0.0013	0.0003	0.1031	0.0466	0.1107	0.0558	0.0017	0.0036
DM	0.0001	0.0002	0.0009	0.0007	0.0004	0.0002	0.0001	0.0001	0.0003	0.0001	0.0000	0.0003
J-Test	0.2492	0.3777	0.5714	0.5475	0.4609	0.3730	0.2987	0.3118	0.4235	0.3316	0.1171	0.4411

Table IA.2
GC Repo Quartiles: 3-month Euribor-Eonia

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the 3-month Euribor-Eonia spread, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)				After UMP (2)								
	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
Panel A: 1st Quartile													
LM	0.0081	0.0007	0.0055	0.0058	0.1291	0.1023	0.1125	0.1244	0.1028	0.0310	0.0434	0.1283	0.0890
DM	0.0000	0.0001	0.0001	0.0036	0.0045	0.0002	0.0106	0.0892	0.0184	0.0002	0.0059	0.0143	0.0076
J-Test	0.2026	0.1509	0.2390	0.1878	0.3729	0.2533	0.5150	0.7752	0.4348	0.2489	0.4146	0.5707	0.4577
Panel B: 2nd Quartile													
LM	0.0292	0.0120	0.0193	0.0379	0.1868	0.1359	0.1670	0.1953	0.1488	0.0433	0.0685	0.1666	0.1291
DM	0.0002	0.0007	0.0121	0.0106	0.0949	0.0477	0.0040	0.0068	0.0200	0.0214	0.0020	0.0124	0.0023
J-Test	0.2475	0.4118	0.3567	0.5146	0.8939	0.6376	0.3521	0.2668	0.4509	0.4644	0.2628	0.5446	0.2771
Panel C: 3rd Quartile													
LM	0.0623	0.0704	0.0455	0.0602	0.1973	0.1987	0.1774	0.2314	0.1601	0.0796	0.0915	0.1920	0.1648
DM	0.0065	0.0075	0.0061	0.0140	0.1185	0.0011	0.0051	0.0893	0.0052	0.0027	0.0073	0.0050	0.0034
J-Test	0.4299	0.2812	0.7190	0.7192	0.8324	0.3314	0.2290	0.8860	0.2297	0.4568	0.6124	0.3890	0.3283
Panel D: 4th Quartile													
LM	0.2056	0.1242	0.0671	0.1767	0.2504	0.2036	0.2232	0.2854	0.1795	0.1012	0.1051	0.2232	0.1665
DM	0.0150	0.0314	0.0030	0.0072	0.1128	0.0182	0.0514	0.0099	0.0022	0.0008	0.0004	0.0061	0.0082
J-Test	0.5789	0.5449	0.1697	0.4472	0.8229	0.7605	0.6542	0.5030	0.2698	0.5593	0.4781	0.5832	0.4697

Table IA.3
GC Repo Quartiles: 3-month Libor-OIS

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the 3-month Libor-OIS spread, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)				After UMP (2)								
	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
Panel A: 1st Quartile													
LM	0.0004	0.0028	0.0002	0.0026	0.1024	0.1235	0.1365	0.1067	0.1031	0.0584	0.0548	0.1068	0.0840
DM	0.0001	0.0000	0.0000	0.0002	0.0173	0.0104	0.0072	0.0048	0.0135	0.0446	0.0025	0.0051	0.0093
J-Test	0.2418	0.1316	0.1457	0.1660	0.7523	0.3311	0.2751	0.2202	0.5589	0.6227	0.5888	0.3924	0.4915
Panel B: 2nd Quartile													
LM	0.0575	0.0331	0.0230	0.0353	0.1622	0.1501	0.1643	0.1515	0.1235	0.0810	0.0678	0.1702	0.1365
DM	0.0126	0.0041	0.0017	0.0040	0.0210	0.0031	0.0390	0.0370	0.0798	0.0261	0.0015	0.0145	0.0008
J-Test	0.3643	0.2021	0.2386	0.2005	0.6419	0.3155	0.8656	0.7466	0.7515	0.6824	0.2307	0.5732	0.1659
Panel C: 3rd Quartile													
LM	0.1103	0.0916	0.0518	0.0718	0.2438	0.1605	0.2050	0.2084	0.1632	0.0994	0.0836	0.1801	0.1441
DM	0.0305	0.0028	0.0030	0.0059	0.0203	0.0951	0.0211	0.0061	0.0989	0.0250	0.0002	0.0012	0.0001
J-Test	0.7118	0.1609	0.1694	0.2476	0.4537	0.8942	0.7823	0.4193	0.7965	0.6748	0.1631	0.2006	0.1315
Panel D: 4th Quartile													
LM	0.2144	0.1502	0.0922	0.1770	0.2601	0.1828	0.2287	0.2383	0.1682	0.1117	0.1470	0.2228	0.1699
DM	0.0153	0.0051	0.0229	0.0627	0.0029	0.0456	0.0667	0.0461	0.0451	0.0281	0.0213	0.0210	0.0062
J-Test	0.3994	0.2288	0.4780	0.6986	0.3057	0.7830	0.8446	0.7850	0.6250	0.6963	0.6449	0.6422	0.2543

Table IA.4
GC Repo Quartiles: 10-Year Government Bond Spreads

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the 10-year government bond spread, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)				After UMP (2)								
	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
Panel A: 1st Quartile													
LM	0.0006	0.0045	0.0011	0.0093	0.0938	0.1086	0.1188	0.1018	0.1046	0.0418	0.0374	0.1181	0.0882
DM	0.0001	0.0010	0.0001	0.0002	0.0014	0.0132	0.0026	0.0018	0.0008	0.0083	0.0044	0.0355	0.0103
J-Test	0.3154	0.3187	0.2529	0.1722	0.3629	0.3722	0.2908	0.3920	0.2950	0.4710	0.5312	0.5717	0.5103
Panel B: 2nd Quartile													
LM	0.0186	0.0116	0.0029	0.0207	0.1579	0.1517	0.2377	0.1921	0.1100	0.0629	0.0543	0.1327	0.1442
DM	0.0011	0.0013	0.0007	0.0112	0.0088	0.0012	0.0282	0.0924	0.0045	0.0032	0.0057	0.0030	0.0187
J-Test	0.1959	0.2110	0.1586	0.3443	0.3038	0.2079	0.6971	0.8905	0.3699	0.3235	0.4097	0.4712	0.6200
Panel C: 3rd Quartile													
LM	0.0513	0.0210	0.0141	0.0447	0.1747	0.2109	0.2781	0.1938	0.1646	0.0762	0.0746	0.1488	0.1647
DM	0.0054	0.0040	0.0005	0.0002	0.0454	0.0115	0.0765	0.0421	0.0279	0.0016	0.0005	0.0101	0.0014
J-Test	0.5639	0.1986	0.2372	0.1553	0.6266	0.5301	0.7424	0.7692	0.5194	0.2367	0.3651	0.5071	0.6325
Panel D: 4th Quartile													
LM	0.0721	0.0312	0.0285	0.0704	0.2540	0.2347	0.2885	0.2317	0.2327	0.1667	0.1616	0.2480	0.2172
DM	0.0016	0.0189	0.0035	0.0003	0.1545	0.0162	0.0274	0.1427	0.0110	0.0011	0.0022	0.0465	0.0360
J-Test	0.2310	0.4399	0.1859	0.4316	0.9467	0.7420	0.5159	0.8665	0.3410	0.1927	0.2720	0.6321	0.7416

Table IA.5
GC Repo Quartiles: CISS

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the CISS, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)				After UMP (2)								
	DE	FR	BE	GCP	DE	FR	BE	NL	AT	ES	IT	GCP	GCPx
Panel A: 1st Quartile													
LM	0.0072	0.0011	0.0007	0.0065	0.0864	0.1161	0.1278	0.1155	0.0844	0.0016	0.0200	0.1199	0.0928
DM	0.0003	0.0001	0.0001	0.0001	0.0696	0.0072	0.0372	0.0239	0.0096	0.0001	0.0020	0.0176	0.0020
J-Test	0.3038	0.2072	0.1850	0.1832	0.7218	0.2747	0.5825	0.4872	0.3190	0.1897	0.2598	0.6088	0.4062
Panel B: 2nd Quartile													
LM	0.0172	0.0092	0.0089	0.0378	0.1394	0.1287	0.1910	0.1243	0.0932	0.0336	0.0456	0.1593	0.1028
DM	0.0000	0.0000	0.0001	0.0324	0.0627	0.0018	0.0951	0.0260	0.0091	0.0050	0.0014	0.0008	0.0043
J-Test	0.1688	0.2202	0.1815	0.5520	0.8351	0.3966	0.8942	0.6820	0.6493	0.5522	0.2197	0.2831	0.2083
Panel C: 3rd Quartile													
LM	0.0701	0.0129	0.0266	0.0771	0.1789	0.2058	0.2038	0.1559	0.1212	0.0595	0.0896	0.1931	0.1212
DM	0.0031	0.0034	0.0144	0.0083	0.0358	0.0172	0.0270	0.0046	0.0100	0.0009	0.0001	0.0064	0.0353
J-Test	0.1718	0.1810	0.3880	0.4728	0.7406	0.7517	0.6888	0.3760	0.3256	0.5798	0.1848	0.4269	0.7379
Panel D: 4th Quartile													
LM	0.1111	0.0944	0.0329	0.1726	0.2269	0.2385	0.2684	0.2241	0.1584	0.1099	0.1507	0.2253	0.2305
DM	0.0168	0.0046	0.0239	0.0109	0.0262	0.0278	0.0038	0.0024	0.0223	0.0353	0.0094	0.0124	0.1332
J-Test	0.4169	0.3748	0.6666	0.3391	0.5063	0.5191	0.6521	0.1471	0.4727	0.7379	0.6550	0.3614	0.8543

Table IA.6
SC Repo Quartiles: 3-month Euribor-Eonia

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the 3-month Euribor-Eonia spread, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)						After UMP (2)					
	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
Panel A: 1st Quartile												
LM	0.0094	0.0070	0.0073	0.0074	0.0068	0.0074	0.0743	0.0410	0.0574	0.0671	0.0159	0.0087
DM	0.0010	0.0011	0.0001	0.0006	0.0007	0.0004	0.0007	0.0288	0.0104	0.0009	0.0001	0.0013
J-Test	0.1865	0.1934	0.3307	0.3866	0.2730	0.3437	0.2762	0.5266	0.3307	0.2978	0.2767	0.2117
Panel B: 2nd Quartile												
LM	0.0223	0.0246	0.0114	0.0125	0.0159	0.0147	0.0810	0.0852	0.0737	0.0805	0.0358	0.0568
DM	0.0037	0.0015	0.0009	0.0002	0.0103	0.0002	0.0010	0.0170	0.0471	0.0155	0.0003	0.0113
J-Test	0.3424	0.2301	0.1797	0.1482	0.5109	0.1464	0.4552	0.6025	0.6347	0.5854	0.1901	0.5269
Panel C: 3rd Quartile												
LM	0.0371	0.0303	0.0296	0.0467	0.0240	0.0280	0.1458	0.1142	0.1588	0.1460	0.0577	0.0621
DM	0.0063	0.0015	0.0086	0.0111	0.0058	0.0004	0.0103	0.0014	0.0048	0.0011	0.0092	0.0001
J-Test	0.7251	0.2282	0.4777	0.5242	0.5760	0.4679	0.5109	0.3569	0.2197	0.6064	0.4902	0.1961
Panel D: 4th Quartile												
LM	0.0783	0.0587	0.0319	0.0581	0.0482	0.0409	0.1834	0.1229	0.1714	0.1653	0.1182	0.0957
DM	0.0021	0.0134	0.0006	0.0041	0.0003	0.0216	0.0867	0.0051	0.0081	0.0091	0.0301	0.0134
J-Test	0.4189	0.3754	0.5299	0.3571	0.1800	0.4666	0.7692	0.3915	0.4667	0.7745	0.5357	0.7124

Table IA.7
SC Repo Quartiles: 3-month Libor-OIS

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the 3-month Libor-Ois spread, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)						After UMP (2)					
	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
Panel A: 1st Quartile												
LM	0.0087	0.0030	0.0082	0.0024	0.0054	0.0025	0.0639	0.0494	0.0562	0.0499	0.0256	0.0172
DM	0.0003	0.0020	0.0006	0.0001	0.0001	0.0001	0.0010	0.0037	0.0023	0.0065	0.0001	0.0017
J-Test	0.1929	0.1340	0.2649	0.2093	0.2380	0.1547	0.3182	0.1906	0.1461	0.4295	0.2560	0.2435
Panel B: 2nd Quartile												
LM	0.0290	0.0296	0.0212	0.0311	0.0061	0.0057	0.1031	0.0946	0.0753	0.1012	0.0428	0.0548
DM	0.0003	0.0006	0.0008	0.0135	0.0041	0.0035	0.0699	0.0034	0.0022	0.0002	0.0069	0.0145
J-Test	0.1906	0.2553	0.2898	0.7136	0.3586	0.4932	0.7226	0.4906	0.5689	0.3579	0.4408	0.5726
Panel C: 3rd Quartile												
LM	0.0507	0.0365	0.0321	0.0629	0.0276	0.0227	0.1649	0.1078	0.1723	0.1319	0.0585	0.0867
DM	0.0090	0.0001	0.0001	0.0420	0.0004	0.0005	0.0031	0.0345	0.0630	0.0007	0.0033	0.0076
J-Test	0.3079	0.3219	0.3189	0.6093	0.2269	0.1349	0.3183	0.5659	0.6999	0.4014	0.7494	0.4561
Panel D: 4th Quartile												
LM	0.0633	0.0824	0.0608	0.0719	0.0407	0.0363	0.1857	0.1204	0.2112	0.1594	0.1159	0.1166
DM	0.0076	0.0513	0.0062	0.0018	0.0077	0.0146	0.0308	0.0159	0.0031	0.0070	0.0048	0.0134
J-Test	0.6206	0.6540	0.8218	0.3942	0.8462	0.3904	0.7131	0.4058	0.3186	0.4416	0.5437	0.4470

Table IA.8
SC Repo Quartiles: 10-Year Government Bond Spreads

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the 10-year government bond spread, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)						After UMP (2)					
	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
Panel A: 1st Quartile												
LM	0.0084	0.0085	0.0013	0.0067	0.0010	0.0038	0.0710	0.0388	0.0775	0.0692	0.0197	0.0125
DM	0.0057	0.0004	0.0000	0.0000	0.0001	0.0000	0.0051	0.0077	0.0102	0.0017	0.0014	0.0042
J-Test	0.2416	0.1172	0.1725	0.1699	0.1247	0.1550	0.5533	0.6230	0.5079	0.2413	0.3560	0.3592
Panel B: 2nd Quartile												
LM	0.0297	0.0167	0.0312	0.0122	0.0131	0.0069	0.0829	0.0919	0.0926	0.0918	0.0307	0.0365
DM	0.0000	0.0015	0.0111	0.0004	0.0023	0.0044	0.0177	0.0102	0.0010	0.0031	0.0191	0.0044
J-Test	0.1239	0.2273	0.3420	0.2006	0.2767	0.2092	0.4266	0.5076	0.5851	0.7409	0.6247	0.2112
Panel C: 3rd Quartile												
LM	0.0563	0.0374	0.0346	0.0288	0.0348	0.0360	0.1125	0.1076	0.1066	0.1055	0.0358	0.0844
DM	0.0050	0.0002	0.0077	0.0097	0.0000	0.0053	0.0244	0.0018	0.0180	0.0017	0.0004	0.0120
J-Test	0.3888	0.1665	0.2848	0.4994	0.1343	0.3973	0.6700	0.3979	0.7585	0.3884	0.4657	0.3558
Panel D: 4th Quartile												
LM	0.0750	0.0634	0.0684	0.0396	0.0535	0.0481	0.1618	0.1140	0.1179	0.1220	0.1174	0.0978
DM	0.0651	0.0011	0.0004	0.0038	0.0009	0.0139	0.0742	0.0006	0.0223	0.0064	0.0101	0.0006
J-Test	0.8409	0.4678	0.3460	0.7656	0.4459	0.3810	0.7358	0.2604	0.4731	0.4268	0.5059	0.3774

Table IA.9
SC Repo Quartiles: CISS

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests of the EH under the null hypothesis that the EH holds. The J-Test is the Hansen (1982) test for overidentifying restrictions in the GMM estimation. All values reported are p-values and calculated as described in the text. Panels report the p-values for the time series conditioned on the CISS, ranked from the highest 25%-quantile (1) to the lowest (4). On October 15, 2008, the ECB introduced a fixed-rate full allotment regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)						After UMP (2)					
	DE	FR	BE	NL	ES	IT	DE	FR	BE	NL	ES	IT
Panel A: 1st Quartile												
LM	0.0076	0.0075	0.0059	0.0075	0.0027	0.0002	0.0634	0.0378	0.0678	0.0692	0.0137	0.0142
DM	0.0008	0.0024	0.0019	0.0002	0.0001	0.0000	0.0082	0.0091	0.0016	0.0107	0.0028	0.0010
J-Test	0.1682	0.2824	0.1309	0.2808	0.2798	0.1260	0.8523	0.3100	0.2309	0.3356	0.4600	0.1874
Panel B: 2nd Quartile												
LM	0.0247	0.0264	0.0134	0.0256	0.0080	0.0130	0.0985	0.0730	0.0822	0.0842	0.0490	0.0332
DM	0.0014	0.0054	0.0097	0.0041	0.0054	0.0051	0.0162	0.0002	0.0226	0.0043	0.0051	0.0038
J-Test	0.5002	0.2364	0.3199	0.5192	0.2353	0.2269	0.4103	0.3678	0.6557	0.2073	0.3908	0.3479
Panel C: 3rd Quartile												
LM	0.0472	0.0504	0.0328	0.0450	0.0376	0.0272	0.1242	0.0963	0.1115	0.1061	0.0692	0.0798
DM	0.0050	0.0230	0.0028	0.0006	0.0088	0.0028	0.0202	0.0256	0.0160	0.0259	0.0028	0.0698
J-Test	0.2265	0.4793	0.6053	0.5219	0.2861	0.1624	0.4527	0.5017	0.4077	0.6815	0.1635	0.7225
Panel D: 4th Quartile												
LM	0.0805	0.0651	0.0422	0.0874	0.0395	0.0320	0.1701	0.1258	0.1693	0.1426	0.0862	0.0857
DM	0.0059	0.0007	0.0332	0.0234	0.0229	0.0006	0.0169	0.0077	0.1121	0.0167	0.0302	0.0083
J-Test	0.4150	0.2806	0.5571	0.6622	0.6585	0.1386	0.4174	0.6219	0.8216	0.5986	0.5363	0.7625

Table IA.10
Conditional Tests of the EH: Reserve Maintenance Periods

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests conditional on the Eurosystem's reserve maintenance periods. Panel A reports the test results when the time series only contains the last week of each maintenance period, while Panel B shows the results for all other days. All values reported are p-values and calculated as described in the text. Maintenance periods typically end on a Tuesday, such that the last week of each maintenance period starts on the last Wednesday prior to the end of the maintenance period. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: Last Week of Maintenance Period

	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.0069	0.0035	0.0059	0.0167	0.1711	0.1276	0.1336	0.1047
DM	0.0003	0.0002	0.0001	0.0007	0.0018	0.0005	0.0002	0.0003
J-Test	0.3017	0.2778	0.1145	0.2690	0.6707	0.3659	0.2349	0.4481

Panel B: All other Days of Maintenance Period

	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.1548	0.1264	0.1331	0.2166	0.1317	0.1612	0.1390	0.1611
DM	0.0014	0.0069	0.0331	0.0024	0.0030	0.0681	0.0046	0.0682
J-Test	0.5077	0.7374	0.8451	0.5826	0.6175	0.7169	0.2152	0.9250

Table IA.11
Conditional Tests of the EH: End-of-Quarter

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests for end-of-quarter seasonalities. Panel A reports the test results when the time series only contains the last week of each quarter, while Panel B shows the results for all other days. All values reported are p-values and calculated as described in the text. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

Panel A: Last Week of Each Quarter								
	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.0187	0.0053	0.0233	0.0168	0.0816	0.0979	0.0489	0.0778
DM	0.0002	0.0033	0.0013	0.0001	0.0288	0.0231	0.0123	0.0003
J-Test	0.3620	0.1786	0.3507	0.2513	0.5261	0.4802	0.3602	0.2043

Panel B: All other Days of Each Quarter								
	Before UMP (1)				After UMP (2)			
	DE	FR	BE	GCP	DE	FR	BE	GCP
LM	0.0502	0.0220	0.0486	0.0380	0.3758	0.2912	0.2773	0.2631
DM	0.0014	0.0013	0.0002	0.0013	0.0696	0.0119	0.0710	0.0004
J-Test	0.3553	0.6206	0.1493	0.3489	0.8509	0.6931	0.9286	0.3505

Table IA.12
Conditional Tests of the EH: MRO Weekday Effects – Double Conditioning

This table shows the results of Lagrange Multiplier (LM) and Distance Metrics (DM) tests for day-of-the-week combinations. The first day of each pairwise combination denotes the forward premium (s_t), and the second day the overnight spot spread (Δi_t). In addition, days are conditioned on the 3-month Euribor-Eonia spread, sorted, and divided into quartiles. The highest quartile represents "high risk", and the lowest quartile "low risk". All values reported are p-values and calculated as described in the text. The ECB main refinancing operations are conducted once a week on every Wednesday. On October 15, 2008, the ECB introduced a fixed-rate full allotment (FA) regime and other unconventional monetary policy (UMP) measures.

	Before UMP (1)						After UMP (2)					
	High Risk			Low Risk			High Risk			Low Risk		
	DE	FR	BE	DE	FR	BE	DE	FR	BE	DE	FR	BE
Panel A: Mon-Tue												
LM	0.0155	0.0082	0.0046	0.0638	0.0538	0.0349	0.0729	0.0617	0.0875	0.1389	0.1469	0.1330
DM	0.0095	0.0027	0.0011	0.0219	0.0153	0.0024	0.0057	0.0039	0.0613	0.0023	0.0184	0.0055
J-Test	0.3167	0.1584	0.1926	0.4694	0.3987	0.1466	0.2415	0.3502	0.6937	0.2798	0.6175	0.4022
Panel B: Tue-Wed												
LM	0.0041	0.0059	0.0093	0.0414	0.0310	0.0503	0.0931	0.0988	0.0543	0.1802	0.2197	0.1465
DM	0.0024	0.0019	0.0062	0.0028	0.0186	0.0071	0.0642	0.0024	0.0216	0.0497	0.0029	0.0148
J-Test	0.1485	0.2543	0.2528	0.1612	0.4364	0.2720	0.8387	0.1491	0.4668	0.6467	0.3067	0.7281
Panel C: Wed-Thu												
LM	0.0349	0.0224	0.0209	0.0525	0.0697	0.0695	0.1251	0.0694	0.0722	0.1880	0.1499	0.1698
DM	0.0021	0.0049	0.0055	0.0176	0.0008	0.0193	0.0207	0.0397	0.0056	0.0185	0.0152	0.0204
J-Test	0.5660	0.5474	0.4027	0.7549	0.2901	0.4442	0.6391	0.5401	0.2404	0.4353	0.5813	0.6364
Panel C: Thu-Fri												
LM	0.0570	0.0505	0.0387	0.1525	0.1926	0.1919	0.0988	0.1200	0.0619	0.1662	0.1646	0.1410
DM	0.0111	0.0041	0.0066	0.0005	0.0020	0.0358	0.0540	0.0053	0.0082	0.0081	0.0047	0.0144
J-Test	0.5239	0.7755	0.4326	0.1235	0.2606	0.7405	0.6656	0.2323	0.4698	0.6314	0.3787	0.5716