Funding Liquidity and Market Liquidity: An Analysis of Current Research Topics in Post-Crisis Money and Fixed-Income Markets

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Funding Liquidity and Market Liquidity

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Part I

Introduction

Summary of Research Results

This dissertation analyzes topics related to funding liquidity and asset prices that have been of utmost importance during and after the recent financial crises. Specifically, this dissertation consists of three research papers that (1) reveal liquidity spirals in the secured and unsecured money markets and asset market, (2) investigate funding liquidity risk in repo forward premiums, and (3) propose a market-wide illiquidity measure from Treasury yield deviations net of holding costs.

One of the key factors contributing to the severity of the financial crisis in 2008 was that financial intermediaries largely financed their asset holdings using extensive leverage in money market short-term liabilities. The first paper provides a comprehensive theoretical model for money markets, incorporating all major sources of liquidity jointly. We explain how shocks can lead to mutually reinforcing liquidity spirals, derive how funding liquidity across money markets is interrelated, and unveil substitution mechanisms and contagion channels between secured and unsecured funding markets. We derive the optimal funding volumes and show which unconventional monetary policies and regulatory measures can reduce money market fragility.

The second paper addresses the pricing implications of funding liquidity risk for the temporal and cross-sectional variation in the forward premium of very short-term interest rates. Using a unique and comprehensive data set of European repurchase (repo) agreements, this paper finds that the forward premium varies significantly with the (net) demand for borrowing and aggregate funding risk. Conditional tests reveal that the unbiasedness hypothesis cannot be rejected when funding liquidity risk is low and borrowing demand is balanced. Overall, we show that funding liquidity risk is the main driver affecting the short end of the term structure of interest rates, and the validity of the expectations hypothesis depends on funding risk premiums and demand for funding immediacy.

The third paper exploits the link between observed mispricings in Treasury bond yields, the amount of arbitrage capital in the market, and holding costs in the repo market. This study proposes to measure market-wide illiquidity by the net deviations between Treasury yield discrepancies and arbitrageurs' cost of carry in the repo market. Deriving security-specific holding costs for the entire cross-section of Treasury bonds from several European countries, the paper finds that measuring illiquidity from profitable net deviations captures episodes associated with shortage of arbitrage capital, and provides information beyond existing measures of illiquidity. Importantly, the findings in this paper show that measuring illiquidity from net deviations improves the information content extracted from aggregate noise in Treasury yields.

Zusammenfassung der Forschungsergebnisse

Die vorliegende Dissertation behandelt aktuelle Themen zu Finanzierungsliquidität und Wertpapierpreisen, deren Erforschung im Zusammenhang mit Finanzkrisen von größter Bedeutung ist. Die Arbeit besteht aus drei Studien, die (1) Liquiditätsspiralen im besicherten und unbesicherten Geld- sowie Wertpapiermarkt aufzeigen, (2) die Bedeutung von Liquiditätsrisiken in Terminaufschlägen untersuchen und (3) eine neue Methode zur Messung von marktweiter Illiquidität anhand kostenbereinigter Zinsabweichungen vorschlagen.

Die erste Studie analysiert im Rahmen eines theoretischen Modells, wie negative Liquiditätsspiralen zwischen dem besicherten und unbesicherten Geldmarkt sowie dem Wertpapiermarkt entstehen können. Das Modell zeigt, wie Wertpapierpreise aufgrund immer restriktiverer Kreditvergabe im Interbankenmarkt weit unter ihren Fundamentalwert sinken können und welche Substitutions- und Ansteckungskanäle zwischen dem besicherten und unbesicherten Geldmarkt bestehen. Die Studie zeigt auf, dass Zentralbanken Liquiditätsspiralen nur dann effektiv in ihren Auswirkungen einschränken können, wenn sie beide Geldmärkte im Zusammenhang betrachten, und Bankenregulierung darauf abzielen sollte, statische Vorschriften durch antizyklische Maßnahmen zu ersetzen.

Die zweite Studie untersucht die Auswirkungen von Liquiditätsrisiken auf Terminaufschläge besicherter Tageskredite (sogenannter "Repos"), die für den Anleihenhandel und Interbankenmarkt von essentieller Bedeutung sind. Die empirischen Ergebnisse zeigen, dass Terminaufschläge sämtlicher Tageskredite statistisch signifikant mit erhöhtem Finanzierungsbedarf und entsprechenden Risiken steigen, was der Hypothese vollständiger Informationseffizienz des Marktes widerspricht. Empirische Tests der Erwartungshypothese zeigen, dass diese statistisch dann nicht widerlegt werden kann, wenn Finanzierungsrisiken in ihrem niedrigsten Quartil sind. Die Ergebnisse dieser Studie tragen wesentlich dazu bei, die zeitlichen und länderspezifischen Unterschiede in Terminaufschlägen am unteren Ende der Zinsstrukturkurve zu erklären.

Die dritte Studie schlägt eine neue Methode zur Messung marktweiter Illiquidität vor, die auf der Berechnung kostenbereinigter Abweichungen entlang der Zinsstrukturkurve von Staatsanleihen beruht. Zinsabweichungen bestehen generell nur, wenn Arbitrageure entweder nicht ausreichend Zugang zu Finanzierungskapital haben oder die Finanzierungskosten der Anleihen im besicherten Geldmarkt höher sind als die Zinsabweichungen selbst. Die empirischen Ergebnisse zeigen, dass die kostenbereinigten Zinsabweichungen in Phasen marktweiter Illiquidität zunehmen und einen Informationsgehalt besitzen, der den aller vorhandenen Illiquiditätsmaße deutlich übersteigt.

Part II

Research Papers

Fragility of Money Markets

Matthias Rupprecht and Jan Wrampelmeyer

This paper was presented at:

- Research Seminar at the University of St. Gallen
- 2016 ECB-IMF Workshop on "Money Markets, Monetary Policy Implementation, and Market Infrastructures"
- 2016 European Financial Management Association
- Research Seminar at the Austrian National Bank
- Research Seminar at the Deutsche Bundesbank
- Research Seminar at the Queen Mary University of London
- Research Seminar at the Swiss National Bank
- Research Seminar at the University of Tilburg
- Research Seminar at the University of Zurich
- Research Seminar at VU Amsterdam

Abstract

We provide a comprehensive theoretical model for money markets that incorporates all major sources of liquidity jointly. In our model, leveraged banks invest in assets and raise short-term funds by borrowing in the unsecured and secured money markets. We explain how shocks can lead to mutually reinforcing liquidity spirals, derive how funding liquidity across money markets is related, and unveil substitution mechanisms and contagion channels between secured and unsecured funding markets. We derive the optimal funding volumes and show which unconventional monetary policies and regulatory measures can reduce money market fragility.

1. Introduction

As a major source of funding for financial intermediaries, money markets are at the heart of the financial system. Well-functioning money markets are crucial for financial stability and disruptions can have severe consequences even for the real economy. In times of immediate liquidity needs, financial institutions borrow in the unsecured money market, obtain funding in the secured (or "repo") market[1], or liquidate assets (Freixas, Laeven, and Peydró, 2015). If liquidity from all of these sources dries up simultaneously, bank failures can occur, which cause contagion and spillover effects throughout the financial system and urge central banks to intervene as the lender of last resort.

This paper provides a theoretical model that includes all major sources of liquidity jointly. Our model provides a framework that explains the intricate dynamics and contagion channels between unsecured and secured funding as well as security markets. We show that mutually reinforcing liquidity spirals arise across funding markets, leading to commonality in illiquidity. Moreover, we highlight the importance of substitution between unsecured and secured funding. Using our model, we discuss how central bank and regulatory policies impact money markets and whether they are able to reduce funding fragility.

A comprehensive model of money markets is important for at least two reasons. First, we gain a thorough understanding of banks' funding risks only with an integrated view and joint modeling approach of all short-term funding sources. Since banks rely on both secured and unsecured funding, fragility crucially depends on the interrelation between these two sources of liquidity. Second, money market fragility contributed significantly to the global financial crisis (see, e.g., French, Baily, Campbell, Cochrane, Diamond, Duffie, Kashyap, Mishkin, Rajan, Scharfstein, Shiller, Shin, Slaughter, Stein, and Stulz, 2010). As a response, central banks introduced various (unconventional) policies to alleviate funding strains, and new regulations addressing liquidity risk have been implemented. Currently, central banks such as the ECB need to decide on exit strategies from unconventional monetary policies and regulators want to understand the efficacy of the new regulatory guidelines. To perform such important tasks, policy makers need a comprehensive approach to assess the impact on money market fragility.

The key feature of our model is that banks can borrow in the secured *and* unsecured money market. In the secured market, borrowing is subject to margins (haircuts to the value of the collateral securities), whereas in the unsecured market borrowers face a credit limit and pay a (default) risk premium atop the risk-free rate. If a small shock to an asset's

[1] A repurchase agreement or "repo" is essentially a collateralized loan based on a simultaneous sale and forward agreement to repurchase securities at the maturity date. Throughout this paper, we use the terms secured funding, collateralized funding, and repo interchangeably.

fundamental value leads to a large, discontinuous drop in the market price, money markets are fragile and there is common illiquidity across secured and unsecured funding as well as security markets.

Our model uncovers two novel mechanisms underlying the fragility of money markets. First, in addition to funding problems in the secured market (Gromb and Vayanos, 2002; Brunnermeier and Pedersen, 2009), we identify a new liquidity spiral, namely, a *credit limit* spiral in the unsecured market. A shock increases borrowers' default risk, which induces lenders to reduce credit limits and provide less unsecured funding. Lower credit limits in the unsecured market lead to further downward pressure on prices, higher default risk, and further credit rationing, thus triggering a credit limit spiral, which reinforces the margin and loss spirals in the secured market (Brunnermeier and Pedersen, 2009). In fact, the availability of unsecured funding in addition to secured funding allows borrowers to further increase their asset holdings and thus worsens the loss spiral, i.e., the eroding effect on capital following an asset price shock.

We show that unsecured spirals and secured spirals mutually reinforce each other, inducing commonality in funding illiquidity across money markets. These mechanisms and interrelations in our model are summarized in Figure 1, which shows the credit limit spiral in the unsecured money market, the margin spiral in the secured money market, and the combined loss spiral, including feedback effects from both money markets.

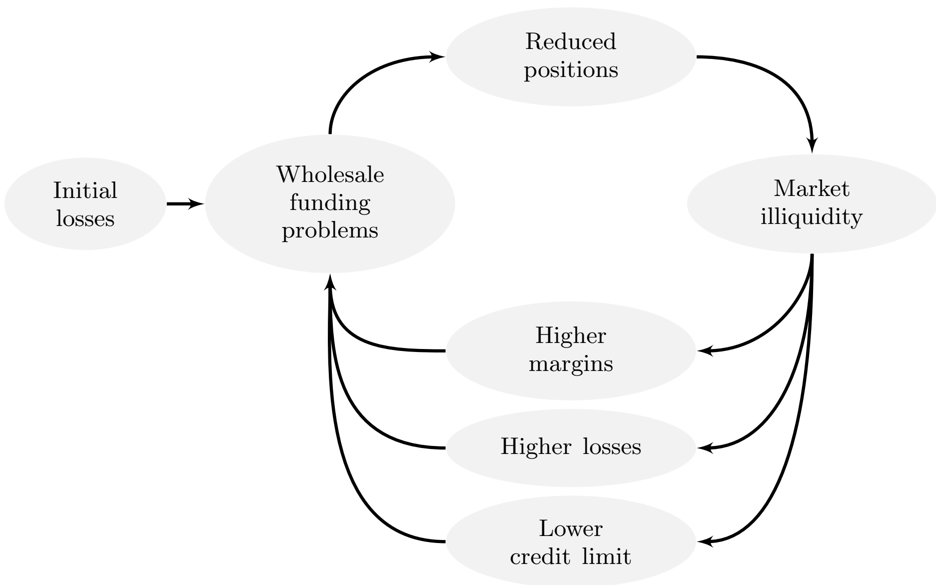

Figure 1: Liquidity Spirals in Money Markets.
The figure shows the credit limit spiral in the unsecured money market (outer circle), the margin spiral in the secured money market (Brunnermeier and Pedersen (2009), inner circle), and the combined loss spiral, including feedback effects from both money markets. Spirals start when initial losses lead to funding problems, i.e., banks' funding constraints are binding in both the unsecured and the secured money market at the same time.

Second, our model brings to light a dual role of margins for money market fragility. On the one hand, an increase in margins further limits the amount a bank can borrow against a collateral asset, thus tightening the funding constraint in the secured market, reducing the availability of secured funding capital, and increasing money market fragility. On the other hand, higher margins relax the funding constraint for unsecured borrowing, ceteris paribus, by reducing the amount of (senior) secured debt in banks' balance sheets, which decreases the probability that a borrower defaults on its unsecured loans. All else equal, this relaxation allows for a substitution of liquidity and implies that the share of unsecured funding increases. This novel theoretical link is consistent with anecdotal evidence that distressed banks increased the share of unsecured borrowing despite reducing total funding, e.g., BNP Paribas in 2008 or Unicredit in 2012.[2]

Substitution also occurs when borrowing in one of the funding markets is unconstrained. In this case, which we call liquid equilibrium, liquidity is not fragile and a loss of funding liquidity in the constrained market can be substituted in the unconstrained market. For instance, if banks have sufficient spare collateral, they can offset a loss of unsecured funding in the secured market. Similarly, markets are not fragile if banks can compensate a loss in secured funding by raising more funds in the unsecured market.

After establishing the market dynamics, we derive the optimal funding provision under the benchmark case when lenders have full information, which is characterized by stabilizing margins in the secured and stabilizing credit limits in the unsecured market. We show that unconventional monetary policies can prevent fragility and restore liquidity, but only when secured and unsecured funding markets are taken into account jointly. For instance, offering refinancing facilities with lower margins ("haircuts") than in the private market eases funding constraints in the secured market, but at the same time lowers the amount that lenders are willing to provide in the unsecured market. Therefore, a joint perspective is crucial as central bank haircuts need to be low enough to compensate for the crowding out of unsecured funding in order to be effective. By contrast, central bank asset purchases affect both funding markets through enhanced market liquidity, which relaxes banks' funding constraints in the secured and unsecured market jointly.

In addition to monetary policy, we examine the effects of the main, recently proposed regulatory measures (e.g., Dodd-Frank Act and Basel III), namely countercyclical capital buffers, leverage ratios, and liquidity coverage ratios. Our model delivers two impor-

[2] In April 2007, as one of the first signs of subprime-related bank distress, BNP Paribas halted redemptions for three investment funds exposed to the U.S. real estate market. From 2007 to 2008, BNP Paribas increased its unsecured borrowing by more than 17%, while reducing secured funding by more than 26%, implying a substantial increase in the share of unsecured funding amidst the subprime crisis. Similarly, UniCredit increased its share of unsecured funding in 2012 despite its substantial exposure to peripheral European economies during the sovereign debt crisis. Empirical studies on unsecured funding show that some banks were able to raise unsecured funding even in distressed periods such as the Lehman crisis (Afonso, Kovner, and Schoar, 2011) and the European sovereign debt crisis (Frutos, Garcia-de Andoain, Heider, and Papsdorf, 2016).

tant results for policy makers and regulators: First, regulation should aim at preventing funding constraints from binding in both the secured and unsecured funding market simultaneously. In fact, as long as financial institutions are able to borrow in one of the two market segments, they can substitute secured and unsecured funding, thereby preventing money market fragility. Second, static measures such as a constant maximum leverage ratio may worsen fragility. In contrast, countercyclical measures can preempt the adverse consequences of excess deleveraging and illiquidity in "bad" times.

Our model is consistent with well-known stylized facts and provides several new testable implications, including (i) commonality in secured and unsecured funding illiquidity, (ii) a marginal increase in margins leads to a marginally higher share of unsecured funding, (iii) higher initial leverage causes a stronger reduction in total asset holdings after a shock, and (iv) central bank liquidity provision counteracts asset fire sales. We perform a simple empirical analysis using bank-level data and the European sovereign debt crisis as an example of an asset/wealth shock. Despite the limited number of observations, the empirical results support the main predictions of our model.

Our paper contributes to the growing body of theoretical literature on funding markets. Only few papers jointly analyze both unsecured and secured funding. Auh and Sundaresan (2015) determine borrowers' optimal liability structure and model the interaction between long-term secured debt and short-term unsecured debt in a corporate finance context. Ahnert, Anand, Gai, and Chapman (2018) highlight asset encumbrance with long-term secured debt, whereas Wolski and van de Leur (2016) study network structures and lenders' asset allocation toward secured and unsecured loans. In the spirit of Goldstein and Pauzner (2005) and Rochet and Vives (2004), Matta and Perotti (2016) model the interaction of repo with demandable debt under asset liquidity risk in a global games approach to bank runs. We contribute to this literature by highlighting how shocks can lead to mutually reinforcing liquidity spirals in both unsecured and secured funding markets.

Most prior research on the interbank market either focuses on unsecured *or* secured funding, sometimes in connection with central bank liquidity. For the unsecured market, various studies highlight reasons for potential market breakdowns, such as liquidity hoarding (e.g., Acharya and Skeie, 2011; Heider, Hoerova, and Holthausen, 2015) or counterparty credit risk (e.g., Stiglitz and Weiss, 1981; Freixas and Jorge, 2008; Bruche and Suarez, 2010). Our model shows that access to secured funding can reduce the frictions and the resulting externalities described in this literature. On the other hand, secured funding strains can reinforce credit limit and loss spirals in the unsecured market and even trigger a market breakdown.

Assuming that banks only have access to secured funding, Gromb and Vayanos (2002) and Brunnermeier and Pedersen (2009) model fire sale mechanisms originating from funding constraints in the secured money market. We show that these fire sales are either magnified or mitigated, depending on whether unsecured funding is constrained and substitution from secured to unsecured funding sufficiently stabilizes the market. Moreover, borrowers' capacity to roll over short-term loans (e.g., Acharya and Viswanathan, 2011; Acharya, Gale, and Yorulmazer, 2011) and the market design (Martin, Skeie, and von Thadden, 2014) affect the fragility of secured funding. To this end, our model sheds light on new dynamics of fragility, that is, secured and unsecured liquidity spirals inducing commonality in funding and asset market illiquidity.

Finally, our model highlights the interrelations between secured and unsecured funding as well as central bank policies. Other papers examine the role of specific central bank measures such as lender of last resort facilities (Acharya and Tuckman, 2014), interest rate cuts (Freixas, Martin, and Skeie, 2011), liquidity injections (Allen, Carletti, and Gale, 2009), or haircut policies (Ashcraft, Gârleanu, and Pedersen, 2011; Koulischer and Struyven, 2014).[3] However, none of these papers proposes a theory encompassing unsecured and secured money markets as well as asset markets to analyze central bank and regulatory policies, as we do in this paper.

The remainder of this paper is structured as follows. Section 2 presents the model setup and the market equilibrium. In Section 3, we derive margins for secured lending and credit limits for unsecured lending. Section 4 analyzes market fragility and liquidity spirals, and highlights the relation between unsecured and secured funding liquidity. In Section 5, we derive the full-information outcome of our model and assess the consequences and efficacy of central bank and regulatory policy for money market liquidity. Section 6 contains a simple empirical exercise. Section 7 concludes.

2. The Model

To model all three major sources of liquidity jointly, we introduce unsecured funding to the model of Brunnermeier and Pedersen (2009), in which assets are funded only in the secured market.

2.1. Assets

There is one asset traded at times $t = 0, 1, 2, 3$, which pays off its fundamental value ν at time 3. The risk-free rate is normalized to zero and the asset is in zero aggregate supply. The fundamental value of the asset accumulates $\kappa > 0$ in each period and evolves

[3] Starting with Poole (1968), a number of papers model banks' central bank reserves management. Recent contributions linking central bank policy and the interbank market include, e.g., Afonso and Lagos (2015) and Bech and Monnet (2016).

according to

$$\nu_{t+1} = \nu_t + \kappa + \sigma_{t+1}\varepsilon_{t+1}, \tag{1}$$

where ε_t has a standard normal cumulative distribution function Φ. Fundamental volatility σ_t follows an autoregressive conditional heteroskedasticity (ARCH) process,

$$\sigma_{t+1} = \underline{\sigma} + \theta|\Delta\nu_t - \kappa|, \tag{2}$$

with $\underline{\sigma}, \theta \geq 0$, implying volatility increases after a shock. We denote the market price of the asset by p_t, and the signed deviation of the price from the fundamental value by

$$\Lambda_t = p_t - \nu_t, \tag{3}$$

representing, e.g., the spread between a bond's price and its par value on the yield curve as in Hu, Pan, and Wang (2013). The absolute amount of this deviation, $|\Lambda_t|$, is our measure of market illiquidity.

2.2. Agents

The economy is populated by three groups of agents. Specifically, *customers* trade assets with other agents called *banks*, who borrow from *lenders* in the secured and unsecured mon

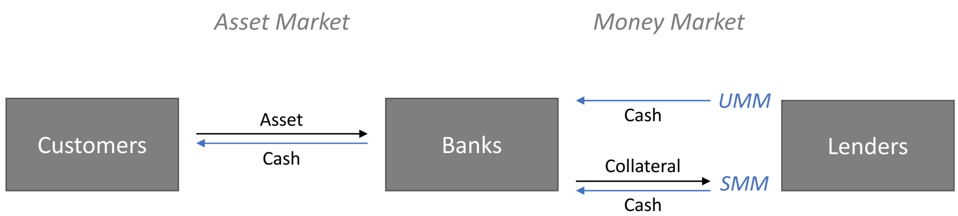

Figure 2: Model Setup.
This figure schematically shows the model setup. Customers trade with banks in the asset market (left-hand side). Banks obtain funding from lenders in the money market (right-hand side). Money market funding can be unsecured (UMM) and secured (SMM).

In the following, we present each group of market participants as well as the trade dynamics between these agents.

Customers. The group of customers is as in Brunnermeier and Pedersen (2009). There are three risk-averse customers $k = 0, 1, 2$ with initial cash holding $W_0^k > 0$ and

[4]The group of customers refers to, e.g., asset managers or hedge funds, banks represent, e.g., large commercials banks or broker-dealers with a liquidity deficit, and lenders are money market funds or (small) commercial banks with a liquidity surplus.

zero shares of the asset. At time 0, customers learn that they will experience an endowment shock of z^k assets at time 3. These shocks represent binding orders that customers must execute in the market until time 3. All shocks are random and aggregate to zero, $\sum_{k=0}^{2} z^k = 0$. With probability $(1-a)$, all customers arrive in the market place at time 0 and trade their endowment shocks with each other. In the complementary case, with probability a, customer $k = 0$ arrives at time 0, customer $k = 1$ at time 1, and customer $k = 2$ at time 2. Thus, at time 2, it holds that $\sum_{k=0}^{2} z^k = 0$, while at times $t = 0, 1$ aggregate supply is non-zero. We focus on the case $z^0 > 0$, $Z_1 > 0$ and $z^2 < 0$, where $Z_t := \sum_{k=0}^{t} z^k$ is the total demand shock. This means that aggregate supply is positive at times 0 and 1, and negative at time 2, which allows us to concentrate on banks' funding structure and asset holdings at times 0 and 1.

After arriving in the market place, customers choose their position y_t^k in each period to maximize their exponential utility function $U(W_3^k) = -\exp(-\gamma W_3^k)$ over final wealth, i.e.,

$$\max_{y_t} -\mathbb{E}_t \left[e^{-\gamma W_3^k} \right], \tag{4}$$

subject to their wealth dynamics

$$W_{t+1}^k = W_t^k + (\Delta p_{t+1} - \kappa)(y_t^k + z^k). \tag{5}$$

Equation (5) states that customers' wealth increases with the asset's (clean) price and asset holdings $y_t^k + z^k > 0$.

Lenders. Lenders are identical, risk-neutral, and deposit their excess funds in the money market as one-period loans. There are two types of money market loans which differ with respect to collateralization. We refer to collateralized loans as *secured* funding and denote the total secured lending volume by M_t^s. Analogously, we refer to uncollateralized loans as *unsecured* funding and denote the total unsecured lending volume by M_t^u.[5]

Lenders monitor a bank's balance sheet as the sum of secured and unsecured money market loans and banks' own capital W_t, hence verifying their asset position $x_t p_t$. We differentiate between the cases of informed and uninformed lenders. If lenders are informed, which will serve as our benchmark scenario in Section 5.1, their information set is $\mathcal{F}_t = \sigma\{z, \nu_0, \ldots, \nu_t, p_0, \ldots, p_t, x_0, \ldots, x_t, \eta_1, \ldots, \eta_t\}$, i.e., lenders know the fundamental value of the asset and thus the true probability of counterparty default.[6] In contrast, if lenders are uninformed they can only observe market prices, such that their information

[5]Alternatively, one could include two groups of lenders that both observe a bank's balance sheet: one group that lends in the secured market and another group that lends in the unsecured market. Results from this alternative setup are the same.

[6]In line with Brunnermeier and Pedersen (2009), we assume that both informed and uninformed lenders know the parameters of the fundamental value process (κ, $\underline{\sigma}$, and θ).

set is given by $\mathcal{F}_t = \sigma\{p_0, \ldots, p_t, x_0, \ldots, x_t\}$. This friction arises from the basic asymmetric information problem in lending markets, where lenders cannot verify the borrower's exact asset risk (e.g., Stiglitz and Weiss, 1981).

Lenders protect against counterparty credit risk by rationing secured and unsecured funding. To that end, the basic problem of an uninformed lender arises from filtering out the extent to which price volatility is due to a fundamental shock or illiquidity, i.e., his prior assumption about the probability of customers' sequential arrival, a. Since we look at money market instruments, which are generally perceived as liquid, we follow Brunnermeier and Pedersen (2009) and let lenders' prior probability of an asynchronous endowment shock be small, i.e., $a \to 0$, so that they find it likely that $p_t = \nu_t$. With this assumption, we can solve lenders' secured and unsecured funding constraints.[7]

For secured funding, lenders protect against collateral risk by setting the margin m_t such that it covers the position's π-value-at-risk (where π is a small number close to zero), i.e.,

$$\pi = \Pr\left(-\Delta p_{t+1} > m_t | \mathcal{F}_t\right). \tag{6}$$

In line with Brunnermeier and Pedersen (2009), we assume that borrowers use funds from other business units to repay lenders when losses exceed margins. This assumption does not affect the results of our model but simplifies equations as the secured interest rate becomes zero. The corresponding secured funding volume satisfies

$$\overline{M}_t^s = \mathrm{VaR}_t^\pi(x_t p_{t+1}). \tag{7}$$

For unsecured funding, lenders acknowledge that secured debt claims enjoy legal seniority over the repayment of unsecured loans in case of a counterparty default. That is, banks must first and fully satisfy secured debt obligations before unsecured creditors receive their funds back (or a residual fraction of them). Hence, unsecured loans bear the risk of severe repayment delay, which is commonly addressed by assigning unsecured loans to defaulted borrowers a zero value in the short run (e.g., Acharya and Skeie, 2011).

We let lenders protect against counterparty default by imposing a credit limit on the amount of unsecured funds banks are able to borrow over one period. In line with common risk management practice in financial institutions and similar in spirit to, e.g., Rochet and Tirole (1996), we model the credit limit by a cap $\overline{M}_t^u$ that is determined by the banks'

[7]If lenders assign a very low probability to aggregate shocks, they assume that market prices are affected by fundamentals rather than illiquidity, and increase margins following a price shock. The case of $a > 0$ is discussed in Brunnermeier and Pedersen (2009) and holds equivalently in our model. That is, lenders need to decide to what extent a change in the price is due to fundamentals or due to order imbalances and illiquidity. In this case, they attribute a price increase or a modest price decline to a change in fundamentals, and behave similarly to the case of $a = 0$. Conversely, for a large price decline lenders actually increase credit limits as the probability of illiquidity is higher, thus anticipating that banks will profit from investing at lower prices.

maximum default probability λ lenders are willing to accept, i.e.,

$$\lambda = \Pr\left(x_t p_{t+1} - M_t^s < \overline{M}_t^u | \mathcal{F}_t\right), \tag{8}$$

so that the corresponding unsecured funding volume satisfies

$$\overline{M}_t^u = \mathrm{VaR}_t^\lambda (x_t p_{t+1} - M_t^s). \tag{9}$$

To compensate for the risk of a short-run loss, lenders demand an interest rate $i_t > 0$, which depends on M_t^u and represents a risk premium over the risk-free rate. Given the lenders' funding constraints, we next consider banks and their optimal investment decision.

Banks. Banks are identical, risk-neutral, and accommodate customers' trading needs by taking long positions x_t in the asset at times 0 and 1, i.e., $x_0, x_1 \geq 0$ (and sell to customer $k = 2$ at time 2). They start out with capital $W_0 > 0$ and fund their asset holdings by raising short-term debt from lenders in the money market. As secured loans are collateralized, they are tied to the asset side as shown in Table 1. Specifically, the secured funding volume on the liability side is the asset price net of the margin, $M_t^s = x_t(p_t - m_t)$, where x_t is the number of assets pledged to the lender. The difference between the asset value tied to secured funding and M_t^s is termed *overcollateralization*, and is equal to the total margin value $x_t m_t$.

Balance sheet

Assets	Liabilities
$x_t(p_t - m_t)$	Secured Debt: M_t^s
$x_t m_t$	Unsecured Debt: M_t^u
	Capital: W_t

Table 1: Banks' Balance Sheet.
The table shows banks' asset holdings and liability structure.

As Table 1 shows, the overcollateralization term is funded with banks' own capital and unsecured loans. Let $\overline{M}_t^u$ denote the maximum amount that banks can borrow in the unsecured market, we can summarize banks' funding constraint as

$$x_t m_t \leq \overline{M}_t^u + W_t. \tag{10}$$

Since unsecured funding is more expensive than secured funding, i.e., $i_t > 0$, banks always lever asset positions in the secured market and only fund the overcollateralization term using unsecured funds. This also implies that banks in our model never willingly hold unencumbered assets.[8] Banks maximize their expected wealth subject to their budget constraint (10), where W_t evolves according to

$$W_{t+1} = W_t + (p_{t+1} - p_t)x_t - i_t M_t^u + \eta_t, \tag{11}$$

and η_t is an independent wealth shock arising from, e.g., other business units. While all banks legally have limited liability, we refer to W_t as working capital in the spirit of a bank's short-term financial wealth, such that if $W_t \leq 0$, banks are bankrupt and must choose $x_t = 0$. In this case, their utility is $\psi_t W_t$, where we let $\psi_t = 1$ capture negative consumption equal to a bank's total loss. In other words, banks fully commit to servicing any of their short-term debt obligations, including unsecured loans, but proceed by first repaying secured loans and, eventually, unsecured loans. Hence, the key bankruptcy assumption is that lenders receive back secured loans immediately, while there might be a significant repayment delay for unsecured loans exposing lenders to a potential loss in the short run.[9] We define competitive equilibria as follows.

Definition 1. *An equilibrium is a price process p_t, such that (i) x_t maximizes banks' expected final wealth subject to the funding constraint* (10)*, (ii) each y_t^k maximizes customer k's expected utility after arriving in the asset market and is zero beforehand, (iii) margins are set according to* (6)*, (iv) the credit limit is set according to* (8)*, and (v) asset and money markets clear simultaneously, $x_t + \sum_{k=0}^{2} y_t^k = 0$.*

In the next section, we analyze the equilibrium outcome of the economy.

2.3. Equilibrium

The equilibrium strategies are solved backwards using dynamic programming. Let Γ be a customer's value function and J the value function of a bank. At time 2, customer k maximizes

$$\Gamma_2(W_2^k, p_2, \nu_2) = \max_{y_2^k} \; - e^{-\gamma\left(\mathbb{E}_2\left[W_3^k\right] - \frac{\gamma}{2}\mathrm{Var}_2\left[W_3^k\right]\right)}. \tag{12}$$

Knowing that the asset pays off at time 3, the solution to this problem is

$$y_2^k = \frac{\nu_2 - p_2}{\gamma(\sigma_3)^2} - z^k. \tag{13}$$

[8] In Section 5.3.3 we discuss regulatory requirements to hold unencumbered assets.

[9] This allows us to focus on short-term funding and curbs banks' risk-taking incentives usually associated with a firm's limited liability (see Brunnermeier and Pedersen (2009) on other bankruptcy assumptions which lead to qualitatively the same results).

Since all customers are in the market at time 2, aggregate demand is zero and $p_2 = \nu_2$. Thus, we get $\Gamma_2(W_2^k, p_2 = \nu_2, \nu_2) = -e^{-\gamma W_2^k}$ and $J_2(W_2, p_2 = \nu_2, \nu_2) = W_2$. This result holds in every period $t = 0, 1, 2$ if all customers arrive in the market at time 0. We focus on the case of customers' sequential arrival, when customers $k = 0$ and $k = 1$ are in the market at time 1 with demand

$$y_1^k = \frac{\nu_1 - p_1}{\gamma(\sigma_2)^2} - z^k, \tag{14}$$

and value function

$$\Gamma_1(W_1^k, p_1, \nu_1) = -e^{-\gamma\left[W_1^k + \frac{(\nu_1 - p_1)^2}{2\gamma(\sigma_2)^2}\right]}. \tag{15}$$

At time 1, it is optimal for banks to invest up to their funding constraint (10) as long as expected profits are larger than costs, i.e.,

$$x_1(\nu_1 - p_1 + \kappa) > i_1 M_1^u, \tag{16}$$

and are indifferent among all possible positions x_1 if Equation (16) is zero. For a liquid equilibrium to exist, we assume that $x_1\kappa \geq i_1 M_1^u$, i.e., non-negative carry.[10]. The shadow cost of capital, denoted by ϕ_1, is 1 plus the net return on capital as long as banks are not bankrupt, i.e.,

$$\phi_1 = 1 + \frac{x_1(\nu_1 - p_1 + \kappa) - i_1 M_1^u}{W_1}. \tag{17}$$

If a bank is bankrupt and $W_1 < 0$, then $\phi_1 = \psi_1$, so that the value function at time 1 is given by $J_1(W_1, p_1, \nu_1, p_0, \nu_0) = W_1\phi_1$.

At time 0, only customer $k = 0$ is in the market and maximizes $\mathbb{E}_0\left[\Gamma_1(W_1^k, p_1, \nu_1)\right]$, while banks maximize their expected wealth, $\mathbb{E}_0[W_1\phi_1]$, subject to the funding constraint (10).

3. Margins and Credit Limits (Time 1)

To determine banks' secured and unsecured funding, we derive lenders' margin requirement and credit limit, respectively. In this section, we show that when lenders are uninformed, margins are an increasing function and credit limits a decreasing function of asset volatility and market illiquidity.

Margins are set according to the asset's π-value-at-risk in Equation (6). Uninformed

[10] Negative carry is the holding cost associated with a long position and prevents investors from trading against a mispricing (e.g., Dow and Gorton, 1994; Gromb and Vayanos, 2010). The resulting wedge between price and fundamental value would thus account for costs rather than illiquidity.

lenders believe that prices change due to a change in the fundamental value, such that

$$\pi = 1 - \Phi\left(\frac{m_1 + \kappa}{\sigma_2}\right). \tag{18}$$

Solving for m_1, we find that margins are increasing in price volatility and market illiquidity, which we summarize in Lemma 1.

Lemma 1. *Margins are an increasing function of price volatility and market illiquidity, and are given by*

$$\begin{aligned} m_1 &= \overline{\sigma} + \overline{\theta}|\Delta p_1 - \kappa| - \kappa, & (19)\\ &= \overline{\sigma} + \overline{\theta}|\Delta \nu_1 + \Delta\Lambda_1 - \kappa| - \kappa, & (20) \end{aligned}$$

where

$$\begin{aligned} \overline{\sigma} &= \underline{\sigma}\Phi^{-1}(1-\pi), & (21)\\ \overline{\theta} &= \theta\Phi^{-1}(1-\pi). & (22) \end{aligned}$$

Higher price volatility arising from a fundamental shock and/or market illiquidity increases margins because $\theta > 0$. Higher margins imply that lenders require banks to have more "skin in the game", i.e., fund more of the asset's value with own capital or other funds. In relative terms, margins are equivalent to a "haircut" h_1 of the asset price, $h_1 = m_1/p_1$. As shown in Table 1, the debt value of each asset is the market price less the margin, such that the total secured funding volume amounts to $M_1^s = x_1(p_1 - m_1)$.

For unsecured loans, lenders set banks' default probability λ and estimate the credit limit by Equation (8) as

$$\lambda = \Pr\left(-\Delta p_2 > \frac{W_1}{x_1}|\mathcal{F}_1\right), \tag{23}$$

i.e., banks default if $W_1 \leq 0$. Analogous to the computation of margins, this translates to

$$\lambda = 1 - \Phi\left(\frac{\frac{W_1}{x_1} + \kappa}{\sigma_2}\right), \tag{24}$$

which we can solve as

$$\overline{M}_1^u = W_1\left(\frac{p_1}{\overline{\overline{\sigma}} + \overline{\overline{\theta}}|\Delta p_1 - \kappa| - \kappa} - 1\right) - M_1^s, \tag{25}$$

where

$$\begin{aligned} \overline{\overline{\sigma}} &= \underline{\sigma}\Phi^{-1}(1-\lambda), & (26)\\ \overline{\overline{\theta}} &= \theta\Phi^{-1}(1-\lambda). & (27) \end{aligned}$$

Equation (25) relates unsecured funding $\overline{M}_1^u$ to a bank's (short-term) leverage by a term $p_1/(\overline{\overline{\sigma}} + \overline{\overline{\theta}}|\Delta p_1 - \kappa| - \kappa)$. As price volatility increases, lenders cut back on money market loans, thus inducing procyclicality in bank leverage and amplifying funding constraints (Shin, 2009). In fact, procyclicality in funding constraints has been identified as one of the major causes of fragility in the recent financial crisis and is now addressed in the latest Basel III capital requirements. To capture this effect, we let $b_1 \equiv \overline{\overline{\sigma}} + \overline{\overline{\theta}}|\Delta p_1| - \kappa$ denote the minimum capital *buffer* (per unit of an asset) that lenders require banks to hold relative to their short-term liabilities. We can further simplify Equation (25) by substituting $M_1^s = (p_1 - m_1)\frac{W_1 + \overline{M}_1^u}{m_1}$, and arrive at a lender's basic lending decision in the money market.

Proposition 1. *Credit limits for unsecured borrowing are decreasing in price volatility and market illiquidity. For $\lambda > \pi$, we have $m_t > b_t$, and lenders are willing to provide unsecured funding up to the constraint, which is equal to:*

$$\overline{M}_1^u = W_t \left(\frac{\overline{\sigma} + \overline{\theta}|\Delta p_1 - \kappa| - \kappa}{\overline{\overline{\sigma}} + \overline{\overline{\theta}}|\Delta p_1 - \kappa| - \kappa} - 1 \right), \tag{28}$$

$$= W_1 \left(\frac{m_1}{b_1} - 1 \right). \tag{29}$$

Lenders demand a premium for the risk of short-term repayment delay, which is priced such that

$$0 = (1 - \lambda) i_1 \overline{M}_1^u + \lambda(-\overline{M}_1^u), \tag{30}$$

solving the interest rate for unsecured loans as

$$i_1 = \frac{\lambda}{1 - \lambda}. \tag{31}$$

For $\lambda \leq \pi$, lenders only provide secured funding and $\overline{M}_1^u = 0$.

The intuition of Proposition 1 is that unsecured lending describes a trade off between earning a higher premium and bearing the risk of repayment default. Proposition 1 also states that the unsecured market is entirely closed when $\lambda \leq \pi$, in which case our model collapses to that of Brunnermeier and Pedersen (2009). Given that banks are largely financed using unsecured funds, in particular before the 2008 financial crisis, we are interested in the case of $\lambda > \pi$. In the next section, we show that banks' exposure to unsecured funding has important implications for the fragility of liquidity, and so from now on we assume that $\lambda > \pi$.

4. Fragility of Liquidity

In this section, we show that liquidity is fragile and liquidity spirals can arise jointly in secured and unsecured funding markets. To that end, we first analyze the impact of illiquidity on banks' funding structure at time 1, and then characterize the role of liquidity risk at time 0.

4.1. Fragility and Liquidity Spirals (Time 1)

Following Brunnermeier and Pedersen (2009), liquidity is fragile when a small shock can lead to a large drop in the equilibrium price. In a stable liquid equilibrium, a small price drop leads to excess demand and prices immediately bounce back to the fundamental value. When markets are fragile, a small price drop can lead to an illiquid equilibrium in which prices are much lower. Consequently, fragility arises when the demand curve is not monotonically decreasing in the price.

If either the secured or unsecured market is unconstrained, markets are not fragile and the asset market remains liquid. For instance, assume that banks fund assets in the secured market until all their capital is deployed, but borrowing constraints in the unsecured market are still slack. In this scenario, an asset shock (e.g., to the fundamental value) increases margins, but the borrower would absorb the reduction in secured funding by raising funds in the unsecured market. Similarly, substitution from unsecured to secured funding occurs if the unsecured credit limit is reached but own capital is abundant. As a result, no fire sales occur and the market price remains equal to the fundamental value, i.e., $p_1 = \nu_1$. Only when borrowers are constrained in both funding markets simultaneously, markets become fragile and equilibrium prices are subject to market illiquidity. Lemma 2 defines fragile liquidity if banks borrow in both the secured and unsecured market.

Lemma 2. *The market is fragile at time 1 if at least one of the following conditions holds:*

1. *Banks' position x_0 is larger than $\underline{x}$.*
2. *$\overline{\overline{\theta}} = \theta\Phi^{-1}(1-\lambda)$ is larger than $\underline{\theta}$ and the probability, a, of sequential arrival of customers is smaller than $\underline{a}$.*

The first condition in Lemma 2 states that the slope of banks' demand curve can become positive if losses on existing positions are sufficiently large. Condition (ii) differs from Brunnermeier and Pedersen (2009) as it depends on the default probability that lenders are willing to accept for *unsecured* loans. Given that $\lambda \geq \pi$ and thus $\overline{\overline{\theta}} \leq \overline{\theta}$, fragility is less likely to arise because lenders are willing to provide unsecured funding at higher default probabilities.

When funding constraints are binding, we find three distinct liquidity spirals that interact with each other and mutually deteriorate market and funding liquidity. The first spiral is a *loss* spiral that erodes banks' capital through losses on existing positions. The second liquidity spiral is a *margin* spiral that leads to higher margin requirements as prices decrease. And third, a *credit limit* spiral emerges in the unsecured market as tighter credit lines reduce available funding capital in response to increasing counterparty default risk. To fully understand the dynamics after a shock to banks' wealth, Proposition 2 summarizes these liquidity spirals.

Proposition 2. *In a stable illiquid equilibrium with selling pressure from customers, $Z_1 > 0$, and banks' position $x_0 > 0$,*

1. *the price sensitivity to a shock $\eta_1 < 0$ is given by:*

$$\frac{\partial p_1}{\partial \eta_1} = \frac{1}{m_1 \frac{2}{\gamma(\sigma_2)^2} + \frac{\partial m_1}{\partial p_1} x_1 - x_0 - \frac{\partial \overline{M}_1^u}{\partial p_1}}. \tag{32}$$

2. *Credit limit spirals arise when $\frac{\partial \overline{M}_1^u}{\partial p_1} > 0$, which happens with positive probability when lenders are uninformed and a is small enough.*
3. *Credit limit spirals amplify the margin spiral, $\frac{\partial m_1}{\partial p_1} < 0$, and loss spiral arising from previous positions $x_0 > 0$.*

Equation (32) can be written as an infinite series to visualize the spiral dynamics, with each term corresponding to one loop in the spiral. For any $k > 0$ and l such that $|l| < k$, it holds that $\frac{1}{k-l} = \frac{1}{k} + \frac{l}{k^2} + \frac{l^2}{k^3} + \ldots$, where $k = m_1 \frac{2}{\gamma(\sigma_2)^2} > 0$ and $l = \frac{\partial m_1}{\partial p_1} x_1 - x_0 - \frac{\partial \overline{M}_1^u}{\partial p_1}$. Intuitively, spirals initiate from a wealth shock that decreases the price by an amount k. The system is fragile because prices drop further due to the three liquidity spirals: lower prices exert losses on existing positions x_0, which deteriorate banks' mark-to-market capital, increase margins because $\frac{\partial m_1}{\partial p_1} < 0$, and decrease the credit limit in the unsecured market as $\frac{\partial \overline{M}_1^u}{\partial p_1} > 0$. The last two effects capture money market fragility, which, together with the loss spiral, are mutually reinforcing with an asset's market illiquidity.

Proposition 2 shows that the price sensitivity to a wealth shock is larger when banks borrow both secured *and* unsecured as compared to borrowing only in the secured market. This is because access to unsecured funds allows banks to further lever their capital by increasing their asset holdings, which amplifies the mutual downward pressure on the market price, such that loss, credit limit, and margin spirals keep reinforcing each other until the illiquid equilibrium is reached.

Fragility and liquidity spirals not only arise following a shock to banks' wealth, but also when there is a shock to fundamentals $\Delta\nu_1$, a shock to volatility, or a shock to customer demand Z_1. In these cases, the price sensitivities are multiples of $\frac{\partial p_1}{\partial \eta_1}$ and liquidity spirals amplify the initial price shock as shown above. Using convexity arguments, it can be shown mathematically that the total price decline of any such shock is larger than the sum of the individual effects.

4.2. Commonality and Substitution of Funding Liquidity (Time 1)

Overall, Proposition 2 shows that secured, unsecured, and asset markets are interconnected and can become illiquid at the same time. While the margin spiral increases the need for additional capital, the loss and credit limit spirals reduce banks' (funding) capital for financing higher margins. These adverse feedback loops continue until funding demand and supply equate to an (illiquid) equilibrium. We further examine the equilibrium funding volumes in Proposition 3.

Proposition 3. *In a stable illiquid equilibrium with $Z_1 > 0$, $x_0 > 0$, and $\Delta p_1 < 0$,*

1. *liquidity spirals reduce secured funding as*

$$\frac{\partial M_1^s}{\partial p_1} = x_1 \left(1 - \frac{\partial m_1}{\partial p_1}\right) + \frac{p_1 - m_1}{b_1} \left(\frac{\partial W_1}{\partial p_1} - x_1 \frac{\partial b_1}{\partial p_1} \frac{m_1}{b_1}\right) > 0, \tag{33}$$

2. *and unsecured funding because*

$$\frac{\partial \overline{M}_1^u}{\partial p_1} = \frac{\partial W_1}{\partial p_1} \left(\frac{m_1}{b_1} - 1\right) + x_1 \left(\frac{\partial m_1}{\partial p_1} - \frac{m_1}{b_1} \frac{\partial b_1}{\partial p_1}\right) > 0. \tag{34}$$

3. *Since $\frac{\partial m_1}{\partial p_1} < 0$, the margin spiral represents a marginal substitution effect from secured to unsecured funding, and total money market funding MM_1 decreases by*

$$\frac{\partial MM_1}{\partial p_1} = \frac{p_1 - b_1}{b_1} \left(\frac{\partial W_1}{\partial p_1} - x_1 \frac{\partial b_1}{\partial p_1}\right) > 0. \tag{35}$$

Ultimately, money market funding depends on the loss spiral, $\frac{\partial W_1}{\partial p_1} = x_0$, and the credit limit spiral given by $\frac{\partial b_1}{\partial p_1} = -\overline{\overline{\theta}}$.

Proposition 3 shows that funding liquidity deteriorates jointly, resulting in less secured and unsecured funding and thus in a decline of total money market volume. Part (i) of Proposition 3 shows that all three liquidity spirals lead to a reduction in secured funding M_1^s, whereas part (ii) shows that unsecured funding M_1^u declines because the loss spiral as well as the increase in the buffer b_1 dominate the margin spiral. The latter effect represents substitution from secured to unsecured funding as higher margins reduce secured funding and, ceteris paribus, increase unsecured funding by the same magnitude. As a consequence, the decline in total money market volume in part (iii) depends no longer on the margin spiral, but occurs because of the loss and credit limit spirals (the latter represented by $\frac{\partial b_1}{\partial p_1}$). This result is intuitive as banks can fund higher margins using their own capital *and* unsecured funds, such that the availability of unsecured funding (assuming capital is constant in the short run) becomes a crucial component contributing to the fragility of short-term funding. This finding differs significantly from Brunnermeier and Pedersen (2009), for whom the margin spiral is indeed the major source of fragility given that arbitrageurs (e.g., hedge funds and other investment firms) typically have no access to unsecured funding. We reaffirm this result for secured funding (part (i)), but find that with access to unsecured funds, i.e., $\lambda > \pi$, the extent of fragility is determined by the loss spiral and credit limit spiral, that is, the ease with which banks can obtain funding in the unsecured money market.

Proposition 3 provides an important insight into the relation between secured and unsecured money markets by unveiling the contagion and substitution channels among different sources of short-term funding. Before discussing the implications for monetary and regulatory policies, we turn to time 0 and analyze the impact of time-1 liquidity risk on banks' funding structure.

4.3. Liquidity Risk (Time 0)

In this section, we show that the risk of higher margins and lower credit limits matters already at time 0 even when funding constraints are not binding.

In Section 2.2, we discussed that the assumption of $\psi = 1$ implies that banks can have negative wealth, which relates W_1 in our model to banks' short-term wealth rather than overall equity. This assumption curbs banks' risk-taking as they choose not to trade to their constraints already at time 0 due to the disutility from becoming bankrupt at time 1.[11] Thus, banks choose position x_0 by maximizing their expected profits $\mathbb{E}_0[\phi_1(W_0 + x_0(p_1 - p_0) - i_0 M_0^u)]$. Solving for x_0 gives the time-0 price p_0 as summarized in Proposition 4.

Proposition 4. *At time 0, the asset price is given by*

$$p_0 = \mathbb{E}_0[p_1] + \frac{Cov_0(\phi_1, p_1)}{\mathbb{E}_0[\phi_1]} - m_0 i_0 - M_0^u \frac{\partial i_0}{\partial x_0}, \tag{36}$$

which decreases with negative covariance $Cov_0(\phi_1, p_1)$, more unsecured funding M_0^u, higher margin m_0, and higher funding cost i_0.

Equation (36) states that the price at time 0 is the expected time-1 price, adjusted for by several liquidity risk terms. That is, a negative covariance term captures liquidity risk as the asset payoff is lower when illiquidity, denoted by ϕ_1, is higher. Moreover,

[11] When banks invest to their constraints already at time 0, the analysis is similar to time 1. Details are provided in the appendix.

higher margins, more unsecured funding and higher interest rates capture the notion of liquidity risk as banks face an increase in funding costs on the entire amount borrowed in the unsecured market once the credit limit becomes binding at time 1.

5. Monetary and Regulatory Policy Implications

We return to the analysis of fragility at time 1 and contrast our results against the benchmark case in which lenders are informed and know the fundamental value of the asset. With these results, we assess several monetary and regulatory policy measures with respect to their effectiveness in reducing or preventing fragility.

5.1. Benchmark Case

An informed lender has information set $\mathcal{F}_t = \sigma\{z, \nu_0, \ldots, \nu_t, p_0, \ldots, p_t, x_0, \ldots, x_t, \eta_1, \ldots, \eta_t\}$ and thus knows the fundamental values and that $p_2 = \nu_2$ in the next period. Proposition 5 describes the optimal unsecured credit limit and margins set by informed lenders.

Proposition 5. *When lenders are informed and know the fundamental value of the asset and that $p_2 = \nu_2$ at time 2, the capital buffer b_1^* and margin m_1^* are set according to*

$$b_1^* = \overline{\overline{\sigma}} + \overline{\overline{\theta}}|\Delta\nu_1 - \kappa| - \kappa + \Lambda_1, \tag{37}$$

$$m_1^* = \overline{\sigma} + \overline{\theta}|\Delta\nu_1 - \kappa| - \kappa + \Lambda_1, \tag{38}$$

such that the total funding volume is characterized by

$$\frac{\partial MM_1^*}{\partial p_1} = (x_0 - x_1)\left(\frac{p_1 - b_1^*}{b_1^*}\right). \tag{39}$$

Thus, the more the price decreases below the fundamental value, i.e., $\Lambda_1 < 0$, the more informed lenders increase the credit limit for unsecured funding and decrease margins for secured funding.

Proposition (5) shows that informed lenders provide stabilizing funding conditions by decreasing margins and increasing credit limits during times of illiquidity. Lenders do so because they know banks will profit when the price returns to the fundamental value at time 2. The difference to Brunnermeier and Pedersen (2009) is that lenders also relax the credit limit knowing that $p_2 = \nu_2$, allowing them to earn more interest on the total unsecured volume lent to banks. Given our previous results that the margin spiral only redistributes funding between the secured and unsecured market (Proposition 3), the optimal funding volume in Equation (39) under full information becomes a function of the optimal capital buffer b_1^*.

In the following, we analyze several central bank and regulatory policies with regard to their effectiveness in stabilizing funding conditions and preventing fragility as shown in Proposition 5.

5.2. Central Bank Monetary Policy

In the recent crises, many central banks conducted unconventional monetary policies in addition to conventional interest rate policy to ease funding strains and price pressure on banks' asset holdings. For example, the Federal Reserve (FED) and European Central Bank (ECB) openly intervened in secondary markets through outright security purchases to provide market liquidity and allow banks to divest illiquid assets. In addition, most central banks created lending facilities for assets that have become highly capital-intense or ineligible as collateral for secured funding in the private market.[12]

In our model, haircut policy can be shown by central banks offering margins m_1^{cb} that are characterized by $m_1^{cb} < m_1$. Unlike informed lenders, central banks have no superior knowledge of an asset's fundamental value and so we analyze haircut policy by margins that are lower than in the private market. Furthermore, we model a central bank's asset purchases by introducing additional demand x_1^{cb} to the market clearing condition, which ultimately reduces customers' supply of assets to $-y_1 - x_1^{cb}$. Proposition 6 provides the main implications of central banks' unconventional policies for fragility.

Proposition 6. *Central bank unconventional policies have the following effects on fragility:*

1. *For any $b_1^* < m_1^{cb} < m_1$, haircut policy stabilizes secured funding but crowds out unsecured funding and fragility remains the same. Haircut policy can only stabilize funding if margins are set such that $m_1^{cb} = b_1^*$, which ultimately leads to banks only borrowing from the central bank.*

2. *For any $x_1^{cb} > 0$, asset purchases reduce fragility by accommodating customers' demand shocks and mitigating liquidity spirals.*

Part (i) of Proposition 6 states that central banks' haircut policy relaxes banks' funding constraints by increasing the amount banks can borrow against pledging their assets as collateral. However, such margins equally reduce the substitution effect, which destabilizes unsecured funding and leads to the same level of fragility as without intervention. The consequence of lower central bank margins is that unsecured funding is crowded out, and only the share of M_1^s on total money market funding increases. As shown by Equation (39),

[12]Some examples of unconventional measures involving haircut policies include the ECB's extension of eligible (riskier) assets for its repo loans in March 2009 and January 2011, or the FED's Term Auction Facility (TAF), Primary Dealer Credit Facility (PDCF), Term Securities Lending Facility (TSLF), and Term Asset-Backed Securities Loan Facility (TALF).

fragility is prevented only if margins are set low enough to accommodate the crowding out effect on unsecured funding, i.e., $m_1^{cb} = b_1^*$, implying that banks fund their entire asset position with the central bank.

By contrast, asset purchases of the central bank always reduce fragility by counteracting customers' excess supply in the market, thereby alleviating funding constraints in both the secured and unsecured market simultaneously and enhancing assets' market liquidity. Clearly, an asset purchase program large enough to absorb the entire excess supply from the market can prevent fragility and eliminate liquidity spirals.

5.3. Regulatory Policy

In the previous section, we have shown that central bank interventions can improve banks' funding conditions during market turmoils. However, such policy measures are not only implemented when funding constraints are already binding, but their scale and efficacy are impossible to determine without central banks possessing full information. This is why it is important to understand whether the current regulatory environment can preserve slack constraints a priori and reduce the possibility of fragility.

We discuss three important policy measures, namely maximum leverage ratio, capital buffer, and liquidity coverage ratio in the context of our model. These measures are part of the Basel III and Dodd-Frank regulatory frameworks and strive to improve banks' resilience to sudden changes in asset values.

5.3.1. Leverage Ratio

Excessive leverage has been one of the key triggers of the recent crises, which led regulators to impose a definite cap on bank leverage. Intuitively, a maximum leverage ratio is only effective when preventing banks from levering all the way up to their constraints. An important outcome from our model is that (funding) liquidity follows procyclical patterns. This implies that a dynamic rather than static leverage ratio is more effective in preserving slack constraints. Leverage is time-varying and depends on liquidity, meaning that when haircuts are low, banks can lever their balance sheet up to an extent where already a small shock can lead to liquidity spirals and cause fragility. A countercyclical leverage ratio can enhance financial stability by limiting leverage in economically good times, so that banks can rely on slack funding constraints in economically bad times. Moreover, banks unexposed to distressed assets are potential providers of market liquidity in times of stress, and may be inhibited from buying assets if constrained by a static leverage ratio. Thus, our model suggests that a dynamic maximum leverage ratio, which takes into account financial cycles would be preferable over a static cap on bank leverage.

5.3.2. Capital Buffers

According to the current regulatory framework, banks are required to hold capital as a percentage of their risk-weighted assets, plus an additional countercyclical capital buffer in good times (if required by national regulators). Such a buffer must be held as additional core capital, which banks can utilize when, e.g., the budget constraint (10) becomes binding. Given that the capital buffer must be held in cash, it adds to a bank's funding capital and can (at least partially) offset an initial shock without banks having to, e.g., (fire-) sell assets.

5.3.3. Liquidity Coverage Ratio

New regulations also comprise a liquidity coverage ratio (LCR), which requires banks to hold high-quality liquid assets (as a fraction of short-term expected liabilities) to better cope with sudden liquidity needs. These assets must be unencumbered and readily convertible into cash, so that in case of an asset shock, these securities can be sold or pledged to obtain funding. Consequently, the capital raised through selling or pledging liquid securities alleviates a bank's funding constraint and compensates for a sudden reduction in short-term liabilities. Yet, a limitation of the LCR is that high-quality liquid assets are defined based on policy makers' pre-established scenario parameters, which may fail to fully reflect the actual funding and market liquidity risks.

6. Empirical Application

As a final step, we perform a simple empirical exercise to assess the main mechanisms of our model. To that end, we take the European sovereign debt crisis as a real-world example of an asset shock, representing significant losses in value to government bonds of Greece, Ireland, Italy, Portugal, and Spain (GIIPS). We analyze changes in banks' funding structure following the shock and highlight the role of margins.

6.1. Data

A complete empirical analysis of our theoretical results would require bank-specific data on assets and liabilities, money market and central bank borrowing volumes, margins, and interest rates. These data are not publicly available, unfortunately. Instead, we combine data from the richest sources available to construct proxies for the various quantities of interest.

First, we use European government bond holdings from stress test data published regularly by the European Banking Association (EBA) since March 2010. From this list, we take all banks that participated in the stress tests for March and December 2010 as well as December 2011. We denote total bond holdings of bank j in year t by $B_{j,t}$.[13] Second, for these banks we collect yearly balance sheet data on money market funding volumes, including secured and unsecured borrowing and lending for 2009 through 2011. We compute each bank's yearly secured (unsecured) *net* borrowing volume as the difference between the secured (unsecured) borrowing and lending volumes. To comply with our theoretical analysis, we consider net borrowers in the money market, for which the sum of secured and unsecured net borrowing is positive.[14] For each bank, we compute the share of unsecured funding, denoted by $S_{j,t}$, as the ratio of unsecured net borrowing over total money market net borrowing. Additionally, we compute a bank's leverage ratio, $L_{j,09}$, as total assets over equity in 2009. Third, we construct a proxy for the average margin of a bank's bond portfolio. We obtain margin span parameters published by LCH.Clearnet, a major clearing house and provider of risk and collateral management services, as a measure of country-specific margins for a range of government bonds .[15] We construct bank-specific margins by the average of margin parameters weighted by each bank's exposure to each country from the EBA stress test data. That is, we multiply each margin with a bank's position in that bond and divide by the total position of that portfolio. We denote the weighted average margin by $m_{j,t}$. Lastly, we obtain data on central bank borrowing from Bruegel, which include a breakdown of Eurosystem liquidity across national European central banks.[16] As a proxy for bank-specific central bank exposure we use the share of their GIIPS holdings relative to all their national peers' GIIPS holdings, taking the full list of banks participating in the stress tests.[17] To measure the reliance on central bank funding, we divide each bank's borrowing volume from the central bank by the bank's total assets. We denote this variable by $CB_{j,t}$. Merging the different data sources results in a total sample of 26 banks. We provide the list of banks and variables that are included in our sample in the Internet Appendix.

[13]We use the March 2010 EBA stress test bond holdings for end-of-year 2009 as stress tests were first conducted in March 2010.

[14]Banks borrow and lend in the money market at the same time, such that the difference between borrowing and lending volumes identifies the "net funding demand" for each bank and market. If net funding demand is positive, a bank is a net borrower, and if negative, it is a net lender. Thus, we investigate net borrowers as those banks tap the money market in need for funding and therefore correspond to the borrowers in our model.

[15]For instance, in March 2010 the spread on German government bonds was 1.49% and on Greek bonds 7.99%, whereas in October 2010 the respective spreads were 1.27% and 17.75%. In 2011, Greek government bonds were ineligible as collateral and thus receive a spread of 100% to compare for changes in margin parameters.

[16]Countries not considered by Bruegel include non-Euro countries such as the U.K. and Sweden for which we collect data manually from the respective national central banks and convert them into Euro. The Dutch central bank does not publish the necessary information, so no data are available for the Netherlands.

[17]For example, BNP Paribas' share of France's central bank funding volume reported by Bruegel is computed as the ratio of its GIIPS exposure relative to all French banks' GIIPS exposure provided by the EBA.

6.2. Regression Analysis

To empirically test the main mechanisms of our model, we perform cross-sectional least squares regressions for changes in variables between two time periods, namely 2009 to 2010 and 2009 to 2011. We use 2009 as the reference date prior to the European sovereign debt crisis and 2010/2011 as time of stress in GIIPS bonds.[18] First, we investigate the relation between margins and the share of unsecured funding. According to the model, we expect a positive relation, as higher margins lead to a substitution from secured to unsecured funding, and thus an increase in $S_{j,t}$. We control for banks' reliance on central bank funding by including the change in $CB_{j,t}$ from 2009 to 2010. In sum, we estimate the following regression:

$$\Delta S_{j,10} = \beta_0 + \beta_1 \Delta m_{j,10} + \beta_2 \Delta CB_{j,10} + \epsilon_j. \tag{40}$$

Second we investigate the relation between banks' deleveraging from 2009 to 2010 and their pre-crisis leverage as well as the change in their reliance on central bank funding. According to our model, banks with higher initial leverage should be affected more by the shock and thus have to deleverage more and rely more on central bank funding. We estimate the following regression model:

$$\Delta B_{j,10} = \beta_0 + \beta_1 \Delta CB_{j,10} + \beta_2 L_{j,09} + \epsilon_j. \tag{41}$$

Table 2 shows the regression results. Despite the limited number of observations and the simplicity of the empirical exercise, the results support the predictions of our theoretical model.

An increase of margins and a decrease of reliance on central bank liquidity is associated with an increase in the share of unsecured borrowing. Moreover, higher leverage in 2009 is associated with larger deleveraging.

7. Conclusion

This paper provides a comprehensive theoretical model for money markets. It offers a unified framework to analyze the relation between secured and unsecured funding liquidity, and the interaction with assets' market liquidity. Our model shows that markets can be fragile and adverse liquidity spirals can arise when banks face funding problems in both the secured and unsecured money market at the same time. In such a scenario, credit limit and loss spirals in the unsecured market are mutually reinforcing with liquidity spirals in the secured market, thereby jointly exerting downward pressure on asset prices

[18]For the sake of brevity, we report the results for 2009 to 2010 in the paper. The 2009 to 2011 results, which are qualitatively similar, are shown in the Internet Appendix.

Table 2

Regression Results for Funding Shares and Bond Holdings

This table shows the results of regressing changes in banks' funding shares (Columns (1) to (3)) and changes in bond holdings (Columns (4) to (6)) on explanatory variables derived from our model. Standard errors are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	Δ_{09}^{10} Share			Δ_{09}^{10} Bonds		
	(1)	(2)	(3)	(4)	(5)	(6)
Δm	0.081^{**}		0.079^{*}			
	(0.037)		(0.038)			
ΔCB		-0.777	-0.553		145.357^{*}	145.282^{**}
		(1.083)	(1.019)		(76.176)	(63.002)
L_{09}				-1.312^{***}		-1.291^{***}
				(0.386)		(0.363)
$const.$	-0.103	-0.030	-0.101	10.745	-19.909^{***}	9.887
	(0.063)	(0.061)	(0.067)	(9.747)	(4.377)	(9.112)
R^2	0.17	0.02	0.18	0.32	0.13	0.45
# Obs.	26	25	25	26	25	25

and deteriorating banks' capital. In contrast, the possibility to substitute unsecured and secured funding can alleviate funding constraints and stabilize money markets.

We derive the optimal funding structure under full information and analyze central bank and regulatory policy. We show that unconventional monetary policies can prevent fragility and restore liquidity, but only when secured and unsecured funding markets are taken into account jointly. That is, haircut policy is effective only if margins are reduced sufficiently to compensate for the crowding out of unsecured funding. In contrast, central bank asset purchases affect both funding markets jointly through enhanced market liquidity and slack funding constraints.

Regarding financial market regulation, our model suggests that regulation should strive for slack funding constraints across banks and time to prevent mutually reinforcing liquidity spirals across funding markets. It also shows that money market funding liquidity follows procyclical patterns, so that a countercyclical maximum leverage ratio and capital buffers enhance banks' resilience to future shocks more adequately than static measures. The recent introduction of the liquidity coverage ratio forces banks to hold unencumbered assets, which can be pledged to obtain secured funding or sold in the market to raise capital during crisis times. An important policy implication from our model is that the most effective regulatory measure is a combination of countercyclical leverage ratio, capital buffers, and unencumbered assets to ease funding strains in times when capital becomes scarce. Jointly, these regulatory measures counteract future fragility and make banks more resilient to adverse market conditions.

Appendix A. Proofs

Proof of Lemma 1. Margins are set according to the asset's π-value-at-risk (where π is a small number close to zero):

$$\pi = Pr\left(-\Delta p_{t+1} > m_t | \mathcal{F}_t\right). \tag{42}$$

Lenders assume price changes are equal to changes in fundamental value, i.e., $\Delta p_t = \Delta \nu_t = \kappa + \sigma_{t+1}\varepsilon_{t+1}$, where $\varepsilon_t \sim \mathbb{N}(0,1)$. Therefore,

$$\pi = 1 - \Phi\left(\frac{m_t + \kappa_t}{\sigma_{t+1}}\right). \tag{43}$$

Solving for m_t completes the proof. □

Proof of Proposition 1. Using similar arguments as in the proof of Lemma 1, the default probability for unsecured loans is

$$\lambda = 1 - \Phi\left(\frac{\frac{W_t}{x_t} + \kappa_t}{\sigma_{t+1}}\right). \tag{44}$$

Banks borrow up to the credit limit and use all capital and unsecured funds to pay margins, such that $x_t = \frac{\overline{M}_t^u + W_t}{m_t}$. Solving for $\overline{M}_t^u$ and substituting the solution for margins from Lemma 1 completes the proof. □

Proof of Lemma 2. In equilibrium, supply equals demand, i.e.,

$$x_1 = -\sum_{k=0}^{k} y_1^k = Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2}. \tag{45}$$

Together with banks' funding constraints, $x_1 \leq \frac{\overline{M}_1^u + W_1}{m_1}$, this yields

$$\overline{M}_1^u + W_1 \geq m_1\left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2}\right). \tag{46}$$

Next, we plug in banks' wealth dynamics $W_1 = W_0 + x_0\Delta p_1 - M_0^u i_0^u + \eta_1$ and define function $G(p_1)$:

$$G(p_1) := m_1\left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2}\right) - \overline{M}_1^u - x_0 p_1 - c_0 \leq \eta_1, \tag{47}$$

where $c_0 = W_0 - M_0^u i_0^u + x_0 p_0$ summarizes all $t = 0$ terms.

If η_1 is sufficiently high, the inequality holds for $p_1 = \nu_1$ and the economy is in a stable liquid equilibrium. If η_1 is sufficiently low, the bank defaults. Fragility arises if $G(p_1)$ can be decreasing in p_1 for intermediate values of η_1.

We first show that fragility arises for $a = 0$. In this case:

$$G^0(p_1) := m_1 \left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2} \right) - W_1 \left(\frac{m_t - b_t}{b_t} \right) - x_0 p_1 - c_0 \tag{48}$$

$$= \left(\bar{\bar{\sigma}} + \bar{\bar{\theta}} |\Delta p_1 - \kappa| - \kappa \right) \left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2} \right) - x_0 p_1 - c_0. \tag{49}$$

There are two terms that can lead to $G(p_1)$ being a decreasing function of p_1. First, when $x_0 > \underline{x}$, i.e., previous positions are large enough, the whole function can be decreasing. Second, when $p_1 < p_0 + \kappa$, $\bar{\bar{\theta}} |\Delta p_1 - \kappa| = \bar{\bar{\theta}} (p_0 + \kappa - p_1)$ is decreasing in p_1, this can make the whole expression negative if $\bar{\bar{\theta}} = \theta \Phi^{-1}(1 - \lambda)$ is large enough.

The final part of the proof is analogous to the fragility proof of Brunnermeier and Pedersen (2009). When $a > 0$ approaches zero, G converges uniformly to G^0 on any compact set of prices, because both margins and credit limit converge to Equations (20) and (29), respectively. Given that the limit function G^0 has a decreasing part, we can choose prices $p_1^a < p_1^b$, such that we obtain $\tau := G^0(p_1^a) - G^0(p_1^b) > 0$. Choose $\underline{a} > 0$ such that the difference between G and G^0 is at most $\tau/3$ for $a < \underline{a}$ by uniform convergence. Then,

$$G(p_1^a) - G(p_1^b) = G^0(p_1^a) - G^0(p_1^b) + [G^0(p_1^a) - G(p_1^a)] - [G(p_1^b) - G^0(p_1^b)] \tag{50}$$

$$\geq \tau - \frac{\tau}{3} - \frac{\tau}{3} = \frac{\tau}{3} > 0, \tag{51}$$

which proves that G has a decreasing part. □

Proof of Proposition 2. Part (i) of the proposition builds on the results from the proof of Lemma 2. When a bank's funding constraint is binding, we have:

$$m_1 \left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2} \right) - \overline{M}_1^u - x_0 p_1 - c_0 = \eta_1. \tag{52}$$

Taking the total derivative with respect to η_1, we get:

$$\frac{\partial m_1}{\partial p_1} \frac{\partial p_1}{\partial \eta_1} \left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2} \right) + m_1 \frac{2}{\gamma(\sigma_2)^2} \frac{\partial p_1}{\partial \eta_1} - \frac{\partial \overline{M}^u}{\partial p_1} \frac{\partial p_1}{\partial \eta_1} - x_0 \frac{\partial p_1}{\partial \eta_1} = 1. \tag{53}$$

Equation (32) follows after rearranging the expression.

Parts (ii) and (iii) follow from analyzing the partial derivatives $\frac{\partial \overline{M}_1^u}{\partial p_1}$ and $\frac{\partial m_1}{\partial p_1}$. For

$\Delta p_1 < \kappa$ and $\kappa > 0$, we have

$$\frac{\partial \overline{M}_1^u}{\partial p_1} = x_0 \frac{\overline{M}_1^u}{W_1} + W_1 \frac{\left(\overline{\theta} - \overline{\overline{\theta}}\right) \kappa}{\left(\overline{\overline{\sigma}} - \overline{\overline{\theta}} \Delta p_1 + \left(\overline{\overline{\theta}} - 1\right) \kappa\right)^2} > 0. \tag{54}$$

Moreover, as a approaches 0, $\frac{\partial m_1}{\partial p_1}$ approaches $-\overline{\theta} < 0$ for $\Delta p_1 < \kappa$. This means that there are credit limit spirals and margin spirals with positive probability. □

Proof of Proposition 3. We obtain part (i) of Proposition 3 by taking the derivative of $M_1^s = x_1(p_1 - m_1)$ with respect to price p_1, which gives us

$$\frac{\partial M_1^s}{\partial p_1} = \frac{m_1 - p_1 \frac{\partial m_1}{\partial p_1}}{m_1^2} \left(\overline{M}_1^u + W_1\right) + \frac{p_1 - m_1}{m_1} \left(\frac{\partial \overline{M}_1^u}{\partial p_1} + \frac{W_1}{\partial p_1}\right) > 0. \tag{55}$$

Plugging $\frac{\partial \overline{M}_1^u}{\partial p_1}$ into Equation (55) leads to part (i) of the proposition.

The results of parts (ii) and (iii) follow directly from the calculations in the proposition.

□

Proof of Proposition 4. The bank's first-order condition is:

$$\mathbb{E}_0 \left[\phi_1 \left((p_1 - p_0) - \frac{\partial i_0}{\partial x_0} M_0^u - \frac{\partial M_0^u}{\partial x_0} i_0\right)\right] = 0. \tag{56}$$

Rearranging gives:

$$\mathbb{E}_0 \left[p_0 \phi_1\right] = \mathbb{E}_0 \left[\phi_1 p_1\right] - \mathbb{E}_0 \left[\phi_1\right] \frac{\partial i_0}{\partial x_0} M_0^u - \mathbb{E}_0 \left[\phi_1\right] \frac{\partial M_0^u}{\partial x_0} i_0. \tag{57}$$

With $\frac{\partial M_0^u}{\partial x_0} = m_0$, we get:

$$p_0 = \frac{\mathbb{E}_0 \left[\phi_1, p_1\right]}{\mathbb{E}_0 \left[\phi_1\right]} - \frac{\partial i_0}{\partial x_0} M_0^u - m_0 i_0. \tag{58}$$

Using $Cov_0(\phi_1, p_1) = \mathbb{E}_0 \left[\phi_1, p_1\right] - \mathbb{E}_0 \left[\phi_1\right] \mathbb{E}_0 \left[p_1\right]$, we arrive at the result of the proposition.

When banks are constrained already at time 0, the corresponding shadow cost of capital ϕ_0 is given by:

$$\phi_0 = \mathbb{E}_0[\phi_1] \left[1 + \frac{x_0(\mathbb{E}_0 \left[\frac{\phi_1}{\mathbb{E}_0[\phi_1]} p_1\right] - p_0 + \kappa) - i_0 M_0^u}{W_0}\right]. \tag{59}$$

□

Proof of Proposition 5. There is no asymmetric information and lenders know the correct distribution of price changes:

$$\Delta p_2 \sim N\left(\kappa - \Lambda_1, \underline{\sigma} + \theta|\Delta\nu_1 - \kappa|\right). \tag{60}$$

Thus, illiquidity does not increase perceived volatility but instead increases expected returns. Using the true price process together with Equations (6) and (8), we obtain the capital buffer b_1^* and margin m_1^*. $\square$

Proof of Proposition 6. Part (i) follows directly from the discussion in the text. For part (ii), note that with asset purchases, function G^0 becomes:

$$G^0(p_1) := m_1\left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2} - x_1^{cb}\right) - \overline{M}_0^u - x_0 p_1 - c_0. \tag{61}$$

Thus, fragility is less likely to arise because customers' demand pressure is smaller.

Similarly, the margin and credit limit spirals are weakened as

$$\frac{\partial p_1}{\partial \eta_1} = \frac{1}{m_1\frac{2}{\gamma(\sigma_2)^2} + \frac{\partial m_1}{\partial p_1}\left(Z_1 + \frac{2(p_1-\nu_1)}{\gamma(\sigma_2)^2} - x_1^{cb}\right) - x_0 - \frac{\partial \overline{M}_1^u}{\partial p_1}}, \tag{62}$$

and

$$\frac{\partial \overline{M}_1^u}{\partial p_1} = x_0\frac{\overline{M}_1^u}{W_1} + \left(Z_1 + \frac{2(p_1 - \nu_1)}{\gamma(\sigma_2)^2} - x_1^{cb}\right)\frac{\left(\overline{\theta} - \overline{\overline{\theta}}\right)\kappa}{\overline{\overline{\sigma}} - \overline{\overline{\theta}}\Delta p_1 + \left(\overline{\overline{\theta}} - 1\right)\kappa}. \tag{63}$$

$\square$

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The Forward Premium in Short-Term Rates

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Abstract

This paper provides the first systematic study of the temporal and cross-sectional variation in the forward premium in very short-term rates. Using a unique and comprehensive data set of European repurchase agreements (repo), we find that the forward premium varies significantly with the (net) demand for borrowing and funding risk. Conditional tests of the unbiasedness hypothesis reveal that the expectations hypothesis (EH) cannot be rejected when funding liquidity risk is low and the demand is balanced. Overall, funding liquidity risk is the main driver affecting the short end of the term structure, and the validity of the EH depends on funding risk premiums and demand for funding immediacy.

1. Introduction

Since Fisher (1896), the expectations hypothesis (EH) has been a pivotal theory for interest rates, affecting all areas in financial economics and, in particular, asset pricing in bond and foreign exchange (FX) markets. Postulating that the long-term rate is purely determined by the current and expected future short-term rates plus a constant risk premium, the EH has mostly been rejected empirically[1]. Even at the very short end of the term structure, where Longstaff (2000b) first tested the EH using general collateral (GC) repo rates, Della Corte, Sarno, and Thornton (2008) reject it statistically, yet confirm the theory's economic validity.

In this paper, we approach the EH from a new angle, asking whether the time variation of funding risk can explain the EH's failure. Specifically, by funding risk we mean immediacy and costs of raising short-term loans in the repo market, which has become the main source of funding in the economy. Most importantly, the overnight repo rate not only constitutes the short rate of the term structure, as introduced by Longstaff (2000b), it also serves as the main funding rate for investors' bond positions along the entire yield curve. As the most prevalent repo maturity and policy target rate, the overnight repo rate is where funding risk materializes, spreading across the term structure through investors' bond trading, and deterring the relation between long- and short-term interest rates as postulated by the EH.

We analyze the impact of funding risk on the forward premium in overnight repo rates, expressed as the spread between the forward and spot rate. Both repos are overnight loans secured with various collateral securities that are ideal to identify any temporal and cross-sectional variation in funding risk. To the extent that the forward rate is an unbiased predictor of the future spot rate, the unbiasedness hypothesis holds in the absence of time-varying risk premiums. Using unique transaction-level data, we find that the unbiasedness hypothesis is statistically rejected when funding risk is high, but cannot be rejected when funding risk is absent.

A better understanding of the forward premium and its impact on 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 and monetary policies needs a thorough understanding and accurate interpretation of interest rates, agents' expectations, and risk premiums. Time and cross-sectional variations

[1] 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).

of short-term rates can indeed obstruct the pass-through efficiency of monetary policy (Duffie and Krishnamurthy, 2016). 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 time-varying risk premiums is crucial for market regulators (e.g., Financial Stability Board, 2012).

We argue that investigating the forward premium in overnight repo rates allows isolating the main assumptions behind the unbiasedness hypothesis, namely, rational expectations and constant risk premiums. First, the use of overnight repos allows removing various sources of (time-varying) risk. Since funding concentrates in very short-term maturities, this reduces term premiums and uncertainty over longer horizons (Hicks, 1946). Additionally, overcollateralization of repos removes or reduces credit risk, making loans inherently informationally insensitive (Holmstrom, 2015) and the nominal repayment virtually certain when secured by safe assets such as European government bonds (Gorton and Ordonez, 2014).[2]

Second, the European repo market studied in this paper provides the ideal institutional setting to form rational expectations on short-term interest rates. The determination of European repo rates benefits from various money market index rates and, most importantly, from the Eurosystem's official target rate for main refinancing operations (MRO), thus facilitating an efficient price discovery process and the reduction of search costs (Duffie, Dworczak, and Zhu, 2017). In addition, the European repo market is an interbank market populated by professional agents who trade on anonymous, transparent, and liquid platforms cleared by central counterparties (Mancini, Ranaldo, and Wrampelmeyer, 2016), which reduce and homogenize counterparty credit risk (e.g., Duffie and Zhu, 2011; Acharya and Bisin, 2014) and determine ex ante margins that are exogenous to market participants, contrary to the prevalent practice in repo markets in the United States (Gorton and Metrick, 2012; Copeland, Martin, and Walker, 2014). Such a trading environment reduces possible arbitrage opportunities and many kinds of frictions that can bias the formation of rational expectations (Longstaff, 2000a).

Another important characteristic of the European repo market is the wide range of eligible collateral assets, which also differ in terms of sovereign credit quality (Mancini, Ranaldo, and Wrampelmeyer, 2016; Boissel, Darrien, Ors, and Thesmar, 2017). Repos can be secured by general collateral (GC), i.e., a wide range of securities with similar characteristics, or limited to a specific collateral security ("specials", SC). GC repos benefit from risk diversification, while special repos inherit idiosyncratic risk from the collateral security (Duffie, 1996). Importantly, special repos as well as GC repos are used to fund

[2]Specifically, a repo is a sale (to the lender) and repurchase (of the borrower) of the collateral asset for an amount smaller than its market value, providing the lender with strong protection against credit risk.

investors' long and short positions across the term structure of bond maturities, providing a direct link between the analysis of the overnight forward premium and its implications for the validity of the EH.

Our analysis proceeds in two steps. First, we analyze the repo forward premium with respect to its variation with funding risk. To do this, we compute the daily forward premium as the spread between the daily forward and spot rates, using the "tomorrow-next" (TN) rate as the forward rate and the overnight (ON) rate as the spot rate. The only difference between these two repos is the settlement time, i.e., ON repos provide immediate funding, while TN repos are settled one business day later. Both contracts have the same maturity, which ensures that the time frame for which the EH should hold and the return measurement period are identical, thus providing a consistent framework to analyze the time variation in term premiums (Longstaff, 1990). Given the contract and institutional design, we hypothesize that, if anything, the variation of the forward premium can be explained by time-varying funding risk. We measure funding risk at two levels: aggregate and repo-specific. The former is represented by the Libor-OIS spread, which is a commonly used proxy capturing money market uncertainty and constraints. The latter is new and is based on the order flow of a given repo contract, computed as the difference between (aggressive) borrower-initiated and lender-initiated trading volumes. A higher value of the ON order flow signals funding demand pressure and thus funding immediacy, i.e., urgency to raise funding capital. We conduct panel regressions of the forward premium with aggregate and specific measures of time-varying risk as explanatory variables. Moreover, we control for other possible determinants of repo rates, including calendar effects such as the end of the monetary policy's maintenance period and quarter ends, which have been shown to affect repo markets (e.g., Munyan, 2017; BIS, 2017).

In the second part of our paper, we perform various conditional tests of the EH across time and collateral securities. Since we effectively analyze one-day differences in repo rates, we employ the vector autoregression (VAR) framework proposed by Bekaert and Hodrick (2001), which proves particularly suitable in detecting very small deviations as shown in, e.g., Della Corte, Sarno, and Thornton (2008). In particular, we examine whether today's forward premium is an efficient predictor of tomorrow's ON 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) and further investigated by Sarno, Thornton, and Valente (2007). We conduct conditional analyses by testing the EH on sample periods characterized by different levels of funding risk. Specifically, we run EH tests on all sample periods from the highest to the lowest quartiles of the underlying funding risk variables.

We use a unique and comprehensive data set representing the vast majority of the European repo market. Our data set spans from 2006 to 2016, 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 (European Central Bank, 2015), covering a total trading volume of EUR 601 trillion, i.e., on average more than EUR 54 trillion per year. These numbers give an idea about the importance and size of the European repo market, which is larger than the estimated size of the repo market in the United States.[3] Given the information granularity of our data, we provide the first systematic study of the temporal and cross-sectional variation in GC and special repo rates across heterogeneous collateral securities.

Several clear results emerge from our study. First, we find compelling evidence that the forward premium is mainly driven by time-varying risk. For GC repos, the variation of aggregate funding risk and repo-specific order flow have a significant effect on the forward premium, even after controlling for time and repo-specific characteristics. This means, tighter funding constraints measured by money market risk premiums (e.g., Libor-OIS spread) increase the forward spread. Also, a stronger demand for funding immediacy in ON (TN) repos decreases (increases) the forward premium. For special repos, we test whether their forward premiums can also be affected by collateral issues. Following the literature, we measure "specialness" as the daily spread between countries' volume-weighted GC and special rates (Duffie, 1996). We find that aggregate funding risk and specialness increase the forward premium of special repo rates. We further test for the impact of funding risk by controlling for calendar effects arising from the European Central Bank's (ECB) monetary policy schedule and financial regulation. The results are robust and deliver consistent findings, in that the GC and special forward premiums depend on aggregate funding risk as well as ON net demand and specialness, respectively.

Second, we find that the statistical rejection of the EH for GC repo rates moves inversely with funding risk, suggesting that in the absence of risk, expectations about future short-term rates are in line with theoretical predictions. By contrast, the EH is typically rejected for specials. For GC, the EH finds support when aggregate funding risk and demand for funding immediacy is negligible. In the cross-section, the rejection of the EH is more prevalent when collateral securities bear sovereign risk premiums, such as for government bonds of EU non-core countries (i.e., Italy and Spain), or idiosyncratic risks as for specials.

Our paper contributes to three strands of the literature. First, we contribute to the forward premium literature. Whereas the forward premium has been predominantly studied in FX and longer interest rates, we provide the first study analyzing forward premiums in very short-term interest rates and show that they are determined by time-varying funding

[3]Estimates of the size of the U.S. repo market range from USD 5.5 trillion in 2012 (Copeland, Davis, LeSueur, and Martin, 2012) to USD 10 trillion in 2008 (Gorton and Metrick, 2012).

risk.

Second, we contribute to the literature on the EH. As a simple but general theory, the EH has attracted an enormous deal of attention in the literature. The most important contributions closest to our paper are Longstaff (2000b) and Della Corte, Sarno, and Thornton (2008), 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 funding risk premium. While the time-series approach has dominated prior research on the EH, none of the previous papers provides (i) a comparative analysis over different repo collateral securities and rates, and (ii) conditional EH analyses on funding risk and calendar effects.

Third, 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 financial crisis on U.S. repos. Mancini, Ranaldo, and Wrampelmeyer (2016) document the overall resilience of the European repo market during the recent crisis, while Boissel, Darrien, Ors, and Thesmar (2017) 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 (funding) risk and demand for funding immediacy, measured by the repo order flow, 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. In the next section, we present the data set. Section 3 performs panel regressions of the forward premium. The econometric procedure of the EH tests is explained in Section 4, and the conditional test results are presented in Section 5. Section 6 concludes.

2. Data

Our data set contains every repo transaction executed on the three major European electronic trading platforms from 2006 to 2016: BrokerTec, Eurex Repo, and MTS Repo, which together represent more than 67% of the entire European repo market in 2014

(European Central Bank, 2015).[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: Belgium, France, Germany, Italy, Netherlands, and Spain, or GC Pooling ECB basket (henceforth "GCP") and GC Pooling ECB Extended basket ("GCX"). 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. GCX), or limited to only a specific security (i.e., a unique ISIN). The former is called "general collateral" (GC) and the latter is a "special". The motives to enter a GC or special repo differ, in that GC repos are generally 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 repos of various countries including 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 GCX, which extends the list of eligible assets to some riskier securities.[6] An important share of German GC repos 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 23'698'541 transactions and about EUR 601'009'581 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 2016, 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

[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).

[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 special repo is often used for trading, in particular short-selling, for which the delivery of a specific collateral security is required.

[6]The GCP basket consists of the safest, very high quality collateral securities, including those securities admitted for collateralization of ECB open market operations and rated at least A-/A3. The GCP Extended basket consists of a larger subset of securities admitted by 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.

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 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, the data structure allows us to properly align investors' expectations by considering the exact settlement times of each repo contract. Specifically, all spot (ON) repos are settled immediately, while "tomorrow-next" (TN) repos entered today are settled at 11 a.m. on the next business day, thus representing one-day forward rates.[9] For the two contracts to become real substitutes, we compute the daily ON repo rate as the average of all ON rates from opening to 11 a.m., and the daily TN rate as the average of all TN rates from opening to closing. Therefore, our repo rates differ from previous studies of the EH using daily closing rates (e.g., Longstaff, 2000b; Della Corte, Sarno, and Thornton, 2008).

Table 1A reports the descriptive statistics of the European repo rates in our sample. Panel A of Table 1A shows the summary statistics of the GC overnight repo rates.

All rates are expressed in percentage points per annum. Mean and standard deviations of ON and TN rates are fairly close together, differing only by a few basis points (bps), and display cross-sectional heterogeneity. For example, the average German GC ON rate is less than one basis point smaller than the average TN rate, while the spread between the mean GC ON and TN rates of Italian repos is more than five times larger than the German spread for the same time period. In general, spreads between TN and ON rates are positive over time and across all countries, suggesting the presence of a forward *premium* in repo rates.

Panel B of Table 1A reports the descriptive statistics of the overnight special rates. The table shows that the differences in means and standard deviations are much larger for specials than for GC rates. For example, the average premium between French ON and TN special rates is almost 10 bps, while for Spain the difference is more than 25 bps – and thus comparable to the size of bond term premiums in long-maturity forward rates (e.g., Fama, 1984b; Fama and Bliss, 1987). With regard to the different time periods, the reduction of the spreads between 2010 and 2016 is even more pronounced for specials than for GC rates, with fairly large cross-sectional differences. Taking into account the

[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, Alkan, Copeland, Davis, Martin, Pingitore, Prugar, and Rivas, 2014).

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

Table 1A

Descriptive Statistics of Daily European Overnight Repo Rates

This table presents summary statistics of daily repo rates of European government collateral securities from 2006 to 2016. Panel A presents repo rates for general collateral (GC) repos and Panel B for special (SC) repos. The forward premium is denoted by s and equals the (average) spread between TN and ON repo rates. All statistics are measured in percentage points per annum.

Panel A: GC Repo Rates								
	DE	FR	BE	NL	ES	IT	GCP	GCX
GC ON Repo Rates								
Mean	0.8930	0.7829	0.7587	0.4818	0.0797	0.1883	1.0126	0.1537
Std Dev	1.4992	1.4035	1.3856	1.1989	0.3970	0.4317	1.5288	0.4411
Min	−2.0000	−1.0667	−1.0000	−1.0357	−1.9375	−0.4155	−0.4800	−0.4142
Max	4.5250	4.6730	4.4750	4.4000	2.6500	1.8654	5.1497	2.9000
GC TN Repo Rates								
Mean	0.9021	0.7946	0.7745	0.4944	0.0909	0.2091	1.0274	0.1687
Std Dev	1.5046	1.4060	1.3929	1.2035	0.3917	0.4440	1.5332	0.4496
Min	−1.0737	−1.1979	−0.7000	−1.0000	−1.6700	−0.4241	−0.5100	−0.5000
Max	4.4750	4.6643	4.4800	4.5000	2.7000	2.0482	4.9667	2.9500
s (bps)	0.9040	1.1703	1.5794	1.2593	1.1266	2.0837	1.4807	1.4921
$s_{2010-16}$ (bps)	0.4277	1.0180	1.1810	0.9744	1.1008	2.0837	1.1909	1.4178
# Obs	2,423	2,464	2,133	1,619	1,242	1,792	2,625	1,631
Start	2006	2006	2006	2008	2008	2010	2010	2006

Panel B: Special Repo Rates						
	DE	FR	BE	NL	ES	IT
SC ON Repo Rates						
Mean	0.7019	0.8737	0.6142	0.3229	0.1340	−0.0886
Std Dev	1.4934	1.5744	1.4287	1.2256	1.1953	0.3553
Min	−2.7321	−1.8726	−2.6500	−2.0000	−2.8400	−2.9190
Max	4.2500	4.5268	4.3500	4.4250	4.3500	1.2125
SC TN Repo Rates						
Mean	0.8319	0.9722	0.7354	0.4516	0.3700	0.0644
Std Dev	1.5300	1.5809	1.4551	1.2313	1.1311	0.3544
Min	−2.9910	−1.7613	−1.1450	−1.2438	−1.1475	−0.6839
Max	4.3088	4.5592	4.3330	4.3057	4.2868	1.4561
s (bps)	13.0009	9.8843	12.1221	12.8934	23.6163	15.2899
$s_{2010-16}$ (bps)	10.0760	8.5791	10.1301	12.1595	25.2395	15.2899
# Obs	2,695	2,814	2,267	1,878	2,165	1,786
Start	2006	2006	2006	2006	2006	2010

different starting dates of GC repos in our sample, the observed differences in the forward premiums in Table 1A serve as a *prima facie* indicator that the test results of the EH may vary across time, countries, and repo type.

Table 1B provides an overview of the traded volume across the countries' collateral securities. With a total volume of EUR 196 and 128 trillion, respectively, German and Italian repos are the most traded in the sample, whereas the total trading volume in the

Table 1B

Descriptive Statistics of Daily European Repo Trading Volumes

This table reports descriptive statistics of the daily trading activity in European government general collateral (GC) and special (SC) repos from 2006 to 2016. Trading volumes (in EUR trillions) and transactions refer to the sum of all repos traded on BrokerTec, Eurex Repo, and MTS Repo. Maturity shares report the percentage of total volume traded in 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	ES	IT	GCP	GCX	All
Total Volume (tn)	196	91	30	29	33	128	34	14	601
Transactions ('000)	6,349	3,852	1,517	1,411	1,880	5,512	98	53	23,699
Maturity (%)									
ON	1.02	4.55	4.17	1.92	2.53	4.03	22.95	19.71	4.17
TN	14.80	24.27	22.17	18.44	18.83	23.63	31.60	36.45	20.61
SN	80.32	68.17	71.91	78.30	73.74	69.58	24.44	28.25	70.52
Other	3.87	3.02	1.75	1.34	4.91	2.76	21.01	15.59	4.69
Repo (%)									
GC	10.70	13.92	15.01	10.42	11.45	33.13	100	100	23.52
SC	89.30	86.08	84.99	89.58	88.55	66.87	0	0	76.48
GC Maturity (%)									
ON	8.04	25.53	25.33	16.20	18.03	11.30	22.95	19.71	16.33
TN	76.53	67.92	70.21	79.79	56.16	40.86	31.60	36.45	49.46
SN	7.09	5.24	2.52	2.34	14.21	42.53	24.44	28.25	23.95
Other	8.35	1.30	1.94	1.67	11.60	5.31	21.01	15.59	10.27
SC Maturity (%)									
ON	0.18	1.15	0.43	0.26	0.52	0.42	n/a	n/a	0.44
TN	7.40	17.21	13.69	11.30	14.00	15.09	n/a	n/a	11.74
SN	89.09	78.34	84.17	87.14	81.43	82.98	n/a	n/a	84.85
Other	3.33	3.29	1.72	1.30	4.04	1.51	n/a	n/a	2.97

GCX index slightly exceeds EUR 14 trillion.

Table 1B shows that specials constitute a market share of more than 76%, and that more than 95% of all trading is conducted in overnight repos (ON, TN, SN).[10] While GC repos are traded predominantly ON and TN, specials are traded mostly TN and SN. Given the cumulative trading volume of more than EUR 600 trillion in one-day forward and spot rates, our analysis of the overnight forward premium thus covers by far the most traded contract type in the repo market and ensures a consistent analytical framework by using identical tenors (Longstaff, 1990).

[10] Other repo terms include maturities from one week to 12 months.

3. The Repo Overnight Forward Premium

In this section, we address the question whether the forward premium can be explained by time-varying risk. In this framework, the natural source of risk is funding liquidity risk. For country c and date t, our baseline regression takes the form

$$y_{c,t} = \gamma_c + \gamma_t + \beta X_{c,t} + \theta R_t + \varepsilon_{c,t}, \quad (1)$$

where $y_{c,t}$ depends on the specification and is either the forward premium $s_{c,t} = f_{c,t} - i_{c,t}$, measured as the spread between the TN ($f_{c,t}$) and ON ($i_{c,t}$) repo rate, or the forward spread, $|s_{c,t}|$. $X_{c,t}$ are country-specific repo determinants, R_t represents aggregate market risk (and is thus independent of c), while γ_t and γ_c are time and repo fixed effects, respectively.

We replicate this regression separately for the forward premium and forward spread. The analysis of the forward premium allows us to understand in which direction funding liquidity risk materializes, i.e., whether it predominantly moves the spot or forward rate. By contrast, the analysis of the forward spread provides us with information on the general misalignment between forward and spot rates during times of (funding) risk. The latter analysis is particularly relevant for our tests of the EH later on, which focus on testing whether the forward *spread* is constant or time-varying.

We analyze the forward premium in short-term rates using overnight order flows and repo specialness as repo-specific determinants as well as the Libor-OIS spread representing aggregate money market risk. The repo ON order flow is the difference between borrower- and lender-initiated ON repo volumes, denoted by *ONDemand*, and the TN order flow is the net borrowing volume of TN repos, denoted by *TNDemand*. In this framework, these two variables represent the microstructural measures of net funding demand, thus capturing the price impact of trading immediacy (Demsetz, 1968) on the forward premium. When analyzing the forward spread, we take the absolute values of the order flows and refer to them as *order imbalance*. The presumption in this specification is that contemporaneous trade influences repo rates, but not the other way round, which reflects (Granger-Sims) causality running from trades to price revisions as in, e.g., Hasbrouck (1991). Repo specialness is the repo market counterpart of bonds' liquidity premiums (e.g., Duffie, 1996), which is computed by the spread between a country's volume-weighted average overnight GC and special repo rates.[11] Higher liquidity premiums are often associated with investors' "flight-to-safety" during crisis times, and so we expect repo specialness to be correlated with higher forward spreads. The Libor-OIS spread is a well-accepted measure of money market funding stress, computed by the difference between the 3-month

[11]Both averages are constructed using all available spot (ON), tomorrow-next (TN), and spot-next (SN) repos.

Euribor and overnight index swap (OIS) rates.[12] Given this set of variables, the following testing hypotheses arise:

(1) *Higher ON borrowing net demand leads to a lower overnight forward premium.*

(2) *Higher TN borrowing net demand leads to a higher overnight forward premium.*

(3) *Higher specialness leads to a higher overnight forward spread.*

(4) *Money market funding stress leads to a higher forward spread.*

Table 2 reports the regression results separately for GC repos in Panel A and special repos in Panel B.

The results for GC repos broadly support our hypotheses. Specifically, higher ON borrowing demand decreases the forward premium (column 1), and higher TN borrowing demand increases the forward premium (column 2). This finding suggests that funding demand pushes the respective repo rates up, thereby affecting the overnight forward premium accordingly. Column (4) of Panel A shows that aggregate funding risk, as measured by the Libor-OIS spread, is also associated with a higher forward premium, indicating that money market participants expect an increase in funding costs during times of high market risks. Panel A of Table 2 also reports the regression results for the forward spread as the dependent variable. Unlike for TN repos, ON order imbalance and the Libor-OIS spread carry a significant positive coefficient, while repo specialness appears less strongly correlated with the forward spread.

The results for special repos are presented in Panel B of Table 2. Three main findings emerge compared to GC repos: First, repo order flows are not significant anymore. Second, specialness becomes significant implying that larger specialness leads to a larger forward premium. Third, the Libor-OIS spread is still significant, thus suggesting hypothesis 4 holds strongly for both special repos as well as GC repos. The first two results, i.e., insignificant repo order flows and significant specialness, are consistent with the nature of special repos, which are mainly driven by net demand for collateral assets rather than cash.

We now repeat our previous analysis including all variables shown to be significantly correlated with the forward premium and spread, i.e., ONDemand and Libor-OIS spread for GC repos, and together with specialness for special repos. This analysis allows us to examine whether these variables, in particular the Libor-OIS spread, remain significant in a multivariate setting and after controlling for several seasonal effects.

[12] For robustness, we also use other risk proxies instead of the Libor-OIS spread, including the TED spread, measured by the difference between the 3-month Euribor and French T-Bill, the Vstoxx 50 implied volatility index, which is the Euro counterpart of the S&P 500 VIX, CDS spreads as well as the European bank sector CDS spreads. All these variables deliver consistent results and details are available upon request.

Table 2

Daily Repo Forward Premium

Reported are panel regression coefficients for the daily forward premium and the daily forward spread. The forward premium is the difference between the TN and ON repo rate, and the forward spread is the absolute value of this difference. LIBOR denotes the 3-month Libor-OIS spread (EUR). Specialness is the daily spread between countries' volume-weighted GC and special rates, and ONDemand and TNDemand, respectively, denote overnight and tomorrow-next net borrowing volumes. In the forward spread analysis, ONDemand and TNDemand are computed as the absolute order imbalance. Countries included are Belgium, France, Germany, Italy, Netherlands, and Spain, as well as Eurex' GC Pooling and GC Pooling Extended indices for the GC panel. Standard errors are clustered at country- and day-level (shown in parentheses). The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

Panel A: GC Repo Rates								
	Forward Premium: $s_{i,t}$				Forward Spread: $\|s_{i,t}\|$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ONDemand	-0.191^{***}				0.069^{***}			
	(0.021)				(0.017)			
TNDemand		0.096^{**}				0.025		
		(0.029)				(0.028)		
Specialness			-0.028				0.031^{*}	
			(0.025)				(0.014)	
LIBOR				0.024^{***}				0.051^{***}
				(0.006)				(0.005)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Day FE	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Adj. R^2 (%)	52.76	51.46	55.61	1.80	60.08	59.99	61.62	9.54
# Obs.	15,825	15,825	11,451	15,929	15,825	15,825	11,451	15,929

Panel B: Special Repo Rates								
	Forward Premium: $s_{i,t}$				Forward Spread: $\|s_{i,t}\|$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ONDemand	-0.446				-0.051			
	(0.397)				(0.240)			
TNDemand		-0.723				0.712		
		(0.579)				(0.676)		
Specialness			0.538^{**}				0.595^{**}	
			(0.158)				(0.164)	
LIBOR				0.122^{***}				0.132^{***}
				(0.020)				(0.015)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Day FE	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Adj. R^2 (%)	2.93	2.89	3.48	2.65	3.59	3.61	4.57	3.51
# Obs.	13,525	13,525	12,941	13,552	13,525	13,525	12,941	13,552

To do this, we redefine Equation (1) by dropping the day fixed effects, and instead account for four calendar issues originating from the schedule of the ECB's monetary policy operations and financial stability regulation: First, we include day dummies in the regression representing the days surrounding the ECB's weekly main refinancing operation (MRO) on Wednesdays. In the Eurosystem, banks apply for new reserves on Tuesdays, which they receive from the ECB on Wednesdays, as documented in Garcia-de-Andoain, Heider, Hoerova, and Manganelli (2016). Hence, Wednesday represents the cut-off day after which banks are endowed with new reserves from the ECB. Second, we include a dummy variable *EOMP*, which is equal to one for the last MRO week of each maintenance period and zero otherwise. The main idea is that the fulfilment of the MRO requirements might prompt liquidity hoarding and a more rigid demand for reserves. Third, we include a dummy variable *EOQ*, which is equal to one for the last five trading days of each quarter and zero otherwise. At quarter ends, the fulfilment of capital and liquidity requirements can create "window dressing", including a reduced supply of reserves or reverse repos (e.g., Munyan, 2017; BIS, 2017). Fourth, we include a dummy variable called *FRFA* that is equal to one after October 15, 2008, which represents the date on which the ECB switched from a variable-rate tender regime to a fixed-rate full allotment procedure. This new system may imply a structural reduction in liquidity needs, which could negatively impact the overnight forward premium.

Table 3

Seasonal and Calendar Effects

Weekday dummies include all weekdays but Wednesdays. EOMP is equal to one for the last week of the ECB's maintenance period and zero otherwise. EOQ is equal to one for the last five trading days of each quarter and zero otherwise. FRFA is equal to one after October 15, 2008 and zero before. ONDemand denotes the net borrowing demand in (1)-(4), and the absolute order imbalance in (5)-(8). Standard errors are clustered at country- and day-level (shown in parentheses). The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively. The star ($\star$) denotes that at least one dummy variable has statistical significance at the 5% or 1% level.

Panel A: GC Repo Rates								
	Forward Premium: $s_{i,t}$				Forward Spread: $\lvert s_{i,t}\rvert$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ONDemand	-0.369^{***}	-0.371^{***}	-0.369^{***}	-0.372^{***}	0.120^{**}	0.121^{**}	0.115^{**}	0.123^{**}
	(0.038)	(0.039)	(0.039)	(0.039)	(0.036)	(0.036)	(0.035)	(0.038)
LIBOR	0.024^{***}	0.024^{***}	0.024^{***}	0.023^{***}	0.052^{***}	0.052^{***}	0.051^{***}	0.052^{***}
	(0.006)	(0.006)	(0.006)	(0.006)	(0.004)	(0.005)	(0.004)	(0.004)
Weekdays	Yes	No	No	No	Yes	No	No	No
EOMP	No	Yes	No	No	No	Yes	No	No
EOQ$^{(\star)}$	No	No	Yes	No	No	No	Yes	No
FRFA	No	No	No	Yes	No	No	No	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R^2 (%)	7.34	7.24	7.81	7.31	9.90	9.88	12.77	9.87
# Obs.	15,929	15,929	15,929	15,929	15,929	15,929	15,929	15,929

Panel B: Special Repo Rates								
	Forward Premium: $s_{i,t}$				Forward Spread: $\lvert s_{i,t}\rvert$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Specialness	0.343	0.339	0.339	0.357^{*}	0.424^{*}	0.420^{*}	0.415^{*}	0.442^{*}
	(0.175)	(0.174)	(0.180)	(0.172)	(0.183)	(0.182)	(0.187)	(0.179)
LIBOR	0.102^{**}	0.102^{**}	0.102^{**}	0.098^{**}	0.106^{***}	0.105^{***}	0.106^{***}	0.100^{***}
	(0.027)	(0.026)	(0.027)	(0.027)	(0.020)	(0.020)	(0.020)	(0.019)
Weekdays$^{(\star)}$	Yes	No	No	No	Yes	No	No	No
EOMP	No	Yes	No	No	No	Yes	No	No
EOQ	No	No	Yes	No	No	No	Yes	No
FRFA	No	No	No	Yes	No	No	No	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R^2 (%)	4.04	4.04	3.99	4.20	5.58	5.54	5.51	5.84
# Obs.	12,994	12,994	12,994	12,994	12,994	12,994	12,994	12,994

Table 3 shows the regression results for GC repos in Panel A and for special repos in Panel B. The main finding from Table 3 is that the Libor-OIS spread remains statistically significant even after controlling for seasonal and calendar effects. Moreover, ON borrowing demand as well as ON order imbalance are also highly significant, whereas repo specialness loses some of its explanatory power in the multivariate setting. Table 3 also shows that calendar effects are mostly insignificant, with Tuesdays for special repos (negative coefficient) and *EOQ* for the GC forward spread (positive coefficient) constituting the only exceptions.

Overall, our findings suggest that the Libor-OIS spread is the main funding risk factor for both GC and special repos, while the ON order imbalance (demand) is a strong predictor of the GC forward spread (premium). Given these results, in the following we analyze how the validity of the EH at the short end of the term structure depends on funding risk in short-term rates.

4. Theory and Methodology of the EH Tests

In this section, we summarize the theoretical relation of the unbiasedness hypothesis postulated by the EH and describe the testing procedure of the VAR-GMM framework.

4.1. The Unbiasedness Hypothesis of the EH

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

$$f_t^n = \mathbb{E}_t(i_{t+h}^n) + c^n, \tag{2}$$

where f_t^n denotes the forward rate, i_{t+h}^n the spot rate at time $t+h$, and c^n is the risk premium. Intuitively, Equation (2) 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 f_t becomes the TN repo rate and i_t is the ON repo rate. Under the EH, both repo rates should only differ by a constant risk premium (or be the same under the pure form of the EH, i.e., $c = 0$).

For every country, the spread-based test of the EH is written as

$$\Delta i_{t+1} = \alpha_1 + \beta_1 s_t + \varepsilon_{t+1}, \tag{3}$$

where ε_{t+1} is the rational expectations error term, $s_t = f_t - i_t$ is the forward premium, and the null hypothesis in Equation (3) is $\alpha_1 = 0$, $\beta_1 = 1$, stating that the forward premium is an unbiased predictor of the future spot spread, Δi_{t+1} (Froot, 1989).

4.2. Methodology

Since tests of Equation (3) 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 (2) that make the VAR model consistent with the unbiasedness hypothesis of the EH (e.g., Sarno, Thornton, and Valente, 2007; Della Corte, Sarno, and Thornton, 2008).[13] To that end, 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.[14]

4.2.1. The VAR Framework

Consider Equation (3) with demeaned spot and forward spreads Δi_t and s_t, respectively. For each country separately, we set up a bivariate VAR system according to

$$\Delta i_t = a(L)\Delta i_{t-1} + b(L)s_{t-1} + u_{1,t}, \tag{4}$$

$$s_t = c(L)\Delta i_{t-1} + d(L)s_{t-1} + u_{2,t}, \tag{5}$$

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 test the time variation of the risk premium without discriminating between the standard and pure form of the EH. Intuitively, Equation (4) determines the future spot spread and Equation (5) generates the current forward premium. As thoroughly documented in the literature, the simultaneous estimation of the VAR equations improves efficiency by considering contemporaneous cross-correlations in the error terms (e.g., Mishkin, 1982; Pagan, 1984). 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 (4) and (5) into a

[13]See Della Corte, Sarno, and Thornton (2008) 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, Sarno, Taylor, and Valente, 2006).

[14]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 perform much worse in small samples. Thus, while reporting LM and DM test statistics, we base our interpretations on the LM test results.

first-order VAR companion form,

$$\begin{bmatrix} \Delta i_t \\ s_t \\ \Delta i_{t-1} \\ s_{t-1} \\ \vdots \\ \Delta i_{t-p+1} \\ s_{t-p+1} \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & \dots & a_{p-1} & b_{p-1} & a_p & b_p \\ c_1 & d_1 & \dots & c_{p-1} & d_{p-1} & c_p & d_p \\ 1 & & & & & & \\ & 1 & & & & & \\ & & \ddots & & & & \\ & & & 1 & & & \\ & & & & 1 & & \end{bmatrix} \begin{bmatrix} \Delta i_{t-1} \\ s_{t-1} \\ \Delta i_{t-2} \\ s_{t-2} \\ \vdots \\ \Delta i_{t-p} \\ s_{t-p} \end{bmatrix} + \begin{bmatrix} u_{1,t} \\ u_{2,t} \\ \\ \\ \\ \end{bmatrix}, \tag{6}$$

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

$$Y_t = \Theta Y_{t-1} + \nu_t, \tag{7}$$

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 system at time t, the one-period forecast of the spot spread and forward premium is given by

$$E_t[Y_{t+1}] = \Theta Y_t. \tag{8}$$

Consistent with the EH in Equation (2), the vector of restrictions can thus be expressed as

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

where $e_1 = (1, 0, \dots, 0)'$ and $e_2 = (0, 1, 0, \dots, 0)'$ are 2p-dimensional indicator vectors. The left-hand side of Equation (9) is the expected future spot spread from Equation (8), and the right-hand side is the current forward premium. When estimated, the set of restrictions forces the coefficients in the VAR system to yield the theoretical relation postulated by the EH. In fact, the coefficient of the forward premium in Equation (4) compares directly with the OLS coefficient in Equation (3),

$$\beta_1 = \frac{e_1'\Theta\Psi e_2}{e_2'\Psi e_2}, \tag{10}$$

where Ψ is the unconditional variance of Y_t, computed from $vec(\Psi) = (I - \Theta \otimes \Theta')^{-1} \times vec(\Sigma_\nu)$. The numerator of the slope coefficient is 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 (9) as

$$a(\theta) = e_1'\Theta - e_2', \tag{11}$$

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

$$H_0 : a(\theta) = 0. \tag{12}$$

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.

4.2.2. 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 sample 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

$$\mathcal{L}(\theta, \gamma) = -\frac{1}{2} g_T(\theta)' \Omega_T^{-1} g_T(\theta) - a_T(\theta)'\gamma, \tag{13}$$

where the first term of Equation (13) 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.[15] When estimating the parameters, the Lagrange multipliers will be different from zero if the restrictions imposed by the EH have 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

$$T\overline{\gamma}'(A_T B_T^{-1} A_T')\overline{\gamma} \rightarrow \chi^2_{(2p)}, \tag{14}$$

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

$$T g_T(\overline{\theta})' \Omega_T^{-1} g_T(\overline{\theta}) \rightarrow \chi^2_{(2p)}, \tag{15}$$

[15] 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 of the constrained GMM maximization problem.

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

4.2.3. 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.[16]

5. Conditional Tests of the EH

In our empirical tests of the EH, we analyze the time variation of the risk premium by conditioning the EH tests on our main (funding) risk variables: First, we explore the time variation of aggregate funding risk as measured by the Libor-OIS spread. Second, we condition our EH tests on ON order imbalance and repo specialness for GC and special repos, respectively. For robustness, we also base our conditional tests on the calendar effects following the ECB's MRO schedule. For the interpretation of the test results, we rely on the LM statistic, which has been shown to be superior to other test statistics such as, e.g., the DM test (see Bekaert and Hodrick, 2001).[17]

5.1. Aggregate Funding Risk

We first condition our tests of the EH on the Libor-OIS spread, which proved highly significant in the regression analysis. The conditioning approach works as follows: For every country and repo, we first construct the respective samples according to the sorted Libor-OIS spread, i.e., from the highest to its lowest value. Then, we determine the samples' quartiles (i.e., the 25%-quantiles), which then serve as the time series for our conditional tests. Specifically, we bias-correct each quartile as described in Section 4.2.3 and test the EH for each subsample separately. If the time variation of the Libor-OIS spread matters for the validity of the EH, we expect the test results to show that the EH is violated more in the highest quartile and less in the lowest quartile. Table 4 reports the p-values of the EH tests, ordered from highest (1) to lowest (4).[18]

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[16]See the appendix for technical details on the data simulation process.

[17]Nevertheless, we also report the DM p-values for comparison.

[18]All results are reported for GARCH innovations.

Table 4

Aggregate Funding Risk: Libor-OIS

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 results for GC repo rates, and Panel B for special repos. Results are shown for generalized autoregressive conditional heteroskedasticity (GARCH) innovations. Country baskets include Germany (DE), France (FR), Belgium (BE), Netherlands (NL), Spain (ES), and Italy (IT), as well as two GC pooling baskets (GCP and GCX). Numbers (1) to (4) refer to quartiles sorted according to the Libor-OIS spread in descending order, i.e., (1) refers to the highest 25% values of the Libor-OIS spread, and (4) to the lowest.

Panel A: GC Repo Rates									
	DE					FR			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0295	0.0578	0.0611	0.1933	LM	0.0022	0.0688	0.0782	0.2661
DM	0.0011	0.0001	0.0284	0.1123	DM	0.0002	0.0022	0.0226	0.0119
J-Test	0.3281	0.2015	0.6081	0.8220	J-Test	0.2657	0.2705	0.4758	0.6938
	BE					NL			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0095	0.0079	0.1478	0.2560	LM	0.0381	0.0430	0.1795	0.1747
DM	0.0006	0.0011	0.0022	0.0369	DM	0.0001	0.0013	0.0605	0.0278
J-Test	0.3873	0.4712	0.4212	0.5803	J-Test	0.2412	0.3513	0.8296	0.9485
	ES					IT			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0121	0.0112	0.0756	0.0756	LM	0.0019	0.0486	0.0259	0.1591
DM	0.0000	0.0002	0.0167	0.0004	DM	0.0000	0.0004	0.0023	0.0384
J-Test	0.1518	0.1441	0.5989	0.4502	J-Test	0.1257	0.4660	0.4319	0.7529
	GCP					GCX			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.1093	0.2183	0.1969	0.5596	LM	0.0014	0.0532	0.0938	0.1021
DM	0.0219	0.0008	0.0274	0.1645	DM	0.0001	0.0000	0.0001	0.0022
J-Test	0.6502	0.2899	0.9007	0.8905	J-Test	0.2739	0.2168	0.2871	0.5710

Panel B: Special Repo Rates									
	DE					FR			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0024	0.0291	0.0386	0.0563	LM	0.0006	0.0296	0.0802	0.0495
DM	0.0002	0.0214	0.0002	0.0000	DM	0.0000	0.0083	0.0201	0.0139
J-Test	0.1714	0.9326	0.1525	0.2277	J-Test	0.2127	0.2950	0.9286	0.5655
	BE					NL			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0140	0.0796	0.1381	0.1336	LM	0.0771	0.0873	0.0481	0.1072
DM	0.0018	0.0127	0.0037	0.0002	DM	0.0000	0.0003	0.0032	0.0036
J-Test	0.3944	0.3658	0.7619	0.2604	J-Test	0.1003	0.1820	0.3206	0.7578
	ES					IT			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0026	0.0021	0.0009	0.0428	LM	0.0053	0.0023	0.0309	0.0373
DM	0.0013	0.0015	0.0005	0.0118	DM	0.0001	0.0019	0.0004	0.0003
J-Test	0.2095	0.2259	0.4899	0.3523	J-Test	0.3403	0.2544	0.3406	0.4450

Panel A of Table 4 reports the p-values for GC repos. The results show that the p-values are lowest when funding risk is highest, and vice versa. The results for special repos are reported in Panel B and show that p-values are generally highest in the low-risk quartile, but not always lowest in the high-risk quartiles. However, the differences are miniscule, suggesting that across all countries and repos, the risk premium varies with aggregate funding risk, as represented by the Libor-OIS spread. While the EH generally seems to find more support in the low-risk quartile, the EH cannot be rejected in any of the quartiles for the GC Pooling basket (GCP). Among all GC repos, the GCP basket is characterized by the highest degree of diversification and has the same collateral requirements, i.e., margins, as for refinancing operations with the ECB. By contrast, the GCX basket also includes collateral securities from countries such as, e.g., Italy and Spain, with more exposure to the European sovereign debt crisis in 2011/12 than countries in the GCP basket such as, e.g., Germany or Austria. In fact, from sorting the Libor-OIS spread, one observes that the highest quartile captures the time periods spanning from August 2007 to July 2009 and from August 2011 to July 2012, i.e., the 2008 financial crisis as well as the peak of the European sovereign debt crisis toward the end of 2011.

In the cross-section of GC repos, we find that the lowest p-values are reported for Spain, the GCX basket and Italy, thus affirming the close link between collateral and funding risk established theoretically (e.g., Brunnermeier and Pedersen, 2009). Moreover, the p-values for special repos are generally closer together than for GC repos, further suggesting that funding risk is more adherent to undiversified, idiosyncratic collateral risk.

5.2. Order Imbalance and Repo Specialness

The regression results in Tables 2 and 3 suggest a high correlation between the GC forward spread and ON order imbalance, and a (weaker) correlation between the special forward spread and repo specialness. Accordingly, we sort both variables as described in the previous section, such that the highest quartile of the ON order imbalance captures the largest absolute deviations between borrower- and lender-initiated trading volumes, and the lowest quartile is given by the smallest deviations or zero. Equivalently, repo specialness is sorted from the highest to its lowest value, and we test the EH for each subsample separately. Table 5 reports the p-values of the conditional EH tests for GC ON order imbalance (Panel A) and repo specialness (Panel B).

The results in Panel A are straightforward. In times of high order imbalance, the EH is rejected, implying that the (lagged) forward premium seems to have no predictive power for the (current) change in the ON repo rate. This means, the EH fails to hold as the mismatch between funding supply and demand increases the misalignment between actual costs (ON rate) and expected costs (forward rate). It is important to emphasize that we are testing one-day forward rates, i.e., the shortest possible forecast horizon over which the misalignment between forward and spot rates results in a statistical rejection of the EH. Conversely, the p-values in Table 5 show that the predictive ability of the

Table 5

GC ON Order Imbalance and SC Specialness

This table reports results of the EH tests conditional on the GC ON order imbalance in Panel A, and specialness for special repos in Panel B. All values reported are p-values and calculated as described in the text. Results are shown for GARCH innovations. Countries included are as described in Table 4. Numbers (1) to (4) refer to quartiles sorted according to ON order imbalance/specialness in descending order, i.e., (1) refers to the highest 25%, and (4) to the lowest.

Panel A: GC Repo Rates - ON Order Imbalance									
	DE					FR			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0195	0.0392	0.0962	0.1606	LM	0.0262	0.0438	0.0722	0.1300
DM	0.0044	0.0008	0.0323	0.0308	DM	0.0011	0.0052	0.0010	0.0024
J-Test	0.3666	0.1638	0.7222	0.5412	J-Test	0.4635	0.8018	0.1816	0.2849
	BE					NL			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0131	0.0343	0.1611	0.2507	LM	0.0878	0.0635	0.0474	0.0849
DM	0.0004	0.0037	0.0027	0.0615	DM	0.0074	0.0027	0.0000	0.0156
J-Test	0.3471	0.3438	0.7212	0.9595	J-Test	0.7470	0.4546	0.2101	0.5870
	ES					IT			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0172	0.0444	0.0800	0.0805	LM	0.0002	0.0654	0.0972	0.1987
DM	0.0002	0.0001	0.0209	0.0001	DM	0.0000	0.0001	0.0010	0.0250
J-Test	0.3940	0.3229	0.6414	0.3069	J-Test	0.1106	0.2861	0.4581	0.8920
	GCP					GCX			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0246	0.0373	0.1049	0.2080	LM	0.0295	0.0667	0.0732	0.1896
DM	0.0010	0.0001	0.0308	0.0034	DM	0.0059	0.0028	0.0010	0.0125
J-Test	0.1822	0.2190	0.7136	0.4887	J-Test	0.8161	0.4585	0.3115	0.5457

Panel B: Special Repo Rates - Specialness									
	DE					FR			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0063	0.0334	0.0444	0.0021	LM	0.0310	0.0016	0.0054	0.0041
DM	0.0003	0.0022	0.0123	0.0008	DM	0.0017	0.0001	0.0023	0.0019
J-Test	0.4220	0.2712	0.6990	0.1672	J-Test	0.2392	0.1764	0.2798	0.3991
	BE					NL			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0290	0.1086	0.0029	0.0460	LM	0.0490	0.0731	0.0446	0.0013
DM	0.0022	0.0002	0.0001	0.0096	DM	0.0041	0.0193	0.0022	0.0008
J-Test	0.2737	0.3527	0.2054	0.4975	J-Test	0.5195	0.4437	0.2709	0.2909
	ES					IT			
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
LM	0.0002	0.0310	0.0010	0.1014	LM	0.0042	0.0066	0.0037	0.0667
DM	0.0001	0.0001	0.0001	0.0052	DM	0.0000	0.0000	0.0030	0.0191
J-Test	0.2461	0.3068	0.1524	0.8039	J-Test	0.1055	0.1759	0.4686	0.9249

forward premium is stronger when order flows in the repo market are more balanced, thus implying a better alignment of expectations.

Panel B provides results for special repos and the time variation of repo specialness. The p-values reported in Table 5 suggest that repo specialness cannot thoroughly account for the time variation in the risk premium as already indicated by the regression results in Table 3. This finding confirms the general notion that special repo rates are much harder to predict than GC rates due to their direct exposure to idiosyncratic collateral risks.

5.3. MRO Calendar Effects

Finally, we run EH tests conditional on weekdays to see whether the time variation of the risk premium is affected by deterministic patterns stemming from the weekly MRO schedule. While the results in Table 3 suggest that day-of-the-week effects cannot explain the variation in the daily forward premium (i.e., only the Tuesday dummy is slightly significant for special repos), we report the findings as a robustness check to verify that the test results of the EH are highly consistent with our results from the regression analysis. To test these patterns, we sort the data according to weekdays, such that the reported weekday always refers to the ON rate and the TN rate to the day before. Table 6 reports the p-values for GC repos in Panel A and for specials in Panel B.

As expected, the test results indicate that no clear pattern emerges from the reported p-values. Except for Italy, Table 6 shows that p-values are never highest on Wednesdays, indicating that the positive liquidity shock on Wednesdays may, for example, lower the ON spot rate, thereby increasing the forward premium. In fact, these findings further support our previous results that the forward premium is largely affected by demand pressure and funding risk as opposed to following specific weekday patterns. If anything, the results show that liquidity provision by the central bank can actually distort short-term expectations, as the additional funds which banks receive on Wednesdays are reallocated across banks through the repo market. For example, banks with a liquidity surplus offer their excess funds in the repo market for a lower rate, which can lead to a misalignment of forward and spot rates to the same extent that deficit banks bid more aggressively in order to obtain funding.

6. 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 relate the rejection of the EH to funding risk in the forward premium of very short-term rates. 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 premiums. 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 risk.

We perform various panel regressions and find clear evidence in support of funding risk in the overnight forward premium. We identify aggregate funding risk and demand

Table 6

Calendar Effects - MRO

This table reports the p-values of the EH tests conditional on weekdays. All values reported are calculated as described in the text. Panel A reports results for GC repo rates and Panel B for special repos. Results are shown for GARCH innovations. Country baskets include Germany (DE), France (FR), Belgium (BE), Netherlands (NL), Spain (ES), and Italy (IT), as well as two GC pooling baskets (GCP and GCX). Weekdays are ordered from Monday (1) to Friday (5).

Panel A: GC Repo Rates											
	DE						FR				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.0560	0.0972	0.0612	0.4133	0.1077	LM	0.0015	0.0107	0.0551	0.3349	0.0653
DM	0.0001	0.0402	0.0221	0.0825	0.0064	DM	0.0009	0.0002	0.0483	0.0415	0.0005
J-Test	0.4800	0.8693	0.6520	0.8782	0.4279	J-Test	0.3040	0.2702	0.7928	0.7666	0.3654
	BE						NL				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.1774	0.0460	0.0600	0.0211	0.0513	LM	0.0195	0.0128	0.0275	0.0214	0.0402
DM	0.1051	0.0046	0.0108	0.0020	0.0026	DM	0.0001	0.0005	0.0206	0.0015	0.0058
J-Test	0.8089	0.5388	0.5193	0.2597	0.2930	J-Test	0.3341	0.5037	0.6384	0.2258	0.4116
	ES						IT				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.0262	0.0128	0.0054	0.0621	0.0010	LM	0.0156	0.0123	0.0537	0.0201	0.0239
DM	0.0120	0.0017	0.0006	0.0006	0.0008	DM	0.0001	0.0002	0.0010	0.0001	0.0006
J-Test	0.3554	0.3868	0.2568	0.3956	0.1840	J-Test	0.2277	0.1737	0.4506	0.2300	0.3930
	GCP						GCX				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.0103	0.0324	0.0082	0.0373	0.0992	LM	0.0271	0.0326	0.0103	0.0568	0.0233
DM	0.0014	0.0006	0.0014	0.0018	0.0492	DM	0.0134	0.0005	0.0002	0.0105	0.0011
J-Test	0.3563	0.2569	0.2231	0.3921	0.8924	J-Test	0.7127	0.4967	0.1594	0.6736	0.3333
Panel B: Special Repo Rates											
	DE						FR				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.0409	0.0529	0.0018	0.0481	0.0590	LM	0.0054	0.0013	0.0200	0.0024	0.0721
DM	0.0001	0.0042	0.0002	0.0001	0.0003	DM	0.0001	0.0001	0.0006	0.0006	0.0001
J-Test	0.3153	0.2046	0.2445	0.2905	0.1753	J-Test	0.2612	0.3334	0.5193	0.2535	0.2255
	BE						NL				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.0562	0.0221	0.0112	0.0030	0.0029	LM	0.0715	0.0338	0.0004	0.0915	0.0070
DM	0.0013	0.0000	0.0034	0.0007	0.0001	DM	0.0103	0.0061	0.0002	0.0005	0.0024
J-Test	0.3477	0.2155	0.7513	0.1556	0.3364	J-Test	0.8741	0.8214	0.2761	0.4922	0.7088
	ES						IT				
	(1)	(2)	(3)	(4)	(5)		(1)	(2)	(3)	(4)	(5)
LM	0.0197	0.0034	0.0029	0.0052	0.0056	LM	0.0150	0.0133	0.0271	0.0065	0.0026
DM	0.0038	0.0021	0.0005	0.0033	0.0004	DM	0.0004	0.0109	0.0063	0.0002	0.0014
J-Test	0.3473	0.4176	0.2276	0.4835	0.2120	J-Test	0.4683	0.5205	0.8253	0.2662	0.3572

for funding immediacy as the main variables affecting the forward premium in general collateral (GC) repos, measured by the Libor-OIS spread and repo order flow, respectively. Together with “specialness”, aggregate funding risk is also the main determinant for the forward premium in special repo rates. We perform conditional analyses of the unbiasedness hypothesis by testing the EH based on the sorted funding risk variables and find clear results in support of the EH when funding risk is in its lowest quartile.

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 EH is more likely to be violated 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.

Appendix: Econometric Procedures

GMM Iterative Procedure

The constrained GMM maximization problem is solved via an iterative procedure. Optimizing the Lagrangian in Equation (13), the first-order condition is given by

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -G_T' \Omega_T^{-1} \sqrt{T} g_T(\overline{\theta}) - A_T' \sqrt{T} \overline{\gamma} \\ -\sqrt{T} a_T(\overline{\theta}) \end{bmatrix}, \tag{16}$$

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

$$\sqrt{T} g_T(\theta_0) \to \mathbb{N}(0, \Omega), \tag{17}$$

$$\sqrt{T} g_T(\overline{\theta}) \approx \sqrt{T} g_T(\theta_0) + G_T \sqrt{T}(\overline{\theta} - \theta_0), \tag{18}$$

and

$$\sqrt{T} a_T(\overline{\theta}) \approx \sqrt{T} a_T(\theta_0) + A_T \sqrt{T}(\overline{\theta} - \theta_0). \tag{19}$$

Under the null hypothesis, $a_T = 0$, and substituting Equations (18) and (19) into Equation (16), we have

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -G_T' \Omega_T^{-1} \sqrt{T} g_T(\theta_0) \\ 0 \end{bmatrix} - \begin{bmatrix} B_T & A_T' \\ A_T & 0 \end{bmatrix} \begin{bmatrix} \sqrt{T}(\overline{\theta} - \theta_0) \\ \sqrt{T} \overline{\gamma} \end{bmatrix}. \tag{20}$$

The formula for a partitioned inverse implies that

$$\begin{bmatrix} B_T & A_T' \\ A_T & 0 \end{bmatrix}^{-1} = \begin{bmatrix} B_T^{-1/2} M_T B_T^{-1/2} & B_T^{-1} A_T' (A_T B_T^{-1} A_T')^{-1} \\ (A_T B_T^{-1} A_T')^{-1} A_T B_T^{-1} & -(A_T B_T^{-1} A_T')^{-1} \end{bmatrix}, \tag{21}$$

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 (16) is considered computationally cumbersome (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

$$\overline{\theta} \approx \tilde{\theta} - B_T^{-1/2} M_T B_T^{-1/2} G_T' \Omega_T^{-1} g_T(\tilde{\theta}) - B_T^{-1} A_T' (A_T B_T^{-1} A_T')^{-1} a_T(\tilde{\theta}), \tag{22}$$

$$\overline{\gamma} \approx -(A_T B_T^{-1} A_T')^{-1} A_T B_T^{-1} G_T' \Omega_T^{-1} g_T(\tilde{\theta}) + (A_T B_T^{-1} A_T')^{-1} a_T(\tilde{\theta}). \tag{23}$$

To obtain the constrained parameters $\overline{\theta}$, we iterate on Equations (22) and (23), 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 (4) and (5) 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.

In the second DGP, we reparameterize the residuals from the first DGP, $\varepsilon_t = F\eta_t$, to capture the effects of temporal heteroskedasticity, where η_t is a vector of idiosyncratic innovations and F is a 2×2 factor loadings matrix. In line with Longstaff (2000b) and Della Corte, Sarno, and Thornton (2008), we use a Factor-GARCH(1,1) model augmented with the square root of the (absolute) overnight rate to accommodate for shifts in the short rate, $h_{j,t} = \omega_j \sqrt{|i_{t-1}|} + \beta_j h_{j,t-1} + \alpha_j \eta_{j,t-1}^2$, with $j \in \{1, 2\}$. We use the absolute value of the short rate to deal with negative repo rates toward the end of the sample. 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.

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Illiquidity and the Cost of Carry

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Abstract

This paper proposes to measure market-wide illiquidity by the net deviations between Treasury securities' price discrepancies and arbitrageurs' cost of carry in the repo market. The resulting difference between a bond's forward yield and the yield curve is the expected net return and provides an unexploited arbitrage opportunity that is uniquely connected to the amount of arbitrage capital in the market. Deriving security-specific holding costs for the entire cross-section of Treasury bonds from several European countries, I find that this illiquidity measure captures episodes associated with shortage of arbitrage capital and provides information beyond existing measures of illiquidity. Importantly, it improves the information content extracted from the aggregate noise in Treasury bond yields.

1. Introduction

Arbitrage requires capital and incurs holding costs. When capital constraints are binding, arbitrageurs are limited in their ability to exploit mispricings due to lack of available trading or funding capital. As argued in Hu, Pan, and Wang (2013), this shortage of liquidity supply can cause prices to trade significantly away from their fundamental values, thus creating *noise* in prices. With abundant capital, however, arbitrageurs trade against mispricings only when these are large enough to compensate them for the holding costs they incur (Gromb and Vayanos, 2010). Consequently, only price discrepancies in excess of holding costs constitute actual arbitrage opportunities, and thereby become informative of the level of liquidity in the market.

In this paper, I identify arbitrage opportunities as price discrepancies in the Treasury market *net* of bonds' holding costs. The underlying hypothesis of this approach is that holding costs constitute a limit to arbitrage conceptually distinct from illiquidity, as they accumulate over the lifetime of a bond position and can prevent arbitrageurs from exploiting a security's mispricing (e.g., Tuckman and Vila, 1992; Dow and Gorton, 1994). To obtain a bond's *expected* net return, traders incorporate a security's *cost of carry*, which represents the expected holding cost associated with funding a long or short position in the repo market. The difference between a security's price discrepancy and the cost of carry is the expected net profit, which arbitrageurs would immediately realize given access to sufficient trading and funding capital. Consequently, shortage of arbitrage capital materializes as a positive price discrepancy net of a security's cost of carry.

The basic premise in this paper is that specialized institutions, such as hedge funds and investment banks, use sale and repurchase agreements ("repos") to establish positions in the Treasury market (e.g., Adrian and Shin, 2010). A repo is essentially a cash loan secured by a collateral security, thus serving as a convenient vehicle for fixed-income specialists to borrow cash and securities to finance bond purchases and cover short sales, respectively. The interest rate ("repo rate") is the financing cost associated with borrowing cash for a long position and the interest earned on a short position. The carry is defined as the difference between a bond's yield-to-maturity and the repo rate, such that the cost of carry of a long (short) position is the bond's negative (positive) carry. Deriving security-specific holding costs for the entire cross-section of Treasury bonds from several European countries, I find that profitable arbitrage opportunities explain less than 44% of the variation in aggregate noise.

Accounting for holding costs in the measuring of illiquidity provides an important improvement over the noise measure proposed by Hu, Pan, and Wang (2013) for at least three reasons. First, holding costs are the most relevant and largest costs over the lifetime of an arbitrage trade (e.g., Gromb and Vayanos, 2010). As such, they exceed other (transaction) costs such as the bid ask spread, which is often miniscule for Treasury bonds and less relevant over longer holding periods. Second, holding costs incorporate the cumulative funding cost in the repo market, which is defined as repo specialness and measured by the difference between the market's general funding rate and the bond's (lower) repo rate. The relation between a bond's specialness and enhanced market liquidity is well-established theoretically (e.g., Duffie, 1996; Vayanos and Weill, 2008; Banerjee and Graveline, 2013) and supported empirically (e.g., Jordan and Jordan, 1997; Krishnamurthy, 2002). These papers show that higher funding costs emerge from positive demand shocks, so that adjusting price discrepancies for the cost of carry helps effectively disentangling liquidity demand from liquidity supply. Third, holding costs constitute a limit to arbitrage conceptually distinct from illiquidity, thereby causing pricing errors fundamentally unrelated to binding capital constraints. To the extent that policy implications are drawn from the information content in prices, disentangling conflicting limits to arbitrage is essential for understanding the mechanisms of financial frictions.

The empirical analysis comprises five European countries, namely, Germany, France, Belgium, Spain, and Italy, and spans the time period from 2006 to 2015. European Treasury and repo markets are ideal for investigating illiquidity and holding costs for several reasons. First, the European repo market is the largest and most active repo market in the world, with an average trading volume of more than EUR 50 trillion per year, and thus several times larger than the repo markets in the U.S.[1] In addition to the size, its institutional framework is designed such that collateral securities are usually likewise eligible for refinancing operations at the European Central Bank (ECB) that uses repos as its main operational policy tool. Since repo rates are the key element in determining the cost of carry, a well-established and integrated repo market like the one studied in this paper is of particular importance. Second, European repos are traded over anonymous, transparent, and liquid platforms cleared by central counterparties, which mitigates potential bias from counterparty credit risk and other frictions (e.g., Mancini, Ranaldo, and Wrampelmeyer, 2016; Duffie and Zhu, 2011; Acharya and Bisin, 2014), thus keeping the information content of repo rates as pure as possible. The price formation is further guided by the Eurosystem's official target rate for main refinancing operations (MRO) as well as various money market index rates, thus facilitating an efficient price discovery process and reducing search costs (Duffie, Dworczak, and Zhu, 2017). Third, European Treasury markets belong to the largest and most active debt markets alongside the U.S. Treasury market, populated by many institutional investors and trading firms devoted to fixed-income relative value arbitrage. As such, these markets are well-suited to derive bond fundamental values by a simple factor structure, allowing for a reliable detection

[1]Estimates of the size of the U.S. repo market range from USD 5.5 trillion in 2012 (Copeland, Davis, LeSueur, and Martin, 2012) to USD 10 trillion in 2008 (Gorton and Metrick, 2012).

of arbitrage opportunities from a fitted yield curve. Moreover, given the size and interconnectedness of European debt markets, a shortage of arbitrage capital in these markets is likely to be witnessed also in overall financial markets. Finally, the countries in the sample are characterized by varying degrees of credit quality, providing cross-sectional heterogeneity, in particular with respect to margin requirements, i.e., funding illiquidity (e.g., Brunnermeier and Pedersen, 2009). Finally, the sample period includes episodes associated with severe liquidity shortages, such as the 2008 financial crisis and the European sovereign debt crisis following shortly thereafter, and is characterized by different monetary policy regimes and central bank interventions in bond and repo markets, thus making the European market particularly suitable for analyzing illiquidity.

The construction of the illiquidity measure proceeds in three steps. First, I back out a smooth zero-coupon yield curve using daily Treasury bond prices. On each day, this yield curve is used to price all available bonds, and yield deviations are identified as the difference between a bond's market yield and the model-implied yield. A positive yield deviation means a security is undervalued, and arbitrageurs would trade against this mispricing by establishing a long position. Conversely, an overvalued security is characterized by a negative yield deviation that arbitrageurs would exploit by creating a short position, which involves borrowing the bond in the repo market and selling it in the cash market.

Second, I compute a bond's carry as the difference between the bond's yield-to-maturity and its repo rate (Koijen, Moskowitz, Pedersen, and Vrugt, 2016). The associated holding cost is the signed carry depending on an arbitrageur's bond position: Negative carry refers to the expected holding cost of a long position and positive carry to the expected holding cost of a short position. Third, I calculate a bond's forward yield as the sum of the bond's market yield and carry, which will be closer to the yield curve than the market yield when the cost of carry is positive. The spread between the forward yield and the yield curve represents a positive expected net return as the yield deviation exceeds the associated cost of carry. In order to measure illiquidity based on unexploited yield deviations, I adjust the forward yield such that it equals a bond's market yield if the cost of carry is negative and equals the model-implied yield if the forward yield "crosses" the yield curve.[2] As opposed to using market yields as in Hu, Pan, and Wang (2013), I measure illiquidity by the root mean-squared distance of bonds' (adjusted) forward yields from their model-implied yields, and label this measure *Illiquidity*.

Using a unique and comprehensive data set of the European repo market, I access every repo transaction executed on the three main automated trading systems: BrokerTec, Eurex Repo, and MTS Repo, which together represent more than 67% of the entire Eu-

[2]If the forward yield crosses the yield curve, it trades contrary to the position implied by the market yield. In this case, the position of the forward yield signals that the yield deviation is unprofitable to trade.

ropean repo market in 2014 (European Central Bank, 2015). The data span from 2006 to 2015 and include every repo transaction over the entire cross-section of Treasury bonds from Germany, France, Belgium, Spain, and Italy. Together, these countries represent a market share of 74% of all Treasury repos traded on these platforms. Given the information granularity of these data, this paper provides the first comprehensive study of arbitrageurs' holding costs across the full maturity spectrum of the Treasury yield curve.

To distinguish the illiquidity measure from the noise measure, holding costs would need to provide a meaningful difference in the cross-section of yield deviations. In other words, if the cost of carry was to materialize only on a few isolated bonds or account only for minor deviations from the yield curve, the information content of the illiquidity measure would be similar to the noise measure.

To gain an understanding of the importance of holding costs, I first examine their magnitude over the entire cross-section of yield deviations. Results show that across all countries and days, on average around 80% of all deviations are unprofitable given the expected holding costs, and more than 90% of these costs materialize as short-selling costs. This implies that only around 20% of all yield deviations are actually informative of illiquidity. Given that arbitrage strategies are often conducted across various habitats of the yield curve (e.g., Vayanos and Vila, 2009), I split the yield curve into different maturity segments and find that holding costs largely materialize at the long end of the curve and for bonds trading at a price premium. This implies that illiquidity is on average rather located at the short end of the yield curve in bonds trading at a discount (e.g., Fontaine and Garcia, 2012). Given that severe liquidity conditions spread across borders and markets, I derive a European-wide illiquidity index, constructed from the (repo) volume-weighted average of the country-specific illiquidity measures. Using this index, I compare the illiquidity measure to the noise measure of Hu, Pan, and Wang (2013), and find that illiquidity only explains between 16% and 44% of the monthly time variation in the noise measure.

To analyze the uniqueness of the information content in the illiquidity measure, I examine its relation to other well-known measures of liquidity and compare the findings to the noise measure. Hu, Pan, and Wang (2013) argue that low correlations with term structure variables indicate that a measure constructed from pricing errors in yields contains information beyond what is provided in Treasury rates themselves. I investigate this relation and find that the illiquidity measure, as opposed to the noise measure, is uncorrelated with both the term structure slope and short rate. This may seem unsurprising given that the carry itself is a combination of the term structure slope and a bond's "pull-to-par", implying that adjusting yield deviations for the cost of carry effectively eliminates the information content retrieved from the term structure. By contrast, the illiquidity measure is more correlated with bond volatility in the Treasury market, which suggests a stronger connection of the illiquidity measure to margins and thus funding illiquidity (e.g., Brunnermeier and Pedersen, 2009).

Another popular measure of liquidity is the on-the-run premium, which represents a single deviation from the yield curve and is usually accompanied by high short-selling costs in the repo market (e.g., Duffie, 1996; Vayanos and Weill, 2008). While on-the-run bonds are indeed profitable to trade given their low funding costs during crisis times (e.g., Krishnamurthy, 2002; Musto, Nini, and Schwarz, 2017), their yield deviations may fail to be generally associated with illiquidity as they typically attract large amounts of arbitrage capital during normal times. Accordingly, I find that the noise measure correlates with these liquidity premiums, while the illiquidity measure cannot be linked to their time variation over the full sample period. Conversely, the illiquidity measure correlates strongly with the liquidity factor proposed by Pástor and Stambaugh (2003) - in fact much stronger than reported for the U.S. in Hu, Pan, and Wang (2013). Finally, I also examine the relation with proxies of funding risk premiums in the unsecured interbank market, such as the Libor-OIS spread, and market risk measures like countries' CDS spreads. The relatively low correlations with these variables as compared to the noise measure provide further evidence that the illiquidity measure is purely related to arbitrage capital and unrelated to other sources such as, e.g., credit risk.

Finally, I also analyze the impact of security-specific repo and bond characteristics as well as central bank liquidity provision on bonds' yield deviations and carry. Regression results show that the supply of bonds available for lending decreases a bond's carry, and bonds' price premiums increase when short-sellers concentrate in a bond (Vayanos and Weill, 2008). Moreover, bonds' carry and price premiums increase with, e.g., bonds' time-to-maturity and central banks' open market operations.

This paper contributes to several strands of the literature. First, this study empirically explores the link between arbitrage capital and market illiquidity as emphasized in the theoretical literature on limits to arbitrage (e.g., Merton, 1987; Shleifer and Vishny, 1997; Kyle and Xiong, 2001; Gromb and Vayanos, 2002; Brunnermeier and Pedersen, 2009). More recent empirical papers on this link include, e.g., Coval and Stafford (2007) and Nagel (2012) on equity markets and, e.g., Mitchell, Pedersen, and Pulvino (2007) on convertible bond arbitrage. Malkhozov, Mueller, Vedolin, and Venter (2017) test the pricing implications of a global illiquidity index constructed from the noise measure and find an illiquidity risk premium. Musto, Nini, and Schwarz (2017) analyze noise at the bond-individual level and report that arbitrage opportunities were most pronounced when funding costs were lowest. This paper adds to the literature by incorporating arbitrageurs' cost of carry into the analysis of price discrepancies in the Treasury market and measures illiquidity net of expected holding costs.

Second, this paper is closely related to the empirical literature on bond liquidity premiums and repo funding costs (e.g., Jordan and Jordan, 1997; Buraschi and Menini, 2002; Barclay, Hendershott, and Kotz, 2006; Pasquariello and Vega, 2009), which explores the theoretical link between equilibrium asset prices, repo markets, and the law of one price established in Duffie (1996). I contribute to these papers by introducing bonds' cost of carry based on a model-free evaluation of a position's expected net return from holding and funding positions in the repo market.

Third, this paper is also related more generally to the literature on asset pricing with transaction costs (e.g., Amihud and Mendelson, 1986; Constantinides, 1986; Heaton and Lucas, 1996; Vayanos, 1998; Vayanos and Vila, 1999; Lo, Mamaysky, and Wang, 2004). While these papers mostly analyze transaction costs, such as the bid ask spread, I examine the impact of the cost of carry on bonds' mispricings. Finally, this paper also contributes more broadly to the growing body of empirical research on repo markets. For example, Gorton and Metrick (2012), Krishnamurthy, Nagel, and Orlov (2014), and Copeland, Martin, and Walker (2014) document the fragility of the U.S. repo market during the financial crisis. Mancini, Ranaldo, and Wrampelmeyer (2016) analyze the resilience of the European repo market during the financial crisis, and Boissel, Darrien, Ors, and Thesmar (2017) show that European repo rates are affected by credit risk of the underlying collateral securities. While all these papers focus on the general collateral (GC) market, this paper adds to the literature by examining the role of specific repos during crisis periods and their use in Treasury bond arbitrage.

The remainder of this paper is organized as follows. Section 2 presents the repo and Treasury data. Section 3 describes the curve-fitting method and derives the illiquidity measure. Section 4 provides details of the cost of carry as well as the illiquidity and noise measures. Section 5 analyzes the time series properties of the illiquidity measure and its relation with other liquidity measures. Section 6 conducts a bond-level regression analysis, and Section 7 concludes.

2. Data

The dataset comprises bond and repo data for every Treasury security of five European countries: Germany, France, Belgium, Spain, and Italy. Treasury data are collected from Datastream, and the repo data combine every repo transaction executed on the three major electronic trading platforms for European repos from 2006 to 2015: BrokerTec, Eurex Repo, and MTS Repo.[3] German, French, Belgian, and Spanish repos are mainly traded on BrokerTec and Eurex Repo, while MTS Repo is the main trading platform for

[3]The choice of countries and time periods is based on the consistency of daily repo transactions, thus precluding other countries such as, e.g., Austria, Finland, or Netherlands. Other electronic trading platforms for European repos include, e.g., SENAF/MEFF Repo or TulletPrebon, but their trading volumes are much smaller.

Italian repos.[4] All trading platforms are operated by a central clearing party (CCP) that provides participants with anonymous trading by serving as the counterparty to both sides of a transaction. In contrast to bilateral repos, CCPs require both parties to post initial margins, which are non-negotiable and allow CCPs to protect against counterparty default (e.g., Miglietta, Picillo, and Pietrunti, 2015).[5]

All repos in this paper are "specific" repos (or often called "specials"), which means the repo collateral is restricted to one specific Treasury security (i.e., by its ISIN/CUSIP), thus making specific repos ideal for trading. By contrast, general collateral (GC) repos can be collateralized by a broader basket of securities, e.g., all securities of a certain country or credit quality. A repo transaction is effectively a collateralized loan, which the (cash) borrower receives against pledging the Treasury security as collateral. The repo loan is the market price of the security less the margin, and the cash borrower pays the repo rate to the cash lender.[6] The borrower's motive is to finance a long position in the Treasury bond, and the lender's motive is to borrow the Treasury security for a short sale.

Specific repos are traded overnight with three distinct settlement days: spot, tomorrow-next, and spot-next. While contracted on the same day, the initial exchange of cash and collateral for tomorrow- and spot-next repos is one and two business days later, respectively. In line with settlement conventions in European Treasury markets, the vast majority of European repos is traded spot-next, providing a convenient coordination with the bond markets' time-to-delivery.[7] For each Treasury security, the daily repo rate is computed by the volume-weighted average of all intraday overnight transactions.

As in Hu, Pan, and Wang (2013), the illiquidity measure is constructed using Treasury bonds with maturity between 1 and 10 years that are non-callable, non-flowering, and with no special tax treatment. To fit a reliable yield curve, I apply the same data filter as in Malkhozov, Mueller, Vedolin, and Venter (2017) and use bonds with maturities of up to 15 years.[8]

Table 1A reports the summary statistics of the repo data. On average, between 56.14% and 84.48% of countries' repo trading volumes attribute to bonds with time-to-maturity between 1 and 10 years. In other words, this segment of the yield curve attracts the vast

[4]MTS Repo provides repo data starting only from 2010.

[5]See also Mancini, Ranaldo, and Wrampelmeyer (2016) for a detailed explanation of CCPs' protection mechanisms and their resilience during the financial crisis. The fragility of bilateral and tri-party repos is documented in, e.g., Gorton and Metrick (2012), Krishnamurthy, Nagel, and Orlov (2014), and Copeland, Martin, and Walker (2014).

[6]This convention differs from, e.g., securities lending markets, where the collateral borrower pays a lending fee to the collateral lender (e.g., Duffie, Gârleanu, and Pedersen, 2002).

[7]The fraction of spot-next repos on total overnight volume is 93% (Germany), 80% (France), 86% (Belgium), 85% (Spain), and 85% (Italy), and for spot repos 0%, 2%, 1%, 1%, and 1%, respectively.

[8]The filtering process follows Gürkaynak, Sack, and Wright (2007) and Pegoraro, Siegel, and Pezzoli (2014). See Malkhozov, Mueller, Vedolin, and Venter (2017) for details.

Table 1A

Repo Data Summary Statistics

This table reports repo summary statistics for bonds with maturity ranging from (1 year to 10 years) for Germany (DE), France (FR), Belgium (BE), Spain (ES), and Italy (IT). All is the aggregate repo trading volume of all Treasury securities. Columns 5-9 report time-series averages of the cross-sectional mean, median, and standard deviation. Columns 10-12 report the time series mean, median, and standard deviation for bonds with maturity ranging from (1 year to 4 years), (7 years to 10 years), and the 5- and 10-year on-the-run (OTR) bonds. Lending is the amount of bonds available for lending in billions of euros.

Country	Sample Period	% All (1Y-10Y)	GC Rate (%)	Repo Rate (%)	Volume (€B)	Lending (€B)	Trades (#)	Traders (#)	Volume (%) (1Y-4Y)	(7Y-10Y)	(OTR)
				Mean							
DE	2006–2009	80.05	2.78	2.73	1.50	2.55	37.21	28.55	45.42	26.22	9.14
	2010–2015	84.48	0.18	0.11	1.39	2.40	45.72	29.89	41.25	27.71	7.52
	All	82.71	1.22	1.16	1.44	2.46	42.32	29.36	42.92	27.12	8.17
FR	2006–2009	66.15	2.79	2.73	0.50	1.78	19.18	16.29	45.65	22.45	11.17
	2010–2015	63.90	0.19	0.13	0.71	1.83	28.09	19.45	43.41	27.50	15.04
	All	64.80	1.23	1.17	0.63	1.82	24.53	18.18	44.31	25.48	13.49
BE	2006–2009	62.61	2.80	2.76	0.33	1.02	15.75	15.62	36.22	28.18	17.26
	2010–2015	57.64	0.20	0.17	0.44	0.88	23.22	20.18	42.93	22.33	14.83
	All	59.63	1.24	1.20	0.40	0.93	20.24	18.35	40.25	24.67	15.80
ES	2010–2015	64.27	0.29	0.16	0.35	0.66	20.87	16.54	45.34	26.47	15.19
IT	2010–2015	56.14	0.29	0.20	0.66	0.83	31.77	n/a	52.01	20.23	9.28
				Median							
DE	2006–2009			2.76	1.31	2.65	34.71	28.62	44.38	27.01	8.99
	2010–2015			0.14	1.17	2.05	42.15	30.00	41.51	23.86	6.86
	All			1.19	1.22	2.27	39.18	29.45	42.85	24.78	7.77
FR	2006–2009			2.74	0.46	1.67	18.41	16.38	45.39	22.81	10.53
	2010–2015			0.16	0.60	1.75	26.22	19.43	43.64	26.07	14.65
	All			1.19	0.54	1.72	23.10	18.21	44.54	24.71	12.89
BE	2006–2009			2.77	0.31	0.95	15.52	15.69	36.09	28.49	16.83
	2010–2015			0.17	0.41	0.83	22.78	20.28	43.00	22.41	14.26
	All			1.21	0.37	0.88	19.88	18.45	41.14	24.38	15.20
ES	2010–2015			0.20	0.32	0.61	20.29	17.23	45.58	26.50	14.83
IT	2010–2015			0.24	0.59	0.80	30.59	n/a	52.10	19.95	9.06
				Standard Deviation							
DE	2006–2009			0.09	0.88	1.03	14.94	6.05	6.59	6.61	2.70
	2010–2015			0.09	0.86	1.48	19.05	6.69	10.23	11.36	3.38
	All			0.09	0.87	1.31	17.41	6.44	9.19	9.77	3.22
FR	2006–2009			0.06	0.27	0.74	7.03	3.51	5.41	6.09	3.60
	2010–2015			0.08	0.47	0.75	11.54	4.54	7.59	8.16	5.04
	All			0.07	0.39	0.75	9.74	4.13	6.89	7.81	4.90
BE	2006–2009			0.03	0.16	0.40	4.65	3.29	8.54	6.80	5.90
	2010–2015			0.02	0.20	0.33	6.52	3.86	6.48	6.45	4.58
	All			0.03	0.18	0.36	5.77	3.64	8.07	7.19	5.29
ES	2010–2015			0.13	0.22	0.34	10.01	5.23	7.58	7.67	5.68
IT	2010–2015			0.11	0.38	0.37	12.42	n/a	7.47	4.47	3.13

majority of total government bond repo trading. The average daily repo rate is several basis points lower than the average daily GC rate for all countries and time periods, generating a positive spread defined as repo specialness (Duffie, 1996). The average daily trading volume per bond ranges between EUR 330 million and EUR 1.5 billion, indicating that the cross-country heterogeneity in repo volumes approximately follows the cross-country differences between the corresponding debt markets. Also reported in Table 1A are the average number of transactions and traders in the market. On average, there are between 16 and 46 transactions per bond and day, with somewhat more trades taking place in the second half of the sample period. Except for MTS Repo, the trading platforms assign traders a unique identification number, which allows computing the average number of traders and gives an idea about the kind of traders in the market. Table 1A shows that the daily average number of traders per bond is fairly close to the average number of transactions, implying that these government bond repos are used for establishing and rolling over traders' bond positions rather than for, e.g., intraday repo round-trip trading.

Table 1A also reports the daily average volume of bonds available for lending. The data are collected by Markit and combine the amount of bonds provided through the securities lending market, which has been shown to be closely connected to the repo market (Corradin and Maddaloni, 2017). Given that the largest part of a government bond issue is held by long-term investors, such as pension funds and insurance companies, the amount of bonds available for lending serves as an indicator for the actual supply of securities in the market available for trading.

The last three columns of Table 1A present the fraction of trading volume in different maturity segments of the yield curve and the percentage of volume traded in the 5- and 10-year on-the-run bonds (OTR). Given that the number of bonds always increases toward the short end of the yield curve, the average trading activity is quite evenly distributed across maturity segments, alleviating the concern that trading is concentrated only in a few bonds. Along those lines, the newest 5- and 10-year issues are popular objects for relative value arbitrage, thus attracting high trading volumes in the repo market. Despite their popularity and corresponding larger relative trading share, on average more than 85% of repo trading concentrates in all other issues.

Table 1B presents the summary statistics of the Treasury data. Across countries and time periods, there are on average 32 bonds every day to fit the yield curve and 25 bonds to construct the illiquidity measure.

Overall, the Treasury bond characteristics compare fairly well with the U.S. data reported in Hu, Pan, and Wang (2013). For example, bond maturity and age remain very stable over time, implying that their time-series variation is unlikely to drive the time series of aggregate yield deviations. Cross-country differences in market liquidity are indicated by the bid ask spread, which is highest for Spain, Italy, and Belgium, and lowest for Germany. Table 1B also shows that bond yields have decreased in similar magnitude over time as repo rates, suggesting that the carry remained relatively stable. Moreover, the average carry is a multiple of the average bid ask spread, emphasizing the relevance of holding costs in comparison to other (transaction) costs. Overall, Tables 1A and 1B show that mean and median values across all countries and variables are close together, alleviating the concern that the cross-section of bonds is dominated by a few securities

Table 1B

Treasury Data Summary Statistics

Bonds with maturity ranging from (3 months to 15 years) are used for curve fitting, and bonds with maturity ranging from (1 year to 10 years) are used to construct the illiquidity measure. Reported are the time-series averages of the cross-sectional mean, median, and standard deviation. Size is the amount outstanding in billions of euros. The bid ask spread is the bid yield minus the ask yield.

Country	Sample Period	# Bonds (3M-15Y)	# Bonds (1Y-10Y)	Coupon (%)	Size (€B)	Bid/Ask (bps)	Maturity (years)	Age (years)	Duration (years)	Price (€)	Yield (%)
							Mean				
DE	2006–2009	39	32	3.96	19.23	1.84	4.22	3.52	3.79	101.82	3.37
	2010–2015	43	36	2.48	18.78	1.29	4.48	3.12	4.18	106.48	0.78
	All	41	35	3.07	18.96	1.51	4.37	3.28	4.03	104.61	1.82
FR	2006–2009	37	26	3.93	17.22	2.12	4.51	3.57	4.05	101.15	3.48
	2010–2015	39	25	2.90	24.88	2.87	4.39	3.65	4.07	106.36	1.10
	All	38	25	3.31	21.82	2.57	4.44	3.62	4.06	104.28	2.05
BE	2006–2009	15	13	4.18	11.53	2.22	5.15	4.04	4.56	101.40	3.65
	2010–2015	18	14	3.58	12.13	4.94	4.76	4.23	4.33	107.92	1.52
	All	17	14	3.82	11.89	3.85	4.91	4.15	4.42	105.32	2.38
ES	2010–2015	26	20	3.90	14.68	8.78	4.64	3.06	4.10	103.81	2.86
IT	2010–2015	36	31	3.78	19.75	5.34	4.36	3.06	3.94	104.09	2.64
							Median				
DE	2006–2009			3.91	19.45	1.40	3.61	2.97	3.38	101.78	3.37
	2010–2015			2.55	18.72	1.06	3.95	2.52	3.79	105.72	0.65
	All			3.10	19.01	1.19	3.81	2.70	3.63	104.15	1.74
FR	2006–2009			3.92	17.64	1.82	4.05	3.10	3.72	101.22	3.49
	2010–2015			2.97	25.17	2.47	3.89	3.07	3.72	106.03	0.98
	All			3.35	22.16	2.21	3.96	3.08	3.72	104.11	1.99
BE	2006–2009			4.08	11.39	1.91	4.95	3.57	4.46	101.55	3.69
	2010–2015			3.80	11.86	4.08	4.40	3.76	4.11	107.85	1.49
	All			3.91	11.67	3.21	4.62	3.69	4.25	105.33	2.37
ES	2010–2015			4.03	14.72	6.74	4.06	2.26	3.76	103.38	2.79
IT	2010–2015			4.00	19.59	4.85	3.72	2.26	3.52	103.74	2.57
							Standard Deviation				
DE	2006–2009			0.82	4.39	1.36	2.63	2.74	2.19	2.65	0.28
	2010–2015			1.27	3.66	0.96	2.68	2.56	2.40	5.21	0.49
	All			1.09	3.95	1.12	2.66	2.63	2.31	4.19	0.41
FR	2006–2009			0.83	3.60	1.07	2.55	2.59	2.12	3.07	0.29
	2010–2015			1.08	5.86	1.53	2.54	2.66	2.22	4.67	0.59
	All			0.98	4.96	1.35	2.55	2.63	2.18	4.03	0.47
BE	2006–2009			0.86	2.85	1.30	2.68	2.78	2.20	3.34	0.32
	2010–2015			0.75	2.49	2.52	2.56	2.67	2.18	4.53	0.62
	All			0.79	2.63	2.03	2.61	2.71	2.19	4.05	0.50
ES	2010–2015			0.98	2.82	5.16	2.67	2.53	2.16	4.48	0.76
IT	2010–2015			0.99	4.86	2.73	2.60	2.52	2.12	4.16	0.74

with extreme observations.

3. Constructing the Illiquidity Measure

3.1. Curve Fitting

A proper identification of over- and undervalued securities requires a smooth estimation of the yield curve, for which various spline- and function-based models have been proposed in the literature.[9] Among the latter, the Nelson-Siegel (1987) model provides a parsimonious parametric function that describes the yield curve by three latent factors (Diebold and Li, 2006). The model assumes the following functional form of the instantaneous forward rate f:

$$f(m, b) = \beta_0 + \beta_1 \exp\left(-\frac{m}{\tau}\right) + \beta_2 \frac{m}{\tau} \exp\left(-\frac{m}{\tau}\right), \tag{1}$$

where m denotes the time to maturity and $b = (\beta_0\ \beta_1\ \beta_2\ \tau)$ is the set of model parameters to be estimated. As $m \to \infty$, $f \to \beta_0$, and as $m \to 0$, $f \to \beta_0 + \beta_1$, such that the model parameters can be interpreted as the long-term level, short-term rate, and the slope and curvature of the forward curve, where τ determines the location of the "hump". To model the term structure of interest rates, a proper set of parameters must satisfy the conditions $\beta_0 > 0$, $\beta_0 + \beta_1 > 0$, and $\tau > 0$. As an alternative to the Nelson-Siegel (1987) model, Hu, Pan, and Wang (2013) and Malkhozov, Mueller, Vedolin, and Venter (2017) employ the Svensson (1994) model, which adds a second hump to Equation (1), allowing for more flexibility than the Nelson-Siegel (1987) model in fitting longer maturities. However, this second hump is not well-defined when observations are rather scarce as for the countries considered in this sample. To avoid potential overfitting, I rely on the Nelson-Siegel (1987) model, which has been shown to provide superior fitting results over more flexible methods for maturity spectrums similar to the one analyzed in this paper (see, e.g., Nymand-Andersen, 2018).[10]

Instead of using the parameterized forward curve and deriving the corresponding zero-coupon yield curve directly, one can back out the model parameters b using bonds' market prices. Let N_t be the number of bonds available on day t with maturity between 3 months and 15 years, and denote their mid prices P_i^t, for $i = 1, \ldots, N_t$. The set of model parameters b_t is estimated by minimizing the weighted sum of squared deviations between actual and model-implied prices according to

$$b_t = \underset{b}{\operatorname{argmin}} \sum_{i=1}^{N_t} \left[(P^i(b) - P_t^i) \times \frac{1}{D_i} \right]^2, \tag{2}$$

where $P^i(b)$ is the model-implied price given parameters b, and D_i is the MaCaulay duration. Following standard practice in the literature, price deviations are weighted by

[9] Spline-based models rely on piecewise polynomial functions that are smoothly connected at selected knots along the maturity space to jointly approximate a smooth yield curve. I experiment with several variations of cubic spline methods and penalty parameters, including the variable roughness penalty (VRP) method proposed by Waggoner (1997) and used by the Bank of England. In line with Hu, Pan, and Wang (2013), results in this paper are highly robust to the specific curve-fitting technique.

[10] Nevertheless, I also employ the Svensson (1994) model for robustness. Despite large fitting errors in the beginning of the sample, results are highly similar to the Nelson and Siegel (1987) model, implying that overall results in this paper are independent of the specific curve-fitting method.

the inverse of bond durations to account for the higher price sensitivity of bonds with longer maturities.

3.2. Cost of Carry

To exploit mispricings in the Treasury market, arbitrageurs establish long positions in securities identified as "cheap" and short positions in securities that trade "rich" to the yield curve. The respective positions are funded in the repo market, where arbitrageurs borrow cash to finance a long position or borrow the security to cover a short position. To finance a long position, arbitrageurs deliver the purchased security as collateral and pay the repo rate to the cash lender. To establish a short position, the arbitrageur "reverses in" the collateral security via repo, and earns the repo rate for lending the proceeds from the asset sale to the cash borrower.

The carry of a fixed-income security is defined as the expected net return from holding a long position financed in the repo market. Assuming the bond price stays constant, the carry is given by the difference between a bond's coupon C_i and the financing cost $r_i \times P_i$, given by the product of the bond's repo rate r_i and its market price P_i, i.e.,

$$Carry_i = C_i - r_i \times P_i. \tag{3}$$

While Equation (3) provides the general intuition, the expected net return on a bond is best described by assuming that the entire term structure of interest rates stays constant over the next period. As shown in Koijen, Moskowitz, Pedersen, and Vrugt (2016), for every period t and market-observed yield y_t^i, a bond's carry c_t^i is computed as

$$\begin{aligned} c_{i,t} &= \frac{P_{i,t+1}^{T-1} + C_i \times 1_{[t+1 \in [coupon\ dates]]} - P_{i,t}^{T}}{P_{i,t}^{T}} - r_{i,t} \times \eta, & (4)\\ &= y_{i,t}^{T} - r_{i,t} \times \eta + \frac{P_{i,t+1}^{T-1} - P_{i,t}^{T-1}}{P_{i,t}^{T}}, & (5)\\ &\cong y_{i,t}^{T} - r_{i,t} \times \eta - D^{mod}(y_{i,t}^{T-1} - y_{i,t}^{T}), & (6)\end{aligned}$$

where $\eta = 365/360$ accounts for the 360-day quoting practice in repo markets. The first term of Equation (6) represents the slope of the term structure, given by the spread between the bond's market yield and the (adjusted) repo rate. The last term is the bond's "pull-to-par", which captures the yield change as the bond rolls down the yield curve, multiplied by the modified duration to hedge against shifts in the term structure (e.g., Krishnamurthy, 2002).

The cost of carry is then simply obtained by adjusting the sign of the carry according to the respective position. For a long position, the cost of carry is the negative carry, i.e., $-c_{i,t}$, which means financing an asset will come at a net cost. Conversely, the cost of carry for a short position is the carry itself, i.e., $c_{i,t}$.

To understand the relation between the carry in Equation (6) and, e.g., short-selling costs in the repo market, it is instructive to decompose the total return of a short position into its individual components. Ignoring the hedging term and the day-count convention, the net deviation is profitable if

$$y_i^T(b_t) - y_{i,t}^T \geq y_{i,t}^T - r_{i,t}. \tag{7}$$

The term on the left-hand side is the bond's yield deviation and the term on the right-hand side is the bond's cost of carry.[11] Following Duffie (1996), repo specialness $s_{i,t}$ is the difference between the GC rate R_t and the bond's repo rate, i.e., $s_{i,t} = R_t - r_{i,t}$. Moreover, under rational expectations, the bond's liquidity premium must be equal to the average future specialness until the bond matures, i.e.,

$$y_i^T(b_t) - y_{i,t}^T \cong \frac{1}{T}\sum_{t=0}^{T}(R_t - r_{i,t}). \tag{8}$$

Denoting the term of the right-hand side in Equation (8) by $s_{i,t}^T$, Equation (7) can be rearranged to

$$s_{i,t}^T - s_{i,t} \geq y_{i,t}^T - R_t, \tag{9}$$

stating that higher repo specialness today must be accompanied by a lower yield-to-maturity in order for the short position to yield a positive expected net return. Moreover, a steeper term slope, as expressed by the right-hand side of Equation (9), implies that a short position is less likely to be profitable given that specialness cannot be negative.

3.3. Forward Yields

To assess whether a price discrepancy is expected to yield a positive net return, arbitrageurs obtain the break-even threshold of a position. To that end, investors compute a bond's forward yield $f_{i,t}$ by adjusting the market yield for the cost of carry according to

$$f_{i,t} = y_{i,t} + c_{i,t}. \tag{10}$$

Equation (10) states that the forward yield is above the market yield when the carry is positive and below the market yield when the carry is negative. In other words, with positive cost of carry, the forward yield is above the market yield on a short position and below the market yield on a long position. With respect to a bond's deviation to the

[11] As in Hu, Pan, and Wang (2013), this framework abstracts from other issues such as, e.g., transaction costs, initial margins, regulator costs, etc.

yield curve, the position is expected to yield a positive net return when the (absolute) deviation exceeds the cost of carry.

To extract illiquidity from the information content in yield deviations, it is necessary to adjust the forward yields such that they are bounded by the yield curve and the market-observed yields. Neither a yield deviation measured from a forward yield that has “flipped” to the other side of the yield curve, nor a forward yield deviation with negative cost of carry provides an informative net deviation. Accordingly, I denote $\tilde{f}_{i,t}$ as the adjusted forward yield, which is equal to the forward yield in Equation (10) when $f_{i,t}$ is located between the market yield and the yield curve. Otherwise, $\tilde{f}_{i,t}$ either equals the model-implied yield if $f_{i,t}$ “crosses” the yield curve, or equals the market yield if the cost of carry is negative.

3.4. Measuring Illiquidity

Using the set of model parameters b backed out from daily bond prices as shown in Equation (2), the corresponding model-implied yields $y^i(b_t)$ are computed for all N_t bonds with maturity between 1 and 10 years. For each day and country, the illiquidity measure is then constructed by calculating the root mean-squared distance between the adjusted forward yields $\tilde{f}_{i,t}$ and the model-implied yields:

$$Illiquidity_t = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t}(\tilde{f}_{i,t} - y^i(b_t))^2}. \tag{11}$$

By contrast, the noise measure of Hu, Pan, and Wang (2013) is designed to capture all deviations across the yield curve, and is constructed by calculating the root mean-squared distance between the market-observed yields and the model-implied yields according to

$$Noise_t = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t}(y_{i,t} - y^i(b_t))^2}. \tag{12}$$

To avoid extreme pricing errors drive either measure, I employ the same filter as proposed by Hu, Pan, and Wang (2013), which is also applied in Malkhozov, Mueller, Vedolin, and Venter (2017). That is, I exclude any bond with yield-to-maturity more than four standard deviations away from the model yield. In line with these papers, this filter is only triggered a few times overall.

To illustrate the difference between the two measures, Figures 1 and 2 plot several examples of par-coupon yield curves, market-observed bond yields, and adjusted forward yields. The top panel of Figure 1 plots three normal days over the sample period, illustrating that the curve fitting method captures the term structure of bond yields reasonably

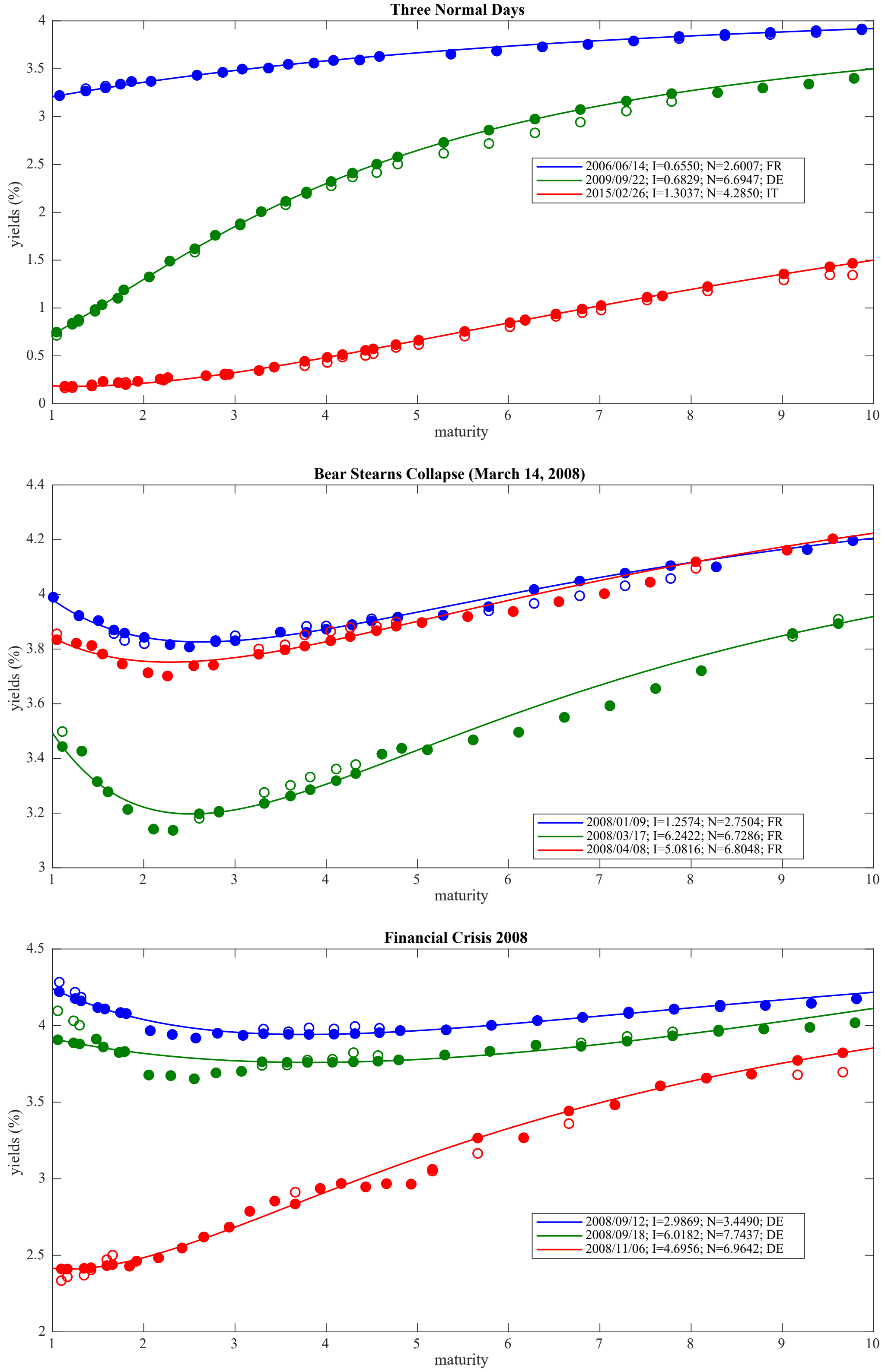

Figure 1: Example of Market-Observed Yields and (Adjusted) Forward Yields (I).
Market yields are marked "○" and (adjusted) forward yields "●". The upper panel plots three normal days, the middle panel plots the days surrounding the collapse of Bear Stearns in March 2008, and the lower panel plots the days surrounding the Lehman default in September 2008. Marked in the legends are the date of observation, the levels of the illiquidity and noise measures, and the country.

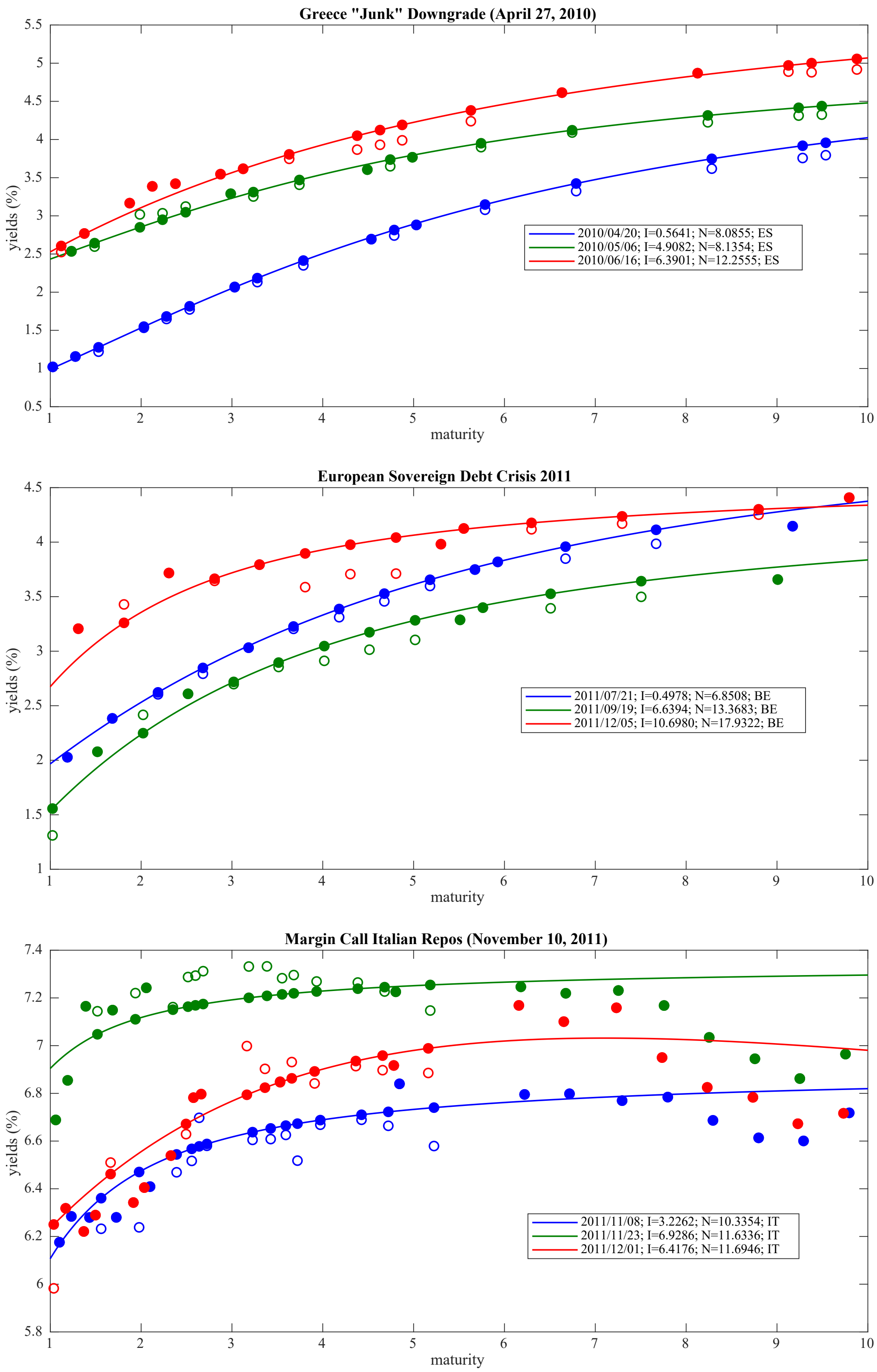

Figure 2: Example of Market-Observed Yields and (Adjusted) Forward Yields (II). Market yields are marked "○" and (adjusted) forward yields "•". The upper panel plots the downgrade of Greece's credit rating to "junk" status, the middle panel shows days during the peak of the European sovereign debt crisis in 2011, and the lower panel plots the days surrounding the raise in initial margins for Italian repos on November 10, 2011 by LCH.Clearnet. Marked in the legends are the date of observation, the levels of the illiquidity and noise measures, and the country.

well across time and countries. The other panels in Figure 1 and Figure 2 plot the days surrounding well-known liquidity events, including the collapse of Bear Stearns in March 2008, the Lehman default in September 2008, the downgrade of Greece's credit rating to "junk" status in March 2010, the peak of the European sovereign debt crisis in 2011, and a major margin call of Italian repos in November 2011.[12]

All these plots show a large dispersion of market and adjusted forward yields around the fitted yield curves, and illustrate that most of these bonds had negative costs of carry during those times. For example, the entire long end of the German yield curve right around the Lehman default shows that the adjusted forward yields are equal to the market yields, implying that the corresponding price premiums represented positive net returns. While these bonds are typically expensive to short-sell, the deviations of these yields were indeed profitable, demonstrating that arbitrage capital was rather scarce at that time. Moreover, this pattern seems to appear across various habitats of the yield curve, suggesting that investment firms were (at least temporarily) abandoning their arbitrage activities. Overall, the forward yields behave similarly for the other events, indicating that the illiquidity measure seems capable of finely disentangling liquidity demand from supply, and detecting the episodes associated with severe shortage of arbitrage capital.

4. Illiquidity, Noise, and the Cost of Carry

4.1. Time Series

The daily time series of the country-specific illiquidity and noise measures are plotted in Figures 3 and 4. Figure 3 plots Germany, France, and Belgium over the full sample period between 2006 and 2015, and Figure 4 plots Spain and Italy between 2010 and 2015.

For all countries and time periods, the plots reveal that the noise measure is always larger than the illiquidity measure, and, most importantly, that the difference between them varies considerably over time. That is, the spread between Noise and Illiquidity almost disappears during crisis times, while it appears relatively large during other times. By construction, Noise is always larger than (or equal to) Illiquidity as it captures the entire cross-section of daily yield deviations, whereas Illiquidity is measured from the subset of all profitable net deviations. Given the bonds' cost of carry, the spread between Noise and Illiquidity in Figures 3 and 4 thus accounts for yield deviations that are expensive to trade, which decrease substantially during, e.g., the period surrounding the Lehman default in September 2008 or the peak of the European sovereign debt crisis in the fall of 2011. As the lack of liquidity supply spreads across the yield curve, more and more bonds

[12]On November 11, 2011, LCH.Clearnet, which provides risk metrics and margins to MTS Repo, raised haircuts on Italian repos from around 5.5% to 11.65%.

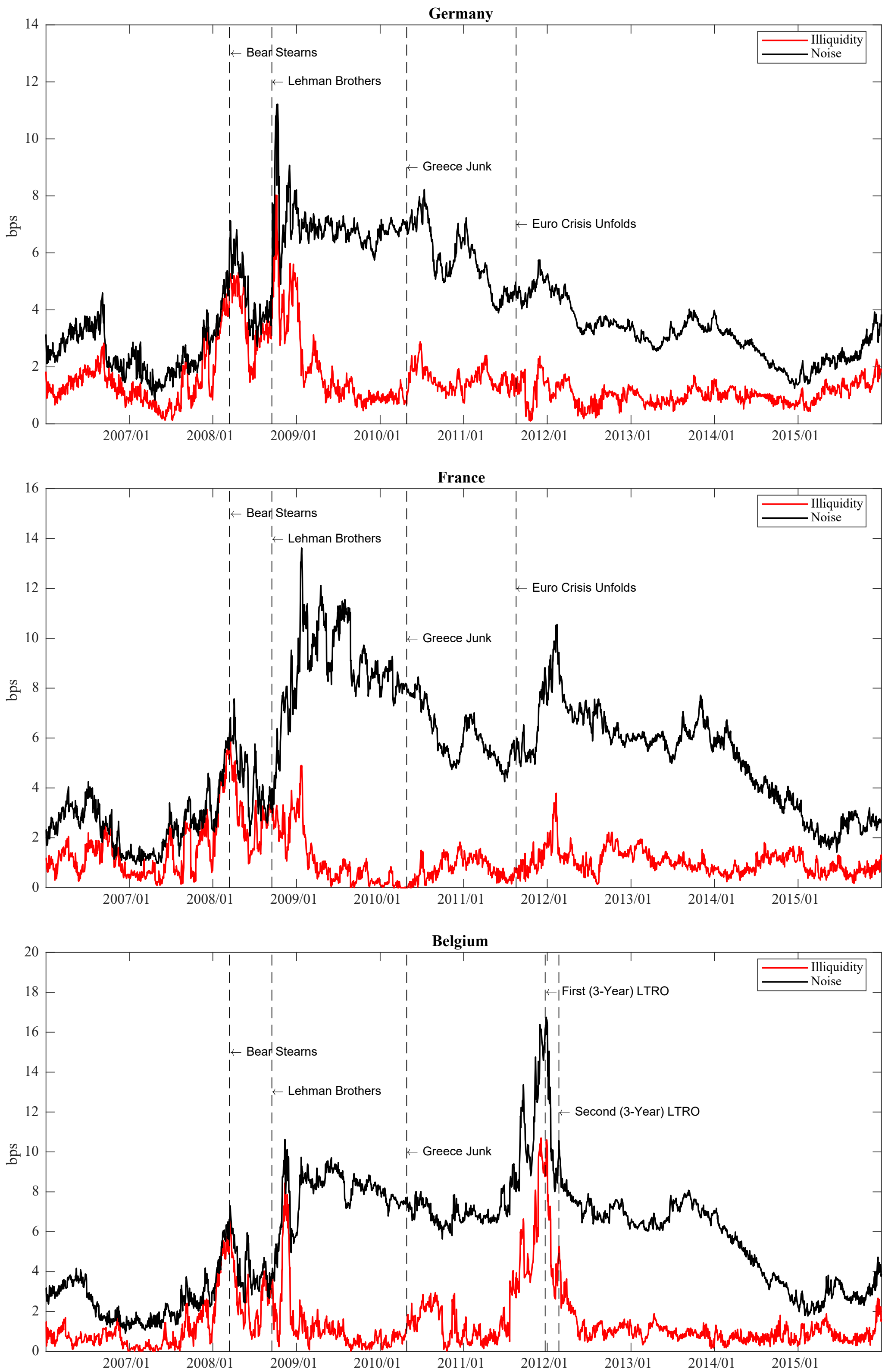

Figure 3: Daily Time Series of Illiquidity and Noise (2006-2015).
Bear Stearns: Collapse of Bear Stearns on March 14, 2008; Lehman Default: September 15, 2008; Greece Junk: Downgrade on April 27, 2010; Euro Crisis Unfolds: Stock Market Crash on August 18, 2011; First (3-Year) LTRO: December 23, 2011; Second (3-Year) LTRO: February 21, 2012.

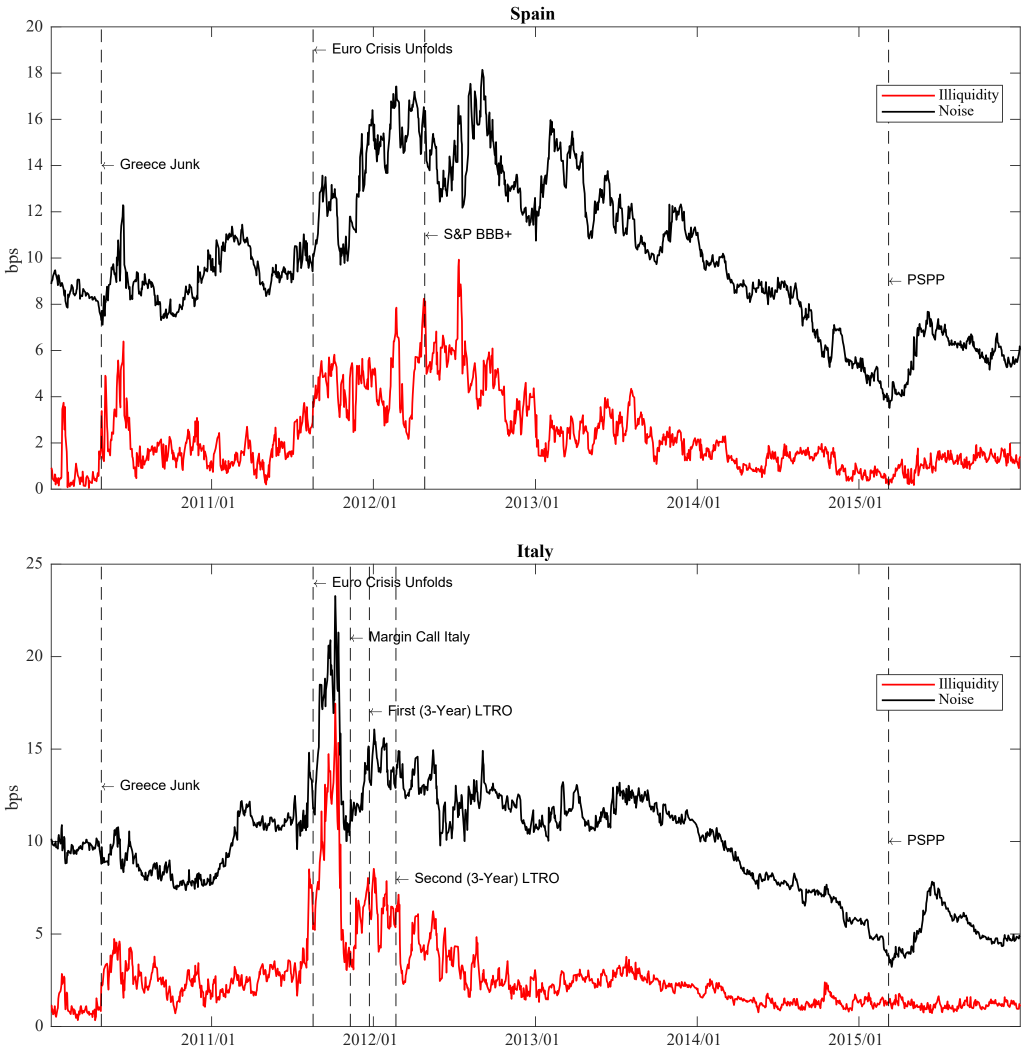

Figure 4: Daily Time Series of Illiquidity and Noise (2010-2015).
Greece Junk: Downgrade on April 27, 2010; Euro Crisis Unfolds: Stock Market Crash on August 18, 2011; Margin Call Italy: November 10, 2011; First (3-Year) LTRO: December 23, 2011; Second (3-Year) LTRO: February 21, 2012; S&P BBB+: Standard & Poor's Downgrade of the Spanish Credit Rating on April 26, 2012; PSPP: Start of the Public Security Purchase Program on March 9, 2015.

become affected and the illiquidity measure converges to the noise measure.

Importantly, however, Figures 3 and 4 also show that the illiquidity measure can differ quite substantially from the noise measure. Most notably, the illiquidity measure decreases much quicker in the aftermath of a liquidity event than the noise measure, which becomes particularly evident in the beginning of 2009 when central banks extended their credit lines to improve liquidity conditions in the financial markets. For example, in response to the freeze in interbank lending after the Lehman default, the ECB introduced a full-allotment liquidity regime in October 2008, along with several major interest rate cuts and an extension of eligible collateral securities for refinancing operations. Similarly, in response to worsening funding conditions for banks in possession of government collateral securities from Italy and Spain, in October 2011 the ECB announced it would conduct outright bond

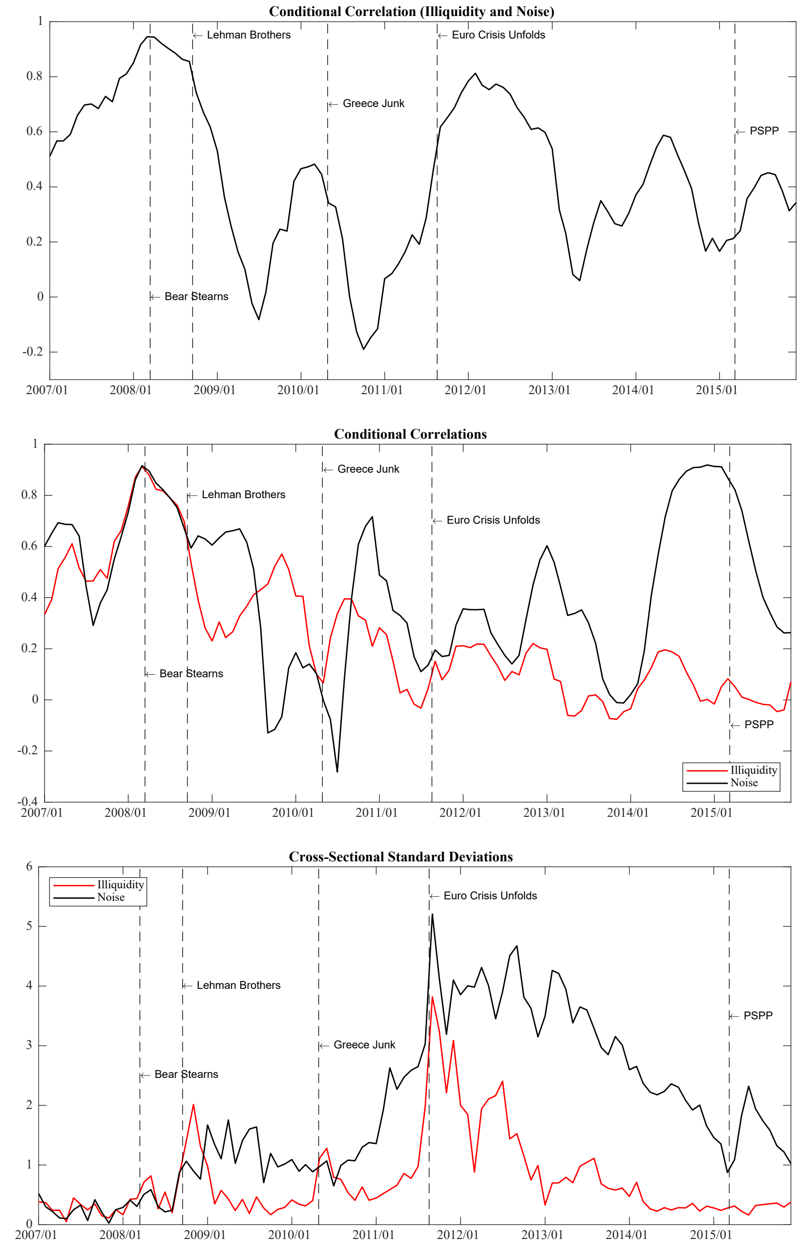

Figure 5: Average Conditional Correlations and Cross-Sectional Standard Deviations. The upper panel plots the average conditional correlation of the illiquidity and noise measures using a one-year rolling window of daily data. The second panel shows the average conditional correlations among all five country-specific measures (Germany, France, Belgium, Spain, Italy). The lower panel depicts the cross-sectional standard deviations of the country-specific illiquidity and noise measures. Plots are shown using monthly data between 2007 and 2015.

purchases in the secondary market and guarantee low margins and borrowing costs over three years as part of two long-term refinancing operations (LTROs). As a consequence, Figures 3 and 4 show that starting from 2013, the illiquidity measure remains more or less constant at an average of around one basis point, while the noise measure only reaches its pre-crisis level in the beginning of 2015. Yet, in March 2015 the ECB started its public security purchase program (PSPP), which left the illiquidity measure mostly unaffected but increased the noise measure, especially for Spain and Italy.

Another interesting aspect shown in Figures 3 and 4 is that the country-specific illiquidity measures show varying degrees of co-movement. To illustrate these patterns, Figure 5 plots average conditional correlations across measures and countries, as well as cross-sectional standard deviations. The upper panel shows that Illiquidity and Noise reach an average correlation of 80% and more around the Bear Stearns collapse in March 2008, the Lehman default in September 2008, as well as during the European sovereign debt crisis. In turn, the average conditional correlation becomes fairly low during non-crisis periods, e.g., reaching negative correlation at the end of 2010. The middle panel of Figure 5 illustrates that the conditional correlations across countries are highest during the 2008 financial crisis, decrease slowly thereafter, and depict modest spikes during several periods associated with the European sovereign debt crisis. The lower panel of Figure 5 plots the average cross-sectional standard deviation, showing more dispersion during crises periods such as in 2011/12. Compared to the noise measure, the illiquidity measure seems to have a lower average dispersion across countries, but increases with cross-country differences in illiquidity as observed, e.g., during the recent financial crises.

To address commonality among the countries, I construct a European illiquidity index from the cross-section of countries by the (repo) volume-weighted average of the country-specific illiquidity measures. Repo volumes are the ideal weights as they represent the actual funding capital lent against all the collateral securities. Accordingly, a country's individual illiquidity measure receives more weight in the index the more funding capital is absorbed by the cross-section of its securities, thus reflecting its "systemic" importance in case funding liquidity evaporates.[13] Figure 6 plots the time series of the Illiquidity index as well as the Noise index, which is constructed analoguosly. Overall, both indices provide a fair representation of their individual constituents and allow for a relative comparison between liquidity events. For example, the Illiquidity index increases more and longer during the 2008 financial crisis than during the European sovereign debt crisis, suggesting that market-wide wealth shocks to arbitrage capital were most pronounced in 2008.

4.2. Illiquidity Facts

Table 2 documents the key facts about the illiquidity and noise measures and provides detailed information on the cost of carry.

Panel A of Table 2 reports the summary statistics of both measures. Unsurprisingly, the illiquidity measure is on average lower than the noise measure for all countries in the sample. In absolute terms, the standard deviations are also larger for the noise measure, but relative to the time-series mean they are much larger for the illiquidity measure. This

[13]Between 2010 to 2015, the index weights are 49% (DE), 17% (FR), 6% (BE), 7%(ES), and 21% (IT).

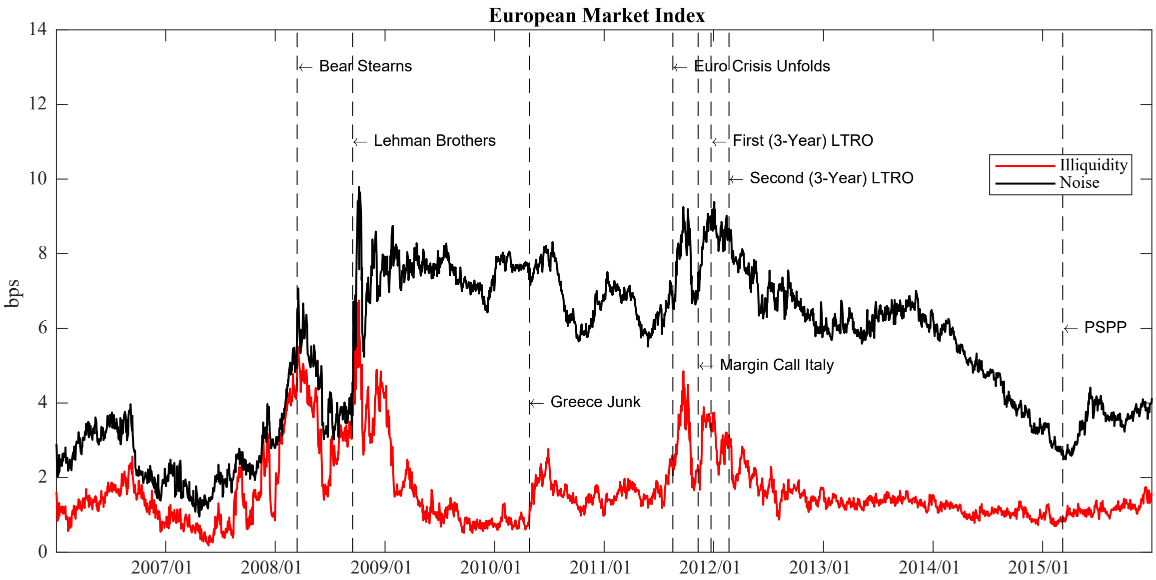

Figure 6: Daily Time Series of the Illiquidity Index and Noise Index.
Greece Junk: Downgrade on April 27, 2010; Euro Crisis Unfolds: Stock Market Crash on August 18, 2011; Margin Call Italy: November 10, 2011; First (3-Year) LTRO: December 23, 2011; Second (3-Year) LTRO: February 21, 2012; PSPP: Start of the Public Security Purchase Program on March 9, 2015.

difference in dispersion is also reflected in the highest and lowest values, suggesting that the illiquidity measure usually remains at a comparably low level and spikes up more prominently during crisis times, as can be seen in the figures above. Since the difference between Noise and Illiquidity amounts to costs, the difference in means indicates that the largest portion of noise indeed constitutes unprofitable deviations.

Panel B provides a detailed overview of these costs. On average, more than 70% of all bonds across the yield curve carry positive costs, of which more than 90% account for short-selling costs. Moreover, the differences between countries are fairly small, suggesting that these costs occur regardless of cross-country differences in the number of bonds or repo trading volume. Panel B also reports the time series means of the cross-sectional average share of unprofitable yield deviations. Across countries, holding costs account for 76% (DE) to 88% (ES) of daily yield curve deviations, implying that on average less than 20% of yield curve deviations are actually profitable to trade and thus informative of illiquidity. To better understand these numbers, deviations are further dissected into maturity buckets (as in Table 1A), and into bonds trading cheap (“Long Noise”) and expensive (“Short Noise”) to the yield curve. The results in Panel B show that the average share of unprofitable deviations at the short end of the yield curve amounts to around 60%, whereas this share increases to more than 90% at the long end of the yield curve. While these numbers seem large at first sight, they are intuitive since bonds such as the most recent 10-year issue are generally in high demand in the cash market, thus trading at a premium (e.g., Jordan and Jordan, 1997) and bearing high short-selling costs

Table 2

Illiquidity, Noise, and Cost of Carry

Panel A reports the summary statistics (in bps) of the illiquidity (Illiq) and noise (Noise) measures for Germany (DE), France (FR), Belgium (BE), Spain (ES), and Italy (IT). Panel B reports the daily averages of bonds' cost of carry (∅ Bonds), the average percentage of costs assigned to short positions (∅ Short Costs), and the average share of yield deviations associated with costs (∅ Noise). The latter is further divided into maturity spectrum (1 to 4 years) and (7 to 10 years), positive deviations (Long Noise), and negative deviations (Short Noise). Panel C reports pairwise correlation coefficients between Illiquidity and costs for two subperiods including the financial crisis (2007-2009) and the European sovereign debt crisis (2010-2011). Panel D reports estimated coefficients and the associated R^2 from the regression $Illiq_t^i = \beta_0^i + \beta_1^i Noise_t^i + \varepsilon_t^i$ for country i and month t. Newey-West t-statistics are reported in squared brackets.

Panel A: Illiquidity and Noise

	DE		FR		BE		ES		IT	
	Illiq	Noise	Illiq	Noise	Illiq	Noise	Illiq	Noise	Illiq	Noise
Mean	1.472	4.036	1.172	5.230	1.419	5.610	2.337	10.012	2.596	9.763
StDev	1.018	1.850	0.898	2.523	1.532	2.779	1.639	3.205	2.039	3.074
Max	8.033	11.216	6.272	13.619	10.698	16.743	9.929	18.142	17.459	23.278
Min	0.104	0.837	0.000	0.890	0.010	0.916	0.053	3.516	0.337	3.223

Panel B: Cost of Carry

	DE	FR	BE	ES	IT
∅ Bonds	69.83%	72.03%	77.09%	76.09%	74.50%
∅ Short Costs	90.32%	95.34%	96.70%	100.00%	100.00%
∅ Noise	76.42%	82.64%	85.10%	88.72%	86.75%
(1Y-4Y)	59.21%	57.22%	61.15%	60.13%	55.95%
(7Y-10Y)	84.89%	95.88%	95.52%	99.90%	99.59%
∅ Long Noise	18.29%	8.40%	6.28%	0.00%	0.02%
(1Y-4Y)	20.26%	9.22%	6.85%	0.00%	0.02%
(7Y-10Y)	8.68%	2.36%	0.00%	0.00%	0.00%
∅ Short Noise	90.26%	93.67%	94.82%	100.00%	100.00%
(1Y-4Y)	80.26%	89.15%	89.16%	100.00%	100.00%
(7Y-10Y)	95.18%	96.23%	97.38%	100.00%	100.00%

Panel C: Pairwise Correlations of Illiquidity and Cost of Carry

	DE	FR	BE	ES	IT
2007-09	−0.212	−0.455	−0.384		
t-stat	[−1.26]	[−2.98]	[−2.43]		
# Obs	36	36	36		
2010-11	−0.266	−0.570	−0.098	0.035	−0.210
t-stat	[−1.29]	[−3.25]	[−0.46]	[0.16]	[−1.01]
# Obs	24	24	24	24	24

Panel D: Illiquidity Loading on Noise

	DE		FR		BE		ES	IT	Market Index	
	2006-15	2010-15	2006-15	2010-15	2006-15	2010-15	2010-15	2010-15	2006-15	2010-15
β_0	0.305	0.699	1.191	0.762	−0.437	−1.701	−1.197	−2.137	0.656	−0.021
t-stat	[1.11]	[5.90]	[7.23]	[3.10]	[−0.97]	[−2.51]	[−4.29]	[−2.85]	[3.41]	[−0.08]
β_1	0.294	0.123	0.002	0.034	0.341	0.511	0.352	0.497	0.189	0.263
t-stat	[3.59]	[3.60]	[0.06]	[0.66]	[3.69]	[4.39]	[10.82]	[5.80]	[4.50]	[5.49]
Adj. R^2 (%)	24.41	17.10	0.00	0.00	31.31	57.46	58.83	59.31	13.66	43.52
#Obs	120	72	120	72	120	72	72	72	120	72

(e.g., Banerjee and Graveline, 2013). As bonds mature older, they become less liquid and often trade at a discount (e.g., Fontaine and Garcia, 2012), which can be seen in Panel B when separating between premium and discount bonds. Across countries, the average share of unprofitable yield deviations that lie "above" the yield curve ranges from 0% (ES) to 18% (DE), while around 95% of deviations "below" the yield curve are due to holding costs. Taking all the information together, Panel B suggests that the vast majority of yield curve deviations are unprofitable to trade given the expected holding costs, and that mostly undervalued securities at the short end of the yield are informative of illiquidity.

Panel C reports pairwise correlations between the cost of carry and the illiquidity measure. Reported are monthly correlations for the period before and after the financial crisis and the two years associated with the peak of the European sovereign debt crisis. Except for Spain, correlations are generally negative, verifying that costs and illiquidity share not a very strong commonality. If anything, the correlations imply that the cost of carry actually decrease in absence of arbitrage activity, as suggested in the theoretical literature on repo funding costs (e.g., Duffie, 1996).

To examine the relation between the illiquidity and noise measures, Panel D reports the factor loadings from regressing monthly illiquidity measures on monthly noise measures (and a constant). While the results show that the two measures co-move positively, the R^2 of these regressions varies significantly, i.e., from 0% for France to 59% for Italy. Repeating this regression only for the period between 2010 and 2015, the reported R^2 are low for France (0%) and Germany (17%), and higher for Belgium (57%), Spain (58%), and Italy (59%). With regard to the co-movement in the overall market, the R^2 is 43.52%, suggesting that less than half of the monthly variation in the noise measure is explained by illiquidity. Since the only difference between the two measures is the cost of carry, this result shows that almost 57% of the monthly variation in the noise measure is driven by the variation in holding costs.

5. Time Series Properties

To further compare the information content in the illiquidity measure to the noise measure and other measures of market liquidity, Table 3 reports the results of an OLS regression of monthly changes in Illiquidity and Noise on several other important market variables proposed in Hu, Pan, and Wang (2013). Since illiquidity is most informative when becoming a market-wide phenomenon, Table 3 reports the regression results using the Illiquidity and Noise market indices. Regressions are first conducted univariately, and then in multivariate form to compare the relative contribution of each variable. The corresponding pairwise correlations of monthly changes in these variables are reported in Table 4. Any country-specific anomalies in comparison to the market index are mentioned in the text.[14] Panel A of Table 3 reports the results for the illiquidity measure and Panel B for the noise measure.

[14] Country-specific results are provided in the internet appendix.

5.1. Treasury Market: Level, Slope, and Volatility

Since both measures are derived from pricing errors in Treasury yields, it is important to first understand how Illiquidity and Noise relate to interest rate level, slope, and volatility of the Treasury market. This examination is particularly informative given that a bond's carry is closely related to the slope of the term structure, such that yield deviations associated with holding costs may be confused with poor curve-fitting. Results are summarized in the top left panels of Table 3. First, regressing monthly changes in Illiquidity on monthly changes in the 3-month Treasury bill rate, I find a negative but statistically insignificant relation. The negative correlation implies that the illiquidity measure increases when the short rate decreases, which is typically associated with crisis periods. The same regression for the noise measure also shows a negative and statistically insignificant relation. The explanatory power of the short rate is rather limited, with an R^2 of 0% for Illiquidity and 6.08% for Noise. In fact, the latter number is fairly similar to the U.S. as reported in Hu, Pan, and Wang (2013).

An important factor in this analysis is the term structure slope, which is computed by the spread between a country's 10- and 1-year government bond yields. Regressing monthly changes in the noise measure on monthly changes in the Term variable, the results show a positive and significant relation with an R^2 of 14.47%. For each individual country, the correlations are also positive and the R^2 ranges from 5.66% (FR) and 6.57% (DE) to 9.09% (IT), 12.32% (ES), and 16.02% (BE). Hence, in this case the market index rather represents the higher end of the correlation spectrum, with the positive coefficient indicating an increase in yield curve deviations during times of economic recession, which is typically associated with a steepening yield curve. The same regression for the illiquidity measure yields essentially no correlation, which is intuitive given that the carry itself is the slope of the term structure. Thus, correcting yield deviations for the cost of carry strongly reduces the correlation between the illiquidity measure and the term slope. However, it is worth emphasizing that the null correlation reported in Table 3 may in fact be due to several confounding effects, including an enduring recession period in many European countries combined with expansive monetary policy, thus reducing illiquidity as shown in Figures 3 and 4. Consequently, the term slope only correlates with the noise measure, on aggregate also somewhat higher than for the U.S. as shown in Hu, Pan, and Wang (2013).

Since both measures are computed from the cross-sectional dispersion in yields, it is instructive to compare them to the volatility in the Treasury market, which is computed by the annualized bond return volatility using a rolling window of 21 business days. The regression results show a positive and significant relation for both Illiquidity and Noise, with an R^2 of 9.81% and 7.29%, respectively. Unlike Hu, Pan, and Wang (2013), who argue that a low correlation with bond volatility is indicative of superior information

Table 3

Monthly Changes on Other Market Variables

Reported are OLS regression coefficients with Newey-West t-statistics in squared brackets. On5Y and On10Y are the on-the-run premiums for 5-year and 10-year bonds, respectively. TB3M is the 3-month Treasury bill rate. GC is the overnight general collateral rate. LIBOR is the spread of 3-month EURIBOR over the 3-month overnight index swap (OIS) rate. CDS is the 5-year senior-CDS spread. VIX is the EuroStoxx 50 implied volatility index. Special is the spread between overnight GC and special repo rates. ΔPSLiq is the innovation in the liquidity factor by Pástor and Stambaugh (2003). Stockret is the monthly return on the EuroStoxx 50 index. BondV is the annualized return volatility of monthly bond returns calculated from 5-year Treasury yields using a rolling window of 21 business days. Term is the spread of 10- over 1-year Treasury yields. Panel A reports results for Illiquidity and Panel B for Noise.

Panel A: Illiquidity

Treasury: Level, Slope, and Volatility	(1)	(2)	(3)	(4)
ΔTB3M	−0.216			−0.934
	[−0.26]			[−1.44]
ΔTerm		−0.003		−0.008
		[−0.38]		[−1.34]
ΔBondV			0.009	0.011
			[2.77]	[2.82]
Adj. R^2 (%)	0.00	0.00	9.81	14.18
# months	119	119	119	119

On-the-Run Premiums and Specialness	(1)	(2)	(3)	(4)
ΔOn5Y	−0.112			−0.113
	[−1.77]			[−1.77]
ΔOn10Y		−0.016		−0.015
		[−0.62]		[−0.54]
ΔSpecial			0.002	0.008
			[0.04]	[0.24]
Adj. R^2 (%)	4.27	0.00	0.00	2.88
# months	119	119	119	119

Stock Market: Ret, VIX, and U.S.	(1)	(2)	(3)	(4)
StockRet	−0.020			0.003
	[−0.87]			[0.13]
ΔVIX		0.034		0.031
		[1.21]		[1.08]
ΔPSLiq			−2.713	−2.440
			[−2.15]	[−2.03]
Adj. R^2 (%)	1.35	5.47	8.63	11.60
# months	119	119	119	119

GC, LIBOR, and Default	(1)	(2)	(3)	(4)
ΔGC	0.172			0.177
	[0.30]			[0.32]
ΔLIBOR		0.010		0.006
		[0.76]		[0.34]
ΔCDS			0.007	0.006
			[1.49]	[1.08]
Adj. R^2 (%)	0.00	2.89	1.09	0.20
# months	119	119	96	96

Panel B: Noise

Treasury: Level, Slope, and Volatility	(1)	(2)	(3)	(4)
ΔTB3M	−0.874			−0.698
	[−0.99]			[−0.97]
ΔTerm		0.014		0.010
		[1.75]		[2.12]
ΔBondV			0.007	0.009
			[2.00]	[2.39]
Adj. R^2 (%)	6.08	14.47	7.29	24.80
# months	119	119	119	119

On-the-Run Premiums and Specialness	(1)	(2)	(3)	(4)
ΔOn5Y	−0.044			−0.054
	[−0.89]			[−0.96]
ΔOn10Y		0.074		0.072
		[3.38]		[3.23]
ΔSpecial			0.045	0.047
			[1.38]	[1.48]
Adj. R^2 (%)	0.00	3.76	2.43	6.50
# months	119	119	119	119

Stock Market: Ret, VIX, and U.S.	(1)	(2)	(3)	(4)
StockRet	−0.027			−0.011
	[−1.37]			[−0.58]
ΔVIX		0.031		0.022
		[1.06]		[0.64]
ΔPSLiq			−1.127	−0.926
			[−0.69]	[−0.68]
Adj. R^2 (%)	3.15	4.70	0.88	4.38
# months	119	119	119	119

GC, LIBOR, and Default	(1)	(2)	(3)	(4)
ΔGC	−0.483			−0.472
	[−0.87]			[−1.00]
ΔLIBOR		0.013		0.011
		[1.05]		[0.74]
ΔCDS			0.008	0.004
			[1.74]	[0.64]
Adj. R^2 (%)	1.92	5.77	1.90	7.43
# months	119	119	96	96

Table 4

Pairwise Correlations (in %)

Pairwise correlation coefficients are computed using monthly changes and reported in percentages. See Table 3 for definitions of variables.

		3	4	5	6	7	8	9	10	11	12	13	14
1	ΔIlliquidity	-6	-9	33	-23	-4	1	-15	25	-31	6	19	15
2	ΔNoise	-26	39	28	-9	21	18	-20	23	-13	-16	26	17
3	ΔTB3M		-49	27	-20	-15	-25	29	-23	-1	53	-26	-14
4	ΔTerm			-2	19	26	21	-6	15	9	-40	27	6
5	ΔBondV				-15	-19	9	-29	30	-33	-0	12	26
6	ΔOn5Y					1	10	-1	11	25	-15	19	-3
7	ΔOn10Y						3	-7	-13	36	-9	8	5
8	ΔSpecial							-5	12	-3	-0	30	-5
9	StockRet								-73	1	24	-28	-62
10	ΔVIX									-14	-15	40	48
11	ΔPSLiq										11	3	18
12	ΔGC											-13	-16
13	ΔLIBOR												32
14	ΔCDS												

content in the noise measure, theory and standard risk management practice argue that bond volatility is in fact one of the main drivers (if not *the* main driver) of repo margin setting, and thus funding illiquidity (e.g., Brunnermeier and Pedersen, 2009). Table 3 reports that the illiquidity measure correlates positively with bond volatility with an R^2 higher than for the noise measure. Adding the 3-month Treasury rate and term slope together with bond volatility in a multivariate regression, Table 3 reports that together they explain 14.18% of the variation in the illiquidity measure and 24.80% of the variation in the noise measure.

5.2. On-the-Run Premiums and Specialness

A commonly used measure of Treasury market liquidity is the on-the-run premium of the newly issued 10-year and 5-year bonds. Both are components of the illiquidity and noise measure as they represent two specific price deviations along the yield curve. Moreover, on-the-run premiums are typically associated with high short-selling costs, which usually account for the entire liquidity premium. Results of the monthly regressions in changes are reported in the top right panels of Table 3. The coefficient of the 10-year on-the-run premium is positive and statistically significant for the noise measure, with an R^2 of only 3.67%. By contrast, the 5-year on-the-run premium is uncorrelated with the noise measure, which may be due to the fact that the on-the-run premium is not very pronounced in most European countries (e.g., Ejsing and Sihvonen, 2009). While on-the-run bonds are mostly used by bond dealers and market makers in the U.S. to hedge against interest rate risk, European markets are characterized by highly liquid futures markets, for which the on-the-run bond is generally not the cheapest to deliver. That said, the illiquidity measure has no positive correlation with the on-the-run premiums. In fact, the coefficients are both negative and (slightly) significant for the 5-year on-the-run premium.

Price premiums are mostly accompanied by repo specialness, which increases with short-selling demand as collateral bonds become harder to source. Since the largest fraction of holding costs materializes as short-selling costs as reported in Table 2, I compute the cross-sectional average of bonds' repo specialness and regress the monthly changes in Noise and Illiquidity on monthly changes in specialness. The results in Table 3 show a positive but insignificant correlation with the noise measure and an R^2 of 2.43%, and a null correlation with the illiquidity measure. Combining on-the-run premiums and specialness in a multivariate regression, the R^2 is 2.88% for the illiquidity measure and 6.50% for the noise measure.

5.3. Stock Market: Return, VIX, and U.S. Equity Market

Liquidity conditions in Treasury markets are mostly indicative of liquidity conditions in overall financial markets, i.e., stock markets in particular. To address this point, I examine how the illiquidity measure compares to the noise measure when relating both to stock market variables. One important liquidity factor is the measure constructed by Pástor and Stambaugh (2003), which captures illiquidity in the U.S. equity market using the idea that order flow induces greater return reversals when illiquidity is high. Given the importance of the U.S. equity market for global liquidity conditions, I use this measure alongside the EuroStoxx 50 equity index, which represents the 50 largest European companies listed on national exchanges in the Eurozone. In addition to the equity indices, I also examine how the illiquidity and noise measures relate to the EuroStoxx 50 implied volatility index, which is the European counterpart of the VIX "fear gauge" constructed from S&P 500 index options. The corresponding regression results are reported in the lower left panels of Table 3. Most importantly, I find that the illiquidity measure has a negative and statistically significant relation with the Pástor and Stambaugh (2003) liquidity factor, implying that a negative shock to systematic liquidity in the U.S. equity market is accompanied by an increase in the European Illiquidity index. This is informative as it highlights the close connection between liquidity conditions across international markets, as documented in Malkhozov, Mueller, Vedolin, and Venter (2017). Moreover, the R^2 of this regression is 8.63%, which makes the Pástor and Stambaugh (2003) liquidity factor, together with bond volatility, the variable with the highest explanatory power. Moreover, the adjusted R^2 of 8.63% is more than twice as large as the R^2 reported for the U.S. noise measure in Hu, Pan, and Wang (2013). The noise measure in this regression is also negatively correlated with the Pástor and Stambaugh (2003) liquidity factor, but this relation is statistically insignificant and the corresponding R^2 is only 0.88%. With regard to the European stock market index, the correlations with the illiquidity and noise measures are both negative, but statistically insignificant with an adjusted R^2 of 1.35% and 3.15%, respectively. All stock market variables together explain 11.60% and 4.38% of the variation in the illiquidity and noise measure, respectively.

5.4. Credit Market: GC, Libor, and CDS Spreads

Since the only difference between the illiquidity and noise measure is costs, it is informative to examine their relation to commonly used funding cost variables, such as the GC repo rate or the Libor-OIS spread. Boissel, Darrien, Ors, and Thesmar (2017) show that repo rates are affected by broader market, counterparty, and credit risk, it is instructive to add CDS spreads to the analysis. Unsurprisingly, the regression results in Table 3 show that the noise measure is positively correlated with the Libor-OIS and CDS spreads, and negatively correlated with the GC rate, displaying an R^2 of 5.77%, 1.90%, and 1.92%, respectively. While the CDS spread is the only significant variable in the univariate regressions, the explanatory power of the multivariate regression is 7.43%. By contrast, regressing monthly changes in the illiquidity measure jointly on monthly changes in the GC rate, Libor-OIS spread, and CDS spreads produces an adjusted R^2 of 0.20%.[15]

5.5. All Together

Finally, considering all variables jointly in one multivariate regression describes how much of the monthly variation in the illiquidity and noise measures are explained by these variables, and, more importantly, how much of the variation remains unexplained. The adjusted R^2 of such regression for the noise measure is 34.20%, and thus lower than the 43.70% reported for the U.S. noise measure in Hu, Pan, and Wang (2013). By contrast, the same regression for the illiquidity measure generates an adjusted R^2 of 22.48%, implying that more than three fourth of the variation in the illiquidity measure remains unexplained.[16]

[15] Additionally, I also compare both measures to the bid ask spread. Regressing monthly changes in the illiquidity and noise measures on monthly changes in the bid ask spread, the coefficients are 0.354 and 0.357, respectively, with corresponding t-statistics of 2.03 and 1.94, and an adjusted R^2 of 9.10% and 9.87%. The pairwise correlations are 31% and 33%, respectively.

[16] Acknowledging the fact that CDS spreads are only available from 2008 onwards, the equivalent regression without CDS spreads generates an adjusted R^2 of 23.67% for the illiquidity measure and 28.41% for the noise measure.

6. Explaining Carry and Yield Deviations

The previous analysis revealed that aggregate net deviations contain information associated with market-wide illiquidity. In this section, I examine the role of bond-specific liquidity and security characteristics as well as central bank interventions for the cross-section of Treasury bond yield deviations and carry.

6.1. Bond, Repo, and Central Bank Liquidity

Starting with repo characteristics, I measure security-specific *Demand* in the repo market as the daily repo order imbalance between reverse repos (cash lender-initiated) and repos (cash borrower-initiated), divided by a bond's nominal amount outstanding (e.g., Corradin and Maddaloni, 2017). The latter is the euro volume of the bond that has been issued since inception. Since the motive of a reverse repo is to borrow the security in order to cover a short position, this variable approximates net short-selling demand for a given bond. Analogously, I define bond-specific *Supply* as the security's daily actual amount available for lending, divided by the bond's nominal amount outstanding. As shown in Tables 1A and 1B, the actual amount available for lending is much lower than the nominal issue size, implying that bonds that are harder to source may carry higher short-selling costs and thus a larger price premium (e.g., Duffie, 1996).

In addition to security-specific demand and supply, I introduce a new measure called *Short-sellers*, which is computed by the difference between the number of traders initiating a reverse repo and traders initiating a repo, divided by the total number of traders. Vayanos and Weill (2008) show that short-sellers prefer to trade in bonds that also other short-sellers find optimal to trade in, thus creating a self-fulfilling constraint: A higher concentration of short-sellers increases borrowing costs and, consequently, the price premium of the security. Therefore, an increase in the number of traders initiating a short position in the same bond serves as a proxy for higher concentration of short-sellers.

To capture bond-specific liquidity, I employ a similar set of variables as proposed in Musto, Nini, and Schwarz (2017), who relate relative pricing errors in U.S. Treasuries to a set of bond-specific characteristics that have frequently been used in the literature as proxies of liquidity. Specifically, I include a bond's *age*, calculated as the (log) number of years since inception, and *ttm*, which measures a bond's time-to-maturity in (log) years (e.g., Amihud and Mendelson, 1991; Fontaine and Garcia, 2012). As additional characteristics, I include the (log) nominal amount outstanding, denoted by *out* (Longstaff, Mithal, and Neis, 2005), and a bond's nominal coupon, denoted by *Coupon*, which is indeed a component of a bond's carry as shown in Equation (3). Lastly, I include a bond's *Bid Ask* spread, computed as the bid yield minus the ask yield, divided by the mid yield.

Finally, I add two measures of central bank liquidity provision to examine their impact on yield deviations and holding costs. The first measure is denoted by *OMO* and summarizes the (log) amount outstanding of the ECB's open market operations, i.e., the weekly main refinancing operations (MRO) and the three-year long-term refinancing operations (LTRO). The second measure, *ExLiq*, captures excess liquidity in the European banking system and is computed by the sum of the (log) balance of banks' current accounts at the ECB and deposit facility, less the sum of banks' reserve requirements and the amount banks hold in the marginal lending facility.

For every day t and security i, the basic regression model takes the form

$$Z_{i,t} = \alpha_i + \alpha_t + \beta X_{i,t} + \varepsilon_{i,t}, \tag{13}$$

where $Z_{i,t}$ is either the bond's yield deviation, $y_{i,t} - y_i(b_t)$, or carry as computed by Equation (6). $X_{i,t}$ captures the set of explanatory variables, and α_i and α_t are security and day fixed effects, respectively.

6.2. Regression Results

Regressions are conducted univariately and in three multivariate specifications. Results for bonds' carry as the dependent variable are reported in Table 5.

With regard to the repo characteristics, the results in Table 5 suggest that the supply of bonds is the most important variable determining a bond's carry. The significant negative coefficient means that an increase in the number of available bonds by one percentage point decreases the carry by on average 2.58 basis points, that is, the holding cost for a short position. By contrast, higher demand for a Treasury security and the presence of more short-sellers increase the carry, but these relations are statistically insignificant. Given that the carry is closely related to the slope of the term structure, the results in Table 5 show that time-to-maturity increases the carry, implying that short positions in bonds located toward the longer end of the yield curve have higher holding costs than bonds at the short end. Moreover, bonds with higher coupons have a higher carry, and bonds with larger issues have a lower carry, while the relation to age and bid ask spread is statistically insignificant.

The results also show a strong positive relation between ECB open market operations and bond carry, meaning that more liquidity provision by the central bank is associated with higher expected returns from holding a long position. This is intuitive since more central bank liquidity provision reduces financing costs by driving repo rates down (e.g., Acharya, Gromb, and Yorulmazer, 2012). In turn, this connection implies that short-selling becomes increasingly costly, given that the repo rate is a short-seller's income and bonds become harder to source when encumbered as collateral for refinancing operations

Table 5

Carry and Security-Specific Liquidity Characteristics

This table reports coefficients from regressing bonds' carry on security-specific characteristics as well as proxies of central bank liquidity provision. Carry is computed as described in Equation (6). Demand is the difference between a bond's (cash) lender- and borrower-initiated trading volumes, divided by a bond's amount outstanding. Supply is the amount available for lending, divided by a bond's amount outstanding. Short-sellers is the net number of lenders, divided by the total number of repo market participants. ttm denotes a bond's (log) time-to-maturity, and age is the (log) age of a bond (in years). Bid Ask is a bond's bid yield minus ask yield, divided by the mid yield. Coupon refers to a bond's nominal coupon, and out is a bond's (log) amount outstanding. OMO refers to the (log) amount of the ECB's open-market operations (in EUR billions), including its main and long-term refinancing operations. ExLiq denotes ECB excess liquidity (in EUR billions), computed as the (log) sum of banks' current account and the ECB's deposit facility, minus the marginal lending facility and reserve requirements. The sample includes all bonds from Germany, France, Belgium, Spain, and Italy with maturity between 1 and 10 years. Standard errors are clustered at security- and day-level (shown in parentheses). The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Demand	0.22										0.43***	−1.05***	0.87***
	(0.15)										(0.14)	(0.28)	(0.29)
Supply		−2.58***									−2.03***	−3.77***	−2.27***
		(0.51)									(0.46)	(0.65)	(0.63)
Short-sellers			0.04								0.02	0.13	−0.01
			(0.04)								(0.05)	(0.08)	(0.08)
ttm				0.35***							0.41***	0.71***	0.71***
				(0.12)							(0.13)	(0.05)	(0.11)
age					−0.02						0.02	−0.13**	−0.21***
					(0.03)						(0.04)	(0.05)	(0.07)
BidAsk						0.00					0.00	−0.00	−0.00
						(0.00)					(0.00)	(0.00)	(0.00)
Coupon							0.32***					0.27***	
							(0.04)					(0.04)	
out								−0.28**				−0.64***	
								(0.12)				(0.11)	
OMO									0.98***				1.03***
									(0.11)				(0.11)
ExLiq										0.00			
										(0.01)			
ISIN FE	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes
Day FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No
Adj. R^2 (%)	84.36	84.78	83.68	84.53	84.38	84.40	43.48	36.48	53.28	48.39	84.29	64.15	62.34
# Bonds	316	314	255	320	320	320	320	316	320	320	249	249	249
# Obs.	257,576	246,791	212,156	258,142	258,142	256,753	258,199	257,578	258,199	236,216	200,019	200,019	200,019

at the ECB. In fact, the latter effect accounts for the main difference between open market operations and banks' excess liquidity, which has effectively no explanatory power.

Table 6 presents the regression results with bonds' yield deviations as the dependent variable. In contrast to the carry analysis, the results show that yield deviations are strongly associated with short-sellers' concentration in a given security. The negative coefficient implies that a one percentage point increase in the number of short-sellers leads to an average increase in the price premium of almost one basis point, thus confirming the findings in the theoretical literature (Vayanos and Weill, 2008). Moreover, the coefficients of a bond's time-to-maturity and coupon are strongly negative, stating that bonds at the long end of the yield curve and bonds with higher coupons are rather associated with liquidity premiums. Together with the respective positive coefficients for the carry, these results confirm that short positions in bonds with longer time-to-maturity carry higher holding costs, which ultimately translate into higher price premiums. In fact, these results underline the importance to account for holding costs when measuring aggregate illiquidity from yield deviations, since especially price deviations at the long end of the yield curve are increasingly unprofitable to trade.

In contrast to Musto, Nini, and Schwarz (2017), the bid ask spread has no explanatory power for yield deviations, which may be in part because market illiquidity has decreased rather quickly after the financial crisis, whereas yield deviations of European bonds remained wide for an extended period of time. To the same token, a bond's age is negatively correlated with yield deviations, which seems counterintuitive given that younger bonds usually trade at a price premium. However, after controlling for central bank liquidity provision, the coefficient turns positive (and insignificant), suggesting that central bank interventions had a significant effect on the cross-section of Treasury bond prices. Indeed, the coefficient on *OMO* is strongly negative, implying that more liquidity provision on average increases bond prices, whereas higher excess liquidity is associated with lower bond prices due to banks depositing excess funds at the ECB rather than increasing their Treasury holdings.

7. Conclusion

This paper proposes a new measure of illiquidity by incorporating the cost of carry into the analysis of aggregate yield deviations. The resulting forward yield represents the break-even yield for investors trading against a security's mispricing, thus allowing to finely disentangle liquidity demand from supply as the underlying cause of bonds' price discrepancies. The cost of carry is defined as the expected net return from holding a bond position funded in the repo market, and is computed by the (duration-adjusted) spread between a bond's market yield and the repo rate. The illiquidity measure is

Table 6

Yield Deviations and Security-Specific Liquidity Characteristics

This table reports coefficients from regressing bonds' yield deviations on security-specific characteristics as well as proxies of central bank liquidity provision. Yield deviations are computed by the difference between a bond's market-observed yield and model-implied yield. Demand is the difference between a bond's (cash) lender- and borrower-initiated trading volumes, divided by a bond's amount outstanding. Supply is the amount available for lending, divided by a bond's amount outstanding. Short-sellers is the net number of lenders, divided by the total number of repo market participants. ttm denotes a bond's (log) time-to-maturity, and age is the (log) age of a bond (in years). Bid Ask is a bond's bid yield minus ask yield, divided by the mid yield. Coupon refers to a bond's nominal coupon, and out is a bond's (log) amount outstanding. OMO refers to the (log) amount of the ECB's open-market operations (in EUR billions), including its main and long-term refinancing operations. ExLiq denotes ECB excess liquidity (in EUR billions), computed as the (log) sum of banks' current account and the ECB's deposit facility, minus the marginal lending facility and reserve requirements. The sample includes all bonds from Germany, France, Belgium, Spain, and Italy with maturity between 1 and 10 years. Standard errors are clustered at security- and day-level (shown in parentheses). The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Demand	0.26										−1.26	2.76*	−0.50
	(0.98)										(0.94)	(1.57)	(1.20)
Supply		2.85									3.25	14.46***	5.38**
		(2.03)									(2.04)	(2.75)	(2.14)
Short-sellers			−0.91***								−0.92***	−1.47***	−0.88**
			(0.28)								(0.28)	(0.45)	(0.37)
ttm				−1.55**							−1.27*	−4.60***	−4.48***
				(0.65)							(0.68)	(0.27)	(0.47)
age					−0.71***						−0.84***	−0.10	0.31
					(0.18)						(0.21)	(0.21)	(0.25)
BidAsk						−0.00					−0.00	−0.00	0.00
						(0.00)					(0.00)	(0.00)	(0.00)
Coupon							−0.85***					−0.39**	
							(0.19)					(0.19)	
out								−1.33*				0.42	
								(0.68)				(0.54)	
OMO									−3.04***				−2.40***
									(0.42)				(0.62)
ExLiq										0.17**			−0.17
										(0.07)			(0.12)
ISIN FE	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes
Day FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No
Adj. R^2 (%)	59.48	59.85	60.31	59.74	59.90	59.86	8.66	6.75	46.24	44.70	61.40	39.24	54.99
# Bonds	316	314	255	320	320	320	320	316	320	320	249	249	249
# Obs.	257,621	246,838	212,201	258,189	258,189	256,799	258,246	257,625	258,246	236,263	200,064	200,064	181,955

computed by the aggregate net deviations between bonds' (adjusted) forward yields and a fitted yield curve, and a European market-wide illiquidity index is constructed from the (repo) volume-weighted average of the country-specific illiquidity measures. Using this index, the main results in this paper show that the majority of yield deviations is unprofitable to trade when accounting for holding costs, such that illiquidity explains less than half of the time-series variation in aggregate noise. The time-series properties of the illiquidity measure indicate that disentangling price discrepancies from holding costs further improves the information content in Treasury prices, so that the illiquidity measure proposed in this paper provides a representative measure of liquidity conditions in the overall financial markets.

Panel regressions show that security-specific repo and bond characteristics as well as central bank liquidity provision largely affect bonds' yield deviations and holding costs, further supporting the approach of this paper to measure illiquidity from net deviations along the Treasury yield curve.

Important policy and asset pricing implications can be drawn from using this illiquidity measure. In essence, the results in this paper suggest that the illiquidity measure is indeed uniquely connected to the lack of arbitrage capital, while the noise measure rather constitutes a measure of combined limits to arbitrage.

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Part III

Appendix

Supplemental Appendix A: Fragility of Money Markets

Additional Tables

Table I.1

Descriptive Statistics

This table provides a list of all banks and variables included in the regression analysis. Descriptive statistics for all variables are given below. All currencies are converted into Euro.

Bank	Country	ΔShare	Δm	ΔCB	L_{09}	ΔBonds
Banca Monte dei Paschi di Siena SpA	IT	−0.048	0.203	0.016	13.090	4.748
Banco Bilbao Vizcaya Argentaria SA	ES	0.148	0.908	−0.012	17.393	-4.095
Banco BPI SA	PT	−0.221	3.131	0.110	21.989	-0.786
Banco Popular Español SA	ES	0.508	0.998	−0.003	15.304	1.287
Banco Santander SA	ES	−0.522	1.013	−0.010	15.033	-14.883
Barclays plc	UK	0.422	0.238	−0.034	23.580	-27.386
BNP Paribas SA	FR	0.050	0.913	−0.003	25.611	-54.812
Caja de Ahorros y Pensiones de Barcelona	ES	0.221	0.905	0.010	12.703	13.527
Commerzbank AG	DE	0.000	0.409	0.008	31.762	-53.481
Dexia SA	BE	−0.046	1.104	−0.041	48.184	-35.496
Erste Group Bank AG	AT	0.001	1.961	−0.063	18.163	-24.898
HSH Nordbank AG	DE	0.356	0.015	−0.001	39.281	-12.635
ING Groep NV	NL	0.020	0.956	n/a	29.253	-35.658
Intesa Sanpaolo SpA	IT	−0.474	0.313	0.007	11.861	-9.631
Jyske Bank A/S	DK	0.637	7.184	−0.030	17.928	-0.618
KBC Group NV	BE	−0.267	1.433	−0.032	18.876	-42.850
Landesbank Baden-Württemberg	DE	−0.170	0.073	−0.034	39.116	-83.138
Lloyds Banking Group plc	UK	−0.491	−0.141	−0.002	23.290	-9.198
Norddeutsche Landesbank-Girozentrale	DE	−0.130	−0.110	−0.005	41.152	-44.364
Raiffeisen Bank International AG	AT	−0.225	0.410	−0.010	10.896	-11.483
Skandinaviska Enskilda Banken AB	SE	0.000	−0.024	0.000	23.159	-13.011
Société Générale SA	FR	0.000	1.524	0.001	21.856	-24.198
Svenska Handelsbanken AB	SE	0.000	−0.220	0.000	25.549	-7.092
Sydbank A/S	DK	−0.454	−0.220	0.000	17.309	-0.208
Bank of Ireland	IE	−0.114	−0.058	0.239	28.355	4.286
UniCredit SpA	IT	−0.014	0.187	0.008	15.560	-29.929
Mean		−0.031	0.889	0.005	23.317	-19.846
Median		−0.014	0.410	−0.002	21.923	-12.823
StDev		0.291	1.502	0.056	9.858	22.695
Min		−0.522	−0.220	−0.063	10.900	-83.138
Max		0.637	7.184	0.239	48.184	13.527

Table I.2

Regression Results for Funding Shares and Bond Holdings (2009–2011)

This table shows the results of regressing changes in banks' funding shares (Columns (1) to (3)) and changes in bond holdings (Columns (4) to (6)) on explanatory variables derived from our model. Central bank figures are unavailable for ING Groep NV and Dexia SA. Standard errors are shown in parentheses. The stars ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

	Δ_{09}^{11} Share			Δ_{09}^{11} Bonds		
	(1)	(2)	(3)	(4)	(5)	(6)
Δm	0.009		0.009			
	(0.007)		(0.007)			
ΔCB		-2.144^{*}	-2.112^{*}		160.870^{**}	118.933^{*}
		(1.152)	(1.132)		(72.423)	(68.074)
L_{09}				-1.437^{***}		-1.190^{***}
				(0.411)		(0.499)
const.	-0.092	-0.007	-0.045	9.830	-25.676^{***}	1.641
	(0.075)	(0.078)	(0.082)	(10.363)	(4.895)	(12.291)
R^2	0.07	0.14	0.20	0.34	0.18	0.36
Obs.	26	24	24	26	24	24

Supplemental Appendix B: Illiquidity and the Cost of Carry

Additional Tables

Table I.1

Monthly Changes on Other Market Variables - Germany

Reported are OLS regression coefficients with Newey-West t-statistics in squared brackets. On5Y and On10Y are the on-the-run premiums for 5-year and 10-year bonds, respectively. TB3M is the 3-month Treasury bill rate. GC is the overnight general collateral rate. LIBOR is the spread of 3-month EURIBOR over the 3-month overnight index swap (OIS) rate. CDS is the 5-year senior-CDS spread. VIX is the EuroStoxx 50 implied volatility index. Special is the spread between overnight GC and special repo rates. ΔPSLiq is the innovation in the liquidity factor by Pástor and Stambaugh (2003). Stockret is the monthly return on the EuroStoxx 50 index. BondV is the annualized return volatility of monthly bond returns calculated from 5-year Treasury yields using a rolling window of 21 business days. Term is the spread of 10- over 1-year Treasury yields. Panel A reports results for Illiquidity and Panel B for Noise.

Panel A: Illiquidity

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−0.499			−1.163	ΔOn5Y	−0.248			−0.253
	[−0.20]			[−0.57]		[−1.86]			[−1.84]
ΔTerm		−0.004		−0.011	ΔOn10Y		−0.012		−0.017
		[−0.22]		[−1.63]			[−0.42]		[−0.56]
ΔBondV			0.017	0.018	ΔSpecial			0.016	0.028
			[2.19]	[2.43]				[0.33]	[0.60]
Adj. R^2 (%)	0.00	0.00	9.18	10.86	Adj. R^2 (%)	13.64	0.00	0.00	12.84
# months	119	119	119	119	# months	119	119	119	119
Stock Market: Ret, VIX, and U.S.					**GC, LIBOR, and Default**				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	0.003			0.006	ΔGC	0.177			−0.015
	[0.08]			[0.25]		[0.15]			[−0.01]
ΔVIX		0.008		0.001	ΔLIBOR		0.003		0.003
		[0.13]		[0.02]			[0.11]		[0.10]
ΔPSLiq			−5.302	−5.306	ΔCDS			−0.031	−0.033
			[−1.96]	[−1.99]				[−1.29]	[−1.60]
Adj. R^2 (%)	0.00	0.00	12.69	11.24	Adj. R^2 (%)	0.00	0.00	2.66	0.66
# months	119	119	119	119	# months	119	119	96	96

Panel B: Noise

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−1.153			−0.699	ΔOn5Y	−0.113			−0.117
	[−0.71]			[−0.48]		[−1.50]			[−1.49]
ΔTerm		0.011		0.007	ΔOn10Y		0.091		0.089
		[1.05]		[1.23]			[4.33]		[4.10]
ΔBondV			0.009	0.008	ΔSpecial			0.050	0.056
			[1.36]	[1.48]				[1.49]	[1.71]
Adj. R^2 (%)	5.42	6.57	4.26	10.62	Adj. R^2 (%)	4.72	6.08	2.59	14.12
# months	119	119	119	119	# months	119	119	119	119
Stock Market: Ret, VIX, and U.S.					**GC, LIBOR, and Default**				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.003			0.004	ΔGC	−0.293			−0.385
	[−0.13]			[0.19]		[−0.35]			[−0.56]
ΔVIX		0.011		0.010	ΔLIBOR		0.008		0.010
		[0.26]		[0.22]			[0.43]		[0.46]
ΔPSLiq			−1.861	−1.783	ΔCDS			−0.006	−0.013
			[−0.83]	[−0.88]				[−0.43]	[−0.96]
Adj. R^2 (%)	0.00	0.00	2.26	0.80	Adj. R^2 (%)	0.00	0.78	0.00	0.70
# months	119	119	119	119	# months	119	119	96	96

Table I.2

Monthly Changes on Other Market Variables - France

Reported are OLS regression coefficients with Newey-West t-statistics in squared brackets. On5Y and On10Y are the on-the-run premiums for 5-year and 10-year bonds, respectively. TB3M is the 3-month Treasury bill rate. GC is the overnight general collateral rate. LIBOR is the spread of 3-month EURIBOR over the 3-month overnight index swap (OIS) rate. CDS is the 5-year senior-CDS spread. VIX is the EuroStoxx 50 implied volatility index. Special is the spread between overnight GC and special repo rates. ΔPSLiq is the innovation in the liquidity factor by Pástor and Stambaugh (2003). Stockret is the monthly return on the EuroStoxx 50 index. BondV is the annualized return volatility of monthly bond returns calculated from 5-year Treasury yields using a rolling window of 21 business days. Term is the spread of 10- over 1-year Treasury yields. Panel A reports results for Illiquidity and Panel B for Noise.

Panel A: Illiquidity

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	0.140			0.122	ΔOn5Y	0.056			0.057
	[0.51]			[0.44]		[1.19]			[1.26]
ΔTerm		−0.001		−0.000	ΔOn10Y		−0.037		−0.036
		[−0.22]		[−0.02]			[−0.95]		[−0.96]
ΔBondV			0.002	0.002	ΔSpecial			−0.009	−0.006
			[0.98]	[0.96]				[−0.40]	[−0.28]
Adj. R^2 (%)	0.00	0.00	0.00	0.00	Adj. R^2 (%)	0.55	0.00	0.00	0.00
# months	119	119	119	119	# months	119	119	119	119

Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.015			−0.023	ΔGC	0.491			0.271
	[−0.83]			[−1.09]		[1.95]			[1.20]
ΔVIX		0.007		−0.013	ΔLIBOR		0.005		−0.006
		[0.46]		[−0.81]			[0.60]		[−0.92]
ΔPSLiq			−1.462	−1.503	ΔCDS			−0.002	0.001
			[−1.53]	[−1.60]				[−0.36]	[0.18]
Adj. R^2 (%)	0.09	0.00	1.57	1.03	Adj. R^2 (%)	2.45	0.00	0.00	0.00
# months	119	119	119	119	# months	119	119	96	96

Panel B: Noise

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−1.045			−0.623	ΔOn5Y	0.127			0.124
	[−1.59]			[−1.10]		[2.13]			[1.88]
ΔTerm		0.011		0.009	ΔOn10Y		0.085		0.075
		[1.81]		[1.50]			[1.17]		[1.15]
ΔBondV			0.003	0.004	ΔSpecial			0.020	0.012
			[1.06]	[1.19]				[0.52]	[0.34]
Adj. R^2 (%)	3.17	5.66	0.07	6.32	Adj. R^2 (%)	3.99	1.85	0.00	5.08
# months	119	119	119	119	# months	119	119	119	119

Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.030			−0.028	ΔGC	−0.404			−0.509
	[−1.26]			[−0.88]		[−0.99]			[−1.03]
ΔVIX		0.022		0.001	ΔLIBOR		0.013		0.015
		[0.96]		[0.04]			[1.23]		[1.06]
ΔPSLiq			−0.687	−0.590	ΔCDS			−0.007	−0.015
			[−0.57]	[−0.46]				[−0.64]	[−1.47]
Adj. R^2 (%)	1.66	0.68	0.00	0.22	Adj. R^2 (%)	0.62	2.98	0.00	4.12
# months	119	119	119	119	# months	119	119	96	96

Table I.3

Monthly Changes on Other Market Variables - Belgium

Reported are OLS regression coefficients with Newey-West t-statistics in squared brackets. On5Y and On10Y are the on-the-run premiums for 5-year and 10-year bonds, respectively. TB3M is the 3-month Treasury bill rate. GC is the overnight general collateral rate. LIBOR is the spread of 3-month EURIBOR over the 3-month overnight index swap (OIS) rate. CDS is the 5-year senior-CDS spread. VIX is the EuroStoxx 50 implied volatility index. Special is the spread between overnight GC and special repo rates. ΔPSLiq is the innovation in the liquidity factor by Pástor and Stambaugh (2003). Stockret is the monthly return on the EuroStoxx 50 index. BondV is the annualized return volatility of monthly bond returns calculated from 5-year Treasury yields using a rolling window of 21 business days. Term is the spread of 10- over 1-year Treasury yields. Panel A reports results for Illiquidity and Panel B for Noise.

Panel A: Illiquidity

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−1.194			−1.120	ΔOn5Y	0.017			−0.011
	[−1.25]			[−1.08]		[0.18]			[−0.13]
ΔTerm		0.009		0.006	ΔOn10Y		−0.230		−0.226
		[1.08]		[0.94]			[−1.43]		[−1.45]
ΔBondV			0.004	0.006	ΔSpecial			0.059	0.051
			[0.77]	[1.11]				[0.87]	[0.82]
Adj. R^2 (%)	3.20	2.19	1.32	6.72	Adj. R^2 (%)	0.00	9.66	0.73	9.27
# months	119	119	119	119	# months	119	119	119	119

Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.039			0.014	ΔGC	−0.461			0.120
	[−1.48]			[0.46]		[−0.66]			[0.18]
ΔVIX		0.059		0.074	ΔLIBOR		0.032		0.024
		[2.09]		[2.01]			[2.36]		[1.44]
ΔPSLiq			1.361	1.995	ΔCDS			0.029	0.024
			[0.59]	[0.92]				[2.45]	[2.12]
Adj. R^2 (%)	1.64	4.88	0.00	6.47	Adj. R^2 (%)	0.00	10.89	15.65	18.95
# months	119	119	119	119	# months	119	119	96	96

Panel B: Noise

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−1.478			−0.641	ΔOn5Y	0.024			−0.005
	[−1.56]			[−0.76]		[0.25]			[−0.05]
ΔTerm		0.020		0.021	ΔOn10Y		−0.175		−0.165
		[2.43]		[3.89]			[−1.03]		[−1.03]
ΔBondV			0.006	0.009	ΔSpecial			0.130	0.123
			[1.29]	[1.80]				[1.99]	[2.04]
Adj. R^2 (%)	5.91	16.02	3.99	25.79	Adj. R^2 (%)	0.00	5.82	7.34	11.68
# months	119	119	119	119	# months	119	119	119	119

Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.063			−0.010	ΔGC	−0.940			−0.405
	[−2.57]			[−0.35]		[−1.52]			[−0.71]
ΔVIX		0.080		0.073	ΔLIBOR		0.036		0.026
		[3.58]		[2.52]			[3.39]		[2.46]
ΔPSLiq			−0.781	−0.133	ΔCDS			0.030	0.023
			[−0.46]	[−0.10]				[2.47]	[2.08]
Adj. R^2 (%)	6.07	10.52	0.00	9.05	Adj. R^2 (%)	2.37	15.36	18.44	23.69
# months	119	119	119	119	# months	119	119	96	96

Table I.4

Monthly Changes on Other Market Variables - Spain

Reported are OLS regression coefficients with Newey-West t-statistics in squared brackets. On5Y and On10Y are the on-the-run premiums for 5-year and 10-year bonds, respectively. TB3M is the 3-month Treasury bill rate. GC is the overnight general collateral rate. LIBOR is the spread of 3-month EURIBOR over the 3-month overnight index swap (OIS) rate. CDS is the 5-year senior-CDS spread. VIX is the EuroStoxx 50 implied volatility index. Special is the spread between overnight GC and special repo rates. ΔPSLiq is the innovation in the liquidity factor by Pástor and Stambaugh (2003). Stockret is the monthly return on the EuroStoxx 50 index. BondV is the annualized return volatility of monthly bond returns calculated from 5-year Treasury yields using a rolling window of 21 business days. Term is the spread of 10- over 1-year Treasury yields. Panel A reports results for Illiquidity and Panel B for Noise.

Panel A: Illiquidity

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	0.347			0.202	ΔOn5Y	−0.017			−0.043
	[1.74]			[1.18]		[−0.55]			[−1.19]
ΔTerm		−0.010		−0.004	ΔOn10Y		−0.031		−0.042
		[−3.77]		[−1.68]			[−1.19]		[−1.34]
ΔBondV			0.005	0.003	ΔSpecial			−0.017	−0.015
			[2.54]	[1.37]				[−0.97]	[−0.89]
Adj. R^2 (%)	3.58	13.99	10.15	10.37	Adj. R^2 (%)	0.00	0.16	0.00	0.00
# months	62	71	71	62	# months	71	71	71	71

Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.036			−0.007	ΔGC	−0.469			−0.100
	[−1.95]			[−0.26]		[−1.28]			[−0.33]
ΔVIX		0.053		0.048	ΔLIBOR		0.040		0.030
		[2.84]		[1.66]			[3.02]		[2.14]
ΔPSLiq			2.958	2.998	ΔCDS			0.008	0.006
			[1.71]	[1.73]				[3.03]	[2.32]
Adj. R^2 (%)	3.83	6.84	1.85	7.74	Adj. R^2 (%)	0.87	10.27	10.15	14.11
# months	71	71	71	71	# months	71	71	71	71

Panel B: Noise

Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−0.157			0.150	ΔOn5Y	−0.056			0.025
	[−0.33]			[0.43]		[−1.33]			[0.56]
ΔTerm		0.013		0.019	ΔOn10Y		0.143		0.143
		[2.44]		[3.53]			[3.88]		[3.18]
ΔBondV			0.003	0.005	ΔSpecial			0.045	0.027
			[0.89]	[1.63]				[1.68]	[0.90]
Adj. R^2 (%)	0.00	12.32	0.51	18.62	Adj. R^2 (%)	0.70	17.00	2.88	16.20
# months	62	71	71	62	# months	71	71	71	71

Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	0.015			0.021	ΔGC	−1.209			−1.063
	[0.52]			[0.52]		[−2.71]			[−2.15]
ΔVIX		−0.007		0.009	ΔLIBOR		0.028		0.014
		[−0.27]		[0.25]			[1.38]		[0.64]
ΔPSLiq			1.298	1.385	ΔCDS			0.004	0.002
			[0.44]	[0.45]				[0.85]	[0.36]
Adj. R^2 (%)	0.00	0.00	0.00	0.00	Adj. R^2 (%)	6.57	1.59	0.00	4.98
# months	71	71	71	71	# months	71	71	71	71

Table I.5

Monthly Changes on Other Market Variables - Italy

Reported are OLS regression coefficients with Newey-West t-statistics in squared brackets. On5Y and On10Y are the on-the-run premiums for 5-year and 10-year bonds, respectively. TB3M is the 3-month Treasury bill rate. GC is the overnight general collateral rate. LIBOR is the spread of 3-month EURIBOR over the 3-month overnight index swap (OIS) rate. CDS is the 5-year senior-CDS spread. VIX is the EuroStoxx 50 implied volatility index. Special is the spread between overnight GC and special repo rates. ΔPSLiq is the innovation in the liquidity factor by Pástor and Stambaugh (2003). Stockret is the monthly return on the EuroStoxx 50 index. BondV is the annualized return volatility of monthly bond returns calculated from 5-year Treasury yields using a rolling window of 21 business days. Term is the spread of 10- over 1-year Treasury yields. Panel A reports results for Illiquidity and Panel B for Noise.

Panel A: Illiquidity									
Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−0.303			−1.126	ΔOn5Y	0.012			0.001
	[−0.62]			[−1.38]		[0.20]			[0.02]
ΔTerm		0.004		−0.002	ΔOn10Y		−0.123		−0.130
		[0.63]		[−0.35]			[−1.32]		[−1.77]
ΔBondV			0.004	0.009	ΔSpecial			0.125	0.129
			[2.09]	[1.80]				[2.21]	[2.94]
Adj. R^2 (%)	0.10	0.00	4.66	14.03	Adj. R^2 (%)	0.00	8.91	22.11	31.81
# months	71	71	71	71	# months	71	71	71	71
Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.078			0.007	ΔGC	−0.258			0.391
	[−2.25]			[0.17]		[−0.51]			[0.63]
ΔVIX		0.137		0.142	ΔLIBOR		0.070		0.053
		[2.54]		[2.12]			[3.08]		[2.00]
ΔPSLiq			0.870	1.116	ΔCDS			0.013	0.008
			[0.36]	[0.46]				[2.29]	[1.39]
Adj. R^2 (%)	9.51	22.04	0.00	19.93	Adj. R^2 (%)	0.00	13.91	12.01	16.01
# months	71	71	71	71	# months	71	71	71	71
Panel B: Noise									
Treasury: Level, Slope, and Volatility					On-the-Run Premiums and Specialness				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
ΔTB3M	−0.518			−0.357	ΔOn5Y	0.018			0.012
	[−1.07]			[−0.38]		[0.28]			[0.25]
ΔTerm		0.013		0.011	ΔOn10Y		−0.092		−0.096
		[2.03]		[1.42]			[−0.99]		[−1.23]
ΔBondV			0.000	0.003	ΔSpecial			0.113	0.116
			[0.13]	[0.58]				[2.09]	[2.58]
Adj. R^2 (%)	2.65	9.09	0.00	8.23	Adj. R^2 (%)	0.00	3.86	15.85	19.74
# months	71	71	71	71	# months	71	71	71	71
Stock Market: Ret, VIX, and U.S.					GC, LIBOR, and Default				
	(1)	(2)	(3)	(4)		(1)	(2)	(3)	(4)
StockRet	−0.054			−0.003	ΔGC	−0.481			−0.108
	[−1.31]			[−0.06]		[−0.70]			[−0.12]
ΔVIX		0.088		0.086	ΔLIBOR		0.043		0.035
		[1.54]		[1.24]			[1.59]		[0.98]
ΔPSLiq			0.807	0.904	ΔCDS			0.006	0.003
			[0.30]	[0.33]				[1.04]	[0.42]
Adj. R^2 (%)	3.27	7.35	0.00	4.71	Adj. R^2 (%)	0.00	3.80	1.41	1.40
# months	71	71	71	71	# months	71	71	71	71

Matthias Rupprecht - Curriculum Vitae

Educational Background

09/2013 – 10/2018	**University of St. Gallen, Switzerland** Ph.D. Program in Finance
09/2011 – 07/2012	**Barcelona Graduate School of Economics, Spain** Master of Science in Finance
10/2010 – 08/2011	**Ludwig-Maximilians-University, Germany** Master of Arts in Economics
10/2006 – 04/2010	**Ludwig-Maximilians-University, Germany** Bachelor of Arts in Economics

Academic Exchanges and Visiting Positions

09/2016 – 06/2018	**London School of Economics, London, UK** Visiting Scholar at the Financial Markets Group
01/2016 – 08/2016	**Princeton University, Princeton, New Jersey, USA** Visiting Scholar at the Bendheim Center for Finance
08/2002 – 06/2003	**McKinley Senior High School, Baton Rouge, Louisiana, USA** Exchange Student

Relevant Work Experience

08/2012 – 08/2013	**CESifo, Munich, Germany** Research Assistant
10/2009 – 03/2010	**Munich Re, Munich, Germany** Student Trainee, Group Development
08/2008 – 09/2008	**UBS Sauerborn, Frankfurt am Main, Germany** Intern, CIO/Hedge Fund Research

Relevant Qualifications

Programming	Experienced User of Matlab, Python, Gauss, and Stata
Quantitative Skills	GMAT: 93^{rd} percentile, GRE: 96^{th} percentile

Awards and Scholarships

01/2016 – 01/2017	Scholarship from the Swiss National Science Foundation
11/2011	VAC Prize for the best graduate (MA Economics)