Time-varying Price Discovery in the European Treasury Markets

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ABSTRACT
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Keywords: Price Discovery, Duration, Liquidity, Government Bond Markets

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JEL Classification: G12, G14, F36
1. Introduction

Central to financial economics is how asset prices are determined in financial markets. To effectively direct economic decisions, security prices should reflect all information about future prospects of issuers, risk-taking behaviors of investors, as well as expectations on future movements of macroeconomic indicators and yield curves. This process becomes more efficient when market participants recognize a certain instrument as the benchmark to which other security prices are related on their risk-return characteristics. Because of its importance in pricing and hedging, economic agents are interested in understanding how the benchmark instrument arises and evolves over time.

Our work is a further contribution to the study of benchmark securities in the European government bond markets which was recently addressed by Dunne, Moore and Portes (2007). The efforts for developing a stronger European financial integration were boosted by the introduction of the euro and have lead to the elimination of many barriers for cross-border transactions and promoted convergences across the government securities markets. This has intensified the competition among sovereign issuers for establishing euro-area benchmarks due to cost advantages associated with the benchmark status. As a result, governments have started to choose strategically issuing dates and security types and even to concentrate their issuances at certain maturities of the yield curve (see Galati and Tsatsaronis, 2001). From a supervisory perspective, it is critical to understand how this competition affects the price discovery process in the secondary market trading. From a market participant’s perspective, market makers, hedge funds and high frequency traders are extremely interested in developing appropriate models for detecting real-time price discrepancies and arbitrage opportunities.

The wholesale sovereign markets we study are fully electronic and characterized by a high degree of transparency. The liquidity is provided by dealers with specific market making obligations. Market makers have to post firm two-sided quotes for a minimum size, a maximum spread and a minimum number of hours during the trading day. Hence, dealers have strong incentives to post frequent and timely updates to their quotes to reflect changes in their expectation of the fundamental drivers of interest rates, their inventory levels and market liquidity. We consider bonds for various maturities issued by the
Treasuries of the four largest Euro area countries: France, Germany, Italy and Spain. While in the short-term yields of similar bonds may diverge, in the long-term they are correlated because they share the same fundamental macroeconomic drivers and a common European interest rate.

This paper focuses on price leadership at key maturity points on the euro government yield curve. Price leadership refers to the market capacity to provide timely and informative prices and, more formally, we define the leading market as the market with quoted yields that best explain the volatility of the fundamental drivers of interest rates. Using high frequency data, not only we identify for each maturity category the leading sovereign market but also we recognize that the price discovery is a dynamic process and suggest a new model to explain how this process changes over time.

Market practitioners seem to recognize that the French, German and Italian sovereign markets are leaders in different segments of the euro yield curve (IMF, 2001). Anecdotal evidence suggests that the French market leads the price discovery at the 2-year maturity due to the presence of active money markets in France. The German market prevails at 5-year and 10-year maturities, driven by the liquid Eurex's German Bund futures market on which the German 5-year and 10-year bonds are the deliverable securities. The Italian market instead is the most informative at the 30-year maturity. Typically, Italian treasury securities receive lower long-term credit ratings and this explains persistent spreads between yields of Italian bonds and yields of treasuries of other European countries. The existence of active cross-country yield spread trading explains the importance of the Italian market at the very long end of the curve.

Academics have considered various methodologies and criteria for identifying benchmark securities: e.g. bonds with lowest yields, largest trade volumes or largest issue sizes. In a recent paper Dunne, Moore and Portes (2007) use end-of-day data and identify the benchmark European Treasury bonds as the bonds with high sensitivity to the variability of a single systematic factor and with low idiosyncratic variability. Their results indicate that French bonds dominate at all the maturity categories they study.

We employ instead the approach developed by Hasbrouck (1995) for estimating the contribution to the price (yield) discovery process of multiple markets trading similar assets. Hasbrouck calls the
contribution to the price discovery the information share of a market. This method relies on the notion of random-walk decomposition which separates permanent and transient components of yield movements. The information share refers to the contribution of a market towards the variance of the permanent or efficient yield component. However, our paper differs from Hasbrouck (1995) because our data is sampled at every quote update rather than at every second. That is, in our empirical investigation we use event time rather than clock time. We find that the contribution of the various countries to the discovery process of the European Treasury yields changes within different maturity buckets in line with the practitioners' views and the anecdotal evidence reported above.

Additionally, we recognize that the price discovery is a dynamic process and we estimate a time-varying price discovery model where the adjustment coefficients to the long-term equilibrium relationships are allowed to change with some explanatory variables. Motivated by previous studies in the equity markets we conjecture that time affects the price discovery process of European Treasury yields. In information-based models (see, for example, Copeland and Galai, 1983; Glosten and Milgrom, 1985; and Kyle, 1985) although prices may immediately react to new public information, they need not fully reflect private information which is only gradually revealed through the trading of informed traders. Similarly to Engle and Russell (1998), we differentiate the deterministic effects from the stochastic effects of time. The deterministic element captures observable time-of-day patterns in trading activities caused by clustering behaviors of discretionary traders as described by Admati and Pfleiderer (1988). We expect less pronounced diurnal patterns because we study wholesale markets for institutional traders who may plausibly enjoy more options than retail traders over the timing of their trades. The stochastic component explains the unpredictable effects of the time between consecutive quote updates on yields. The market microstructure literature shows that the speed with which security prices change conveys information (see Easley and O'Hara, 1992 for the theoretical rationale, and Dufour and Engle, 2000 for the empirical evidence). In particular, shorter times between transactions are associated with higher impacts of trades on prices which may indicate either the presence of informed trading or, more generally, informational asymmetry.
Our empirical results clearly show that faster quote changes are associated with faster sovereign yield adjustments to the long-run equilibrium relationships. As predicted by Admati and Pfleiderer (1988), we find a peak in the speed of yield adjustments in the morning after the opening period. In addition, yields take shorter time to converge around the opening of the U.S. equity markets. The speed of yield adjustments is significantly and negatively related to the time between consecutive quote updates. More frequent quote revisions indicate periods of enhanced information arrival about the common efficient interest rate and, consequently, lead to faster yield adjustments.

Prior studies suggest that liquidity affects the price discovery process. Brandt and Kavajecz (2004) show that price discovery takes place with the more recently-issued and more liquid bonds. Mizrach and Neely (2007) provide evidence that market liquidity explains the variations of the information share of the spot market versus the futures market for U.S. Treasury securities. Although our objective is similar to Mizrach and Neely’s work, we recognize how daily information shares are often poorly estimated and therefore we adopt a dynamic price discovery model with coefficients that are allowed to change not only from day to day but also within each trading day. Our findings suggest that the speed of yield adjustments is significantly higher during periods of enhanced market liquidity.

Our paper is related to a number of current works on price discovery of the government bond markets. The microstructure literature suggests three major mechanisms governing the yield discovery process. First, yields are driven by changes in the public information set, such as scheduled macroeconomic news announcements. Fleming and Remolona (1999) study the adjustment process of prices in the U.S. Treasury markets on the arrival of public information. They argue that public information can impact prices even without trading and that trading by market makers around these sharp price changes is also affected by inventory management strategies.

The second mechanism for yield discovery is related to the presence of market participants with superior information (see Yuan, 2004 for theoretical predictions). In the government bond markets, private information occurs because certain investors possess better abilities to understand the economic fundamentals, the current state of the economy, the effect of public news on bond prices and the dynamics
of bond demand and supply. Kim and Verrecchia (1994, 1997) argue that if this type of private information exists, public news releases reinforce the information asymmetry among market participants. Hence, if yields are not fully revealing, market participants would rely more on order flows to draw inference about the announcements. Balduzzi, et al. (2001) and Green (2004) provide evidence that on announcement days order flows have significantly stronger impacts on bond prices.

We focus on a third mechanism, the multiple-market price discovery process. Assuming that certain sovereign securities are in some degree fungible and share common fundamental components, an informational shock in one market could cause yields in other markets to move in the same direction even without any local trade. A natural question that emerges is to what extent a particular market provides more timely and informative quotes. Mizrach and Neely (2007) compare price leadership of the future and the cash markets for U.S. Treasury securities. They find that the futures markets lead the cash markets and the daily information share of futures markets increases with the maturity of bonds and trading activity. They show that the daily information share varies over time and that microstructure factors such as relative spread and realized volatility can explain a large proportion of the changes in information share. Although our objective is similar to Mizrach and Neely’s work, we recognize how daily information shares are often poorly estimated and therefore we adopt a dynamic price discovery model with coefficients that are allowed to change not only from day to day but also within each trading day. We also study how the price discovery process changes around economic announcements. We expect the speed of yield adjustments to increase. Our findings suggest that the yield adjustment coefficients vary significantly before and after the announcements. Yields take shorter time to converge immediately after the announcements and the speed of yield adjustments peaks at about twenty to thirty minutes after the releases. The information contained in the economic news is fully captured into bond yields about one hour after the announcements.

Our study has some important implications for academics, practitioners and policy makers. For academics, we build on the interactions between asset pricing and market microstructure and provide a better understanding of the behavior of market makers in competing markets and the effects of
informational shocks in the determination of asset prices. In particular, we show that the time between quote updates affects the speed of yield convergence. For practitioners, we identify the bonds that act as the price leaders at the different parts of the yield curve and determine the factors driving price leadership over time. For policy makers concerned with financial integration in Europe, our paper provides additional evidence showing that despite persistent yield differentials, the European government bond markets have become integrated and sovereign yields rapidly converge to their long-run equilibrium relationships.

The remainder of this paper is organized as follows. Section 2 provides some institutional background and reviews the characteristic features of the MTS markets. Section 3 describes the data used for the analysis while section 4 presents Hasbrouck's information share approach and our time-varying price discovery model. Section 5 discusses the empirical results and section 6 concludes.

2. Institutional background

We study the MTS (Mercato dei Titoli di Stato) market, a major electronic platform for fixed income securities in Europe. Originally founded in 1988 as the Italian government bond market, MTS has expanded to nearly all countries in the European Union creating local markets in which it holds a minority stake in partnership with major market making firms or local debt management offices. MTS also operates EuroMTS, a London-based market for pan-European benchmark fixed-income securities. Galati and Tsatsaronis (2001) note that MTS accounts for 40% of government bond transactions in Europe. Persaud (2006) estimates that MTS accounts for 71.9% of the electronic trading volume of European cash government bonds.

MTS is an inter-dealer, fully-electronic, quote-driven market with two types of participants: market makers and market takers. To be eligible as market makers, institutions must satisfy stringent requirements both in terms of net asset values and trading volumes on MTS during the previous year.¹ Market makers are required to post two-sided quotes, which are called proposals, for a minimum of 5
hours during the trading day, for a maximum spread and for minimum quantities which range from €2.5 to €10 million depending on the maturity and the benchmark status of the instrument. When specifying the size of a proposal market makers are allowed to enter different block and drip quantities. The block size is the overall size of the proposal while the drip size is the quantity visible to all market participants. Once the drip part of a proposal is exhausted the hidden part of the block becomes accessible. Market makers can voluntarily provide quotes for other securities, in which case they are not subject to any quoting obligations. Market makers of bonds trading on both domestic and EuroMTS markets are allowed to post parallel quotes, i.e. they can simultaneously provide proposals for the same bond on different markets, with different drip quantities. Note that, at times, these quote updates are recorded with one millisecond delay on the parallel platform. When focusing on these parallel quote updates, whereas for German, French and Spanish bonds the revision on the Euro platform often leads the revision on the local platform perhaps because the parallel dealer is operating out of the Euro platform, for Italian bonds the revision on the local platform often leads the quote change on the Euro platform. All the other market participants can only use market orders to hit the best outstanding quotes.

Government, agency and quasi-government bonds for most of the Euro area countries are traded on the MTS platforms. Some of these securities are awarded benchmark status. To be eligible of the benchmark status, government bonds must be issued within the previous two years with principal amount outstanding of €5 billion. Benchmark quasi-government securities are required to have a gross issuance of at least €7 billion in the preceding 12 months and at least 8 committed market makers. Domestic markets trade both benchmark and non-benchmark bonds while only benchmark securities are accepted on EuroMTS.

Trading on MTS is pre-trade anonymous between participants. Traders know their counter-parties only after their transactions are executed. Once MTS receives a proposal for a specific bond it applies price-time priority rules, ranks buy and sell proposals and then publishes the best five quotes on either side of the market. Aggregated drip quantities available at the best five price levels are transmitted in real-time to the rest of the market or to other information systems like Bloomberg or Reuters. Trades are executed

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1 Currently, market makers must have net assets of at least €39 million and a trading volume on MTS during the
when proposals are either hit by incoming orders or matched with opposite-side proposals. Executed trades are immediately and automatically reported. Orders of odd-lots are subject to market maker's acceptance for up to 30 seconds. After this period, if the market maker does not respond, the orders are automatically cancelled.

Trading hours on MTS include three phases: pre-market (7:30am-8:00am Central European Time - CET), pre-open (8:00am-8:15am CET) and regular trading (8:15am-5:30pm CET). During the pre-market phase, market makers can only see their own proposals and input, modify, suspend and reactivate their proposals. Auto-matching of proposals is only activated when the regular trading session starts and terminates when the market closes.

Finally, the clearing and settlement process on MTS is initiated immediately after trades are executed. Settlement instructions are automatically generated and transmitted to the designated institutions. All participants must be members of a clearing institution either directly or indirectly through an agent bank. Settlements can be conducted in either form of net delivery against payment or gross delivery versus payment basis depending on the type of instruments and markets. The settlement cycle is T+3 for bonds and T+2 for short term securities.

3. Data

Our data includes transaction and quote records for bonds traded on the MTS markets from October 1, 2005 to September 30, 2006. We select the most actively traded bonds issued by the German, Italian, French and Spanish governments with an outstanding amount of €5 billion or more and divide them into four time-to-maturity groups: 2-year, 5-year, 10-year and 30-year. In particular, for each country and each maturity category we select the bond with the highest number of trading days and the largest total trading volume over the sample period.

We compute yields based on quote midpoints rather than actual transaction prices. Using quote midpoints as the reference prices is preferable because transaction prices are often stale whereas market

previous year of at least €38 billion. Market takers must have net assets of at least €10 million.
makers have strong incentives to timely update their firm and tradable quotes. Moreover, using quote midpoints helps to avoid distortions generated by transient effects such as the bid/ask bounce.

We prepare our data for the analysis as follows. First, we consider only quotes recorded within MTS continuous trading hours. Second, we indentify all simultaneous entries on parallel platforms and adjust for the 1 millisecond delay. Third, although the database reports all the changes to the best three ask and bid quotes we compute the overall best bid and ask prices across the parallel platforms and keep only the changes to the best quotes. Moreover, at times, market makers briefly suspend active quoting and post large spreads. Clearly, no trader would trade at such poor prices. We exclude all the observations with relative quoted spread higher than 50 basis points. MTS applies even more restrictive filters when compiling end-of-day data. Fourth, we sort the quote series for all the bonds within the same maturity category chronologically using the electronically recorded time stamps which have a resolution of up to the millisecond and construct quote time series in "event time", i.e. time is incremented once a new quote in any sovereign market in the same maturity group is recorded. For example, if at $t=9:15:30:105$ a new quote is posted on the Italian market, we form a vector of quotes, $p_t$, which includes the new Italian quote update and the best prevailing quotes for the German, French and Spanish markets which, obviously, are the same as the quotes in $p_{t-1}$. Fifth, we notice that either because the market has suspended market making obligations or because market makers have quoting obligations for only 5 hours during the trading day, often market markets start quoting later than the official opening time and stop quoting before the official closing time. In order to make sure that we study only periods of the trading day with overlapping quotes for all the bonds in each maturity group we run the daily clock from 2 minutes after the time all the bonds have recorded a first valid quote to 2 minutes prior to the time of the earliest of the

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2 Our cleaned data has 1,705,158 observations; these were obtained after excluding 22,015 observations due to quotes posted outside trading hours, 3,200,122 observations due to unchanged quotes and 885 observations which have relative quoted spreads higher than 50 basis points.

3 Such accurate time stamps allow us to precisely sort all quote updates and even the ones that are recorded within the same second (specifically, 106,842 of the quote updates in our sample are recorded within the same second of another quote). We recognize that trades and orders submitted by market participants located in various countries and connected via local terminals may have systematically different time delays before they are centrally recorded and processed. However, we believe that this does not affect the results of our analysis because often a particular trading desk makes market in multiple securities within a particular maturity bucket and we study the price formation process as it is seen by all the market participants who receive MTS prices.
final daily quote updates for the four bonds. We also remove one day because not all the bonds were quoted on that day. Finally, to adjust for the discrepancies in the time to maturity and coupons of bonds within the same maturity group we use the time series of mid-quote prices to construct the time series of yields (see Appendix A for details of the procedure to compute bond yields).

Please insert the Table 1 about here

Table 1 reports summary statistics for our 16 chosen government bonds. We note that the average quoted depth and the average daily trading volume are largest for the 10-year bonds which are clearly the most actively traded. Among the four countries, Italian bonds are the most actively traded, have the highest average daily trading volume and the lowest quoted spreads. This pattern arises because trading of Italian sovereign bonds is concentrated on the MTS market while transactions of bonds of other countries also take place not only on MTS but also on other electronic and over-the-counter markets. However, this does not mean that the quotes for bonds of other countries are less informative than the quotes for Italian bonds. In fact, because the quotes posted on MTS are firm and tradable the daily average numbers of quote updates for German, Spanish and French bonds are comparable to those posted for Italian bonds.

4. Methodology

The price discovery model is built upon the information share method introduced in Hasbrouck (1995). A detailed discussion of the information share approach and alternative methods can be found in Ballie, et al. (2002), Harris, et al. (2002), de Jong (2002), Lehmann (2002) and Huang (2002). This method relies on the notion of the random-walk decomposition which separates price movements into an efficient price component shared by all markets and a transitory component influenced by short-term effects like bid-ask bounce, inventory control and noise. The efficient price variance can be then decomposed into different components attributable to different markets. This quantity is called information share reflecting the magnitude of the contribution that each market makes to the total variance of the efficient price. First we review Hasbrouck’s methodology and then we present a time-varying extension.
4.1 Hasbrouck’s price discovery model

The information share method assumes that a vector of yields \( p_t \) \( (p_{1,t},...,p_{n,t}) \) follows a random walk so that yields are integrated of order of one or \( I(1) \). We assume that these yields are linked by an arbitrage relationship; in our case, bond yields are clearly driven by the same Euro area interest rate (alternative examples would be spot and futures prices for a particular underlying asset or prices for the same asset sampled over two competing trading platforms). Even though yields are non-stationary, they are cointegrated and, hence, there are linear combinations of these yields which are stationary. In a bivariate case, the two yields \( p_{1,t} \) and \( p_{2,t} \) are said to be cointegrated if the two yields have a long-term equilibrium relationship which could be defined as \( (p_{1,t} - p_{2,t} - \mu) \). This expression is often called the error correction term. We follow Hasbrouck (1995) and define the term \( \mu \) as the mean difference between the two yields, \( \mu = \text{E}(p_{1,t} - p_{2,t}) \). Namely, \( \mu \) captures any long-term difference between the two yields which could be due to persistent credit and liquidity premiums.

In a multivariate case, if yields \( p_t = (p_{1,t},...,p_{n,t}) \) are cointegrated, Engle and Granger (1987) prove that these yields can be modeled using a Vector Error Correction Model (VECM):

\[
\Delta p_t = \beta(z_{t-1} - \mu) + \sum_{i=1}^{m} a_i \Delta p_{t-i} + u_t
\]

(1)

where \( z_t \) is the vector of \((n-1)\) yield differences, \( z_t = [(p_{1,t} - p_{2,t}),..., (p_{1,t} - p_{n,t})]' \), \( m \) is the number of autoregressive lags, \( a's \) are matrices of coefficients, \( u_t \) is the innovation vector and \( \beta \) is the matrix of the adjustment coefficients which intuitively measure the speed of price/yield adjustments toward the long-term equilibrium. Often the researcher can identify \textit{a priori} one of the yields, \( p_{1,t} \), as the benchmark based on either theoretical motivations or given the structure of the market. For example, for NYSE listed stocks, Hasbrouck (1995) chooses \( p_{1,t} \) as the best price at the NYSE whereas \( p_{i,t} \) is the best price posted on regional markets trading the same stock. In this paper we do not impose \textit{a priori} a benchmark yield in

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\(^{4}\) In our paper, we replace price with yield which is a more appropriate term for bond markets.
the VECM; instead, we assume that the euro benchmark yield curve is not uniform and we let the data provide information on the price leader in the various maturity categories. In our model, we define the error correction term as the sum of $n-1$ differences between every pair of yields $p_{i,j}$ and $p_{j,i}$, $z_{i,j} = (p_{i,j} - p_{j,i}) \forall i = 1,...,n (i \neq j)$. The $\beta_{i,j}$ coefficient captures the speed with which the yield $p_{i,j}$ responds to deviations from its long-term relationship with the yield $p_{j,i}$. Thus, the yield changes $\Delta p_{i,j}$ can be written as:

$$\Delta p_{i,j} = \sum_{j=1, j\neq i}^{n} \beta_{i,j} (p_{i,j-1} - p_{j,i-1} - \mu_{i,j}) + \sum_{s=1}^{m} \sum_{k=1}^{n} a_{i,s,k} \Delta p_{s,j-k} + u_{i,j},$$  \hspace{1cm} (2)

With this approach we let the data determine the contribution of each market to the price discovery process. First, we test for non-stationarity in the various time series of bond yields. Second, we test whether within each maturity bucket the time series of bond yields are cointegrated and we determine the number of cointegrating relationships. Finally, we estimate the equation (2) above where if the yields are cointegrated we expect the adjustment coefficient $\beta_{i,j}$ to be statistically significant and negative. With this specification we can more easily interpret the marginal impacts of explanatory factors on $\beta_{i,j}$ when this coefficient is allowed to change over time.

Alternatively, the VECM can be represented as a Vector Moving Average (VMA) by using the Wold decomposition theorem:

$$\Delta p_{i} = \Psi(L)u_{i},$$ \hspace{1cm} (3)

where $\Psi$ is a polynomial in the lag operator $L$. If we call $\Psi(1)$ the sum of the moving average coefficients, $\Psi(1)u_{i}$ captures the long-term impact of an innovation on each yield. Hence, the variance of the common component driving all the yields is $\Lambda \Omega \Lambda'$ where $\Omega$ is the correlation matrix of yield innovations and $\Lambda$ is any row in the matrix $\Psi(1)$. Hasbrouck (1995) suggests that this total variance can be decomposed into different components attributable to the various markets trading the same asset. The contribution of each market to the variance of the common component is defined as the market’s
information share. It reflects the contribution that each market makes to the efficient yield variance. If $\Omega$ is diagonal, the information share of market $i$, $IS_i$, can be easily computed as:

$$IS_i = \frac{\Lambda_i^2 \Omega_i}{\Lambda \Omega \Lambda'}$$  \hspace{1cm} (4)

where $\Lambda_i$ is the $i^{th}$ element of $\Lambda$ and $\Omega_i$ is the $i^{th}$ diagonal element of the correlation matrix $\Omega$.

If $\Omega$ is not diagonal, the information share of a market is not uniquely identified. Hasbrouck (1995) suggests the use of the Cholesky factorization to decompose $\Omega$ into upper and lower triangular matrices ($\Omega = FF'$ where $F$ is the lower matrix). The yield innovation $u$ can be written as the product of the matrix $F$ and a zero mean and unit variance matrix $s$, $u = Fs$ where $\text{Var}(s) = I$. Let $[\Lambda F]$ denote the $i^{th}$ element of the row matrix $\Lambda F$. The information share of a market, which depends on its order in the VECM, can be computed as:

$$IS_i = \frac{([\Lambda F])^2}{\Lambda \Omega \Lambda'}$$  \hspace{1cm} (5)

Hasbrouck (1995) notes that the VECM provides a good fit when it is estimated on intraday data for a single day and suggests sampling the data using short intervals (for example, every second of the trading day) to reduce contemporaneous correlation bias (see Lehmann, 2002). Hence, we estimate the VECM separately for each day, compute the daily upper and lower bounds of the information share for each market, take the average of the upper and lower bounds and then average again these values across all the days in the sample period. Because our data is sampled in "event time" rather than in "clock time", we do not need to estimate models with long lags and to fit polynomials with constrained moving average coefficients to reduce the number of parameters as in Hasbrouck (1995). Instead, we find that a VECM with five lags provides a good fit for our data. Our approach involves analyzing relatively shorter time series which are easier to handle and allow for faster estimations and this is possible without losing any of the relevant information contained in the original data. However, it is evident from the estimation results that the upper and lower bounds of the information shares are often very large and very volatile from one day to the next reducing the reliability of the information share estimates. Clearly, a more flexible
methodology is needed to produce better estimates of this yield discovery process.

4.2 Time-varying price discovery

It is seems reasonable from the discussion in the introduction and in the previous section to assume that the price discovery process varies over time. In fact, Hasbrouck (1995, 2003, 2007) points out that a static VECM is not adequate for modeling the price discovery process over an extended period of time. As in Zebedee and Hulburt (2001), we introduce a dynamic VECM by allowing the parameters of the error correction terms (the loadings) to vary over time. This model is used to identify the factors affecting the dynamics of the price discovery process; for example, we test the relevance of time durations. Based on previous empirical results, we expect that the speed of the yield adjustments will change over time with periods characterized by slow changes and periods characterized by fast yield convergence.

Similarly to Engle and Russell (1998), we distinguish between the deterministic effects and the stochastic effects of time. This differentiation is motivated by the presence of diurnal periodicities in financial data. Figure 1 illustrates the intraday patterns in the number of quote updates for the sample bonds within the four maturity groups. The number of quote updates is cumulated for each five minute interval for each trading day and then is averaged over the whole sample. The early hours after the opening are characterized by slow trading, large quoted spreads, and infrequent quote updating. The daily pattern in the number of quote updates is bimodal with two peaks at around 9:00am CET and 4:00pm respectively. In particular, the frequency of quote updates gradually increases as the European dealers open their desks until about 9:30am when it slows down until lunchtime at about 12:00pm, then it peaks again with the opening of the U.S. markets at around 3:30pm and finally it decreases towards the closing.

[Please insert the Figure 1 about here] The presence of diurnal effects and time-of-day periodicities are well documented in the market microstructure literature. Empirical studies (see for example Harris (1986), Jain and Joh (1988), and McInish and Wood (1992)) report U-shaped patterns in intraday quoted bid/ask spreads and trading volume. Madhavan et al. (1997) provide evidence that information asymmetry decreases steadily
throughout the day while the cost of transacting increases over the day. In a theoretical framework, Admati and Pfleiderer (1988) argue that these time-of-day effects reflect the clustering behaviors of informed and uninformed traders. That is, if uninformed traders can choose when to trade, they tend to concentrate around periods when the trading volume is highest and their expected cost of trading is lowest. Because informed traders try to conceal their trading, they also trade during those periods by pooling with the uninformed traders. We conjecture that these intraday patterns are important to the price discovery process of the European Treasury markets. This rationale arises because these Treasury securities are widely held by institutional investors who are more likely to have superior information and have greater discretion over the timing of their trades. In addition, macroeconomic news is often released before the U.S. markets open. Therefore, it seems reasonable to believe that the frequency of quote updates affects the price discovery process and that the speed of yield adjustment may exhibit intraday periodicities.

The stochastic element of time reflects changes in the information set. Easley and O'Hara (1992) show that informed traders only trade when they have information while the trading motives of uninformed traders are exogenous. Hence, the time between trades conveys information. Long times between trades are often associated with periods of no news arrival while short time between trades may indicate intense information arrival. Empirical studies have provided overwhelming evidence to support this hypothesis. Specifically, Dufour and Engle (2000) show that transactions arriving after shorter duration are more informative, consequently leading to higher permanent impacts on prices. We hypothesize that the frequency of quote updates affects the speed of yield adjustment. In particular, we assume that fast changing markets are associated to changes in the information about the common efficient yield and consequently yields will adjust faster to the long term equilibrium relationship when markets are very active.

In addition, we also investigate the empirical relevance of market liquidity. The previous literature suggests a significant relation between liquidity and price discovery. Studying the U.S. Treasury markets, Brandt and Kavajecz (2004) show that price discovery takes place with the more recently-issued and
more liquid bonds. Green (2004) claims that order flow reveals fundamental information about the yield curve because it causes a stronger impact on bond prices during the periods of enhanced market liquidity. Mizrach and Neely (2007) note that market liquidity explains the variations of the information share for the spot market and the futures market of U.S. Treasury securities. Using the best quotes we compute two liquidity measures encompassing different liquidity dimensions, the average relative spread and average the quoted depth. The relative spread is the bid/ask spread divided by the mid-quote price whereas the depth is the average of the bid and ask sizes. The relative spread measures is a proxy for the round-trip cost of executing a normal market size trade while the quoted depth indicates the quantity that investors can trade at the best prices.

To capture these effects, we suggest using the following specification for the VECM where the parameters attached to the error correction terms are allowed to vary with some explanatory variables. For example, \( \beta_{i,j} \) may vary with the durations between consecutive yield quote changes:

\[
\Delta p_{i,t} = \sum_{j=1,j\neq i}^{n} \beta_{i,j-1} (p_{i,t-1} - p_{j,t-1} - \mu_{i,j-1}) + \sum_{s=1}^{m} \sum_{k=1}^{m} a_{s,s,k} \Delta p_{s,t-k} + u_{i,t},
\]

where

\[
\beta_{i,j-1} = \gamma_{i,j}^{l} + \sum_{l=2}^{L} \gamma_{i}^{l} K_{i,t-1} + \gamma_{i}^{S} S_{i,t-1} + \gamma_{i}^{D} D_{i,t-1} + \gamma_{i}^{T} T_{i,t-1},
\]

\( \gamma_{i,j}^{l} \) is the constant, \( K_{i} \) is a dummy variable which equals 1 if the quote update takes place at time knot \( l \) and zero otherwise, \( T_{i} \) is the duration between two consecutive quote updates at time \( t-1 \) and \( t \), respectively. \( \gamma_{i}^{S} \), \( \gamma_{i}^{D} \) and \( \gamma_{i}^{T} \) are the coefficients for the relative spread, the depth and the time duration respectively. In our VECM, the cointegrating vectors of each equation are specified in such a way so that the adjustment coefficient \( \beta_{i,j} \) is expected to be negative, allowing for an easier interpretation of the time-varying yield adjustments.

In order to capture the time-of-day effects we divide the trading day into five knots (\( L=5 \)): 8:15am-9:00am (opening), 9:00am-12:00pm (morning), 12:00pm-3:00pm (lunchtime), 3:00pm-4:00pm (U.S.
equity market opening), 4:00pm-5:30pm (closing). We treat the first knot 8:15am-9:00am as the benchmark and \( \gamma^1 \) is the adjustment coefficient for this first knot. For other knots \((l=2,\ldots, L)\), the coefficient \( \gamma^l \) measures the change in the speed of yield adjustment from the opening to the time knot \( l \). Because the total adjustment coefficient \( \beta_{t,j,t} \) is expected to be negative by construction, yields would take a shorter (longer) time to converge during the knot \( l \) if \( \gamma^l \) is negative (positive). In addition, we expect a positive relation between market liquidity and the adjustment process. Since market liquidity increases in quoted depth and decreases in relative spread, we expect the coefficient \( \gamma^S \) to be positive and \( \gamma^O \) to be negative.

The coefficient \( \gamma^T \) explains how the stochastic element of quote duration affects the speed of yield adjustment to the long-term equilibrium relationship among the various European sovereign markets. In particular, we expect the coefficient \( \gamma^T \) to be positive, indicating that the speed of yield adjustment decreases with long durations.

4.3 Price discovery during economic news announcements

Prior studies indicate that scheduled macroeconomic news announcements significantly affect the price discovery process. Kim and Verrecchia (1994, 1997) argue that if market participants differ in their abilities to interpret economic data, public news releases reinforce the information asymmetry among market participants. Since informed traders are more likely to trade at these periods, market participants gradually learn this private information on the fundamentals by observing the direction of transactions and order flows. Balduzzi, et al. (2001) and Green (2004) provide evidence that on announcement days order flows have significantly stronger impacts on bond prices and that the adjustments to news generally take place right after the announcements and gradually die out within the next fifteen minutes.

However, if we have a basket of securities which share common fundamental components and hence are in some degree fungible, the price effect of news will be fragmented across the various markets where
these securities trade. We expect that the speed of yield adjustments will be significantly higher when
economic news is released and informational asymmetry increases. To capture this reaction, we allow the
yield adjustment coefficients to vary around economic news announcements as:

$$
\Delta p_{i,t} = \sum_{j=1}^{n} \beta_{1,j} (p_{i,t-1} - p_{i,t-1} - \mu_{i,j-1}) + \sum_{s=1}^{m} \sum_{k=1}^{s} a_{1,s,k} \Delta p_{s,j-k} + u_{i,t},
$$

where

$$
\beta_{i,j-1} = \gamma_{i,t}^{1} + \sum_{l=2}^{L} \gamma_{i,t}^{L} K_{l,j-1} + \gamma_{i,t}^{S} S_{i,j-1} + \gamma_{i,t}^{D} D_{i,j-1} + \gamma_{i,t}^{T} T_{i,j-1} + \sum_{q=1}^{Q} \gamma_{i,t}^{q} I_{q,t-1},
$$

(7)

We use dummy variables $I_{q,t}$ ($I_{q,t} = 1$ if a quote occurs at the period $q$ and zero, otherwise) to allow
the adjustment coefficients to vary over six different periods ($Q=6$) around the time of the news
announcements: half-hour before the announcements (-30min), up to ten minutes after announcements (0-
10min), ten to twenty minutes after announcements (10min-20min), twenty to thirty minutes after
announcements (20min-30min), thirty to 1hour after announcements (30min-1hour) and from 1-hour up
to 2 hours after announcements (1hour-2hour). The coefficients $\gamma^{q}$'s measure the changes in the
adjustment coefficients around news announcements and are expected to be negative for periods
immediately after the news is announced.

We obtain the time-series of the scheduled economic news releases from Bloomberg. The data
includes the events, the dates as well as the time of the announcement. We separate economic news from
the U.S. and from the euro-area. Goldberg and Leonard (2003) show that German yields are more
responsive to U.S. economic news than they are to European ones. They argue that U.S. news tends to be
released earlier than their European counterparts, making market participants to pay more attention to
signals in the U.S. data. In addition, we only consider the U.S. and euro-area news which Goldberg and
Leonard find to significantly affect bond prices. The details of these releases are provided in Table 2.

[Please insert the Table 2 about here]
5. Empirical Results

This work addresses the following questions about the nature and dynamics of the price discovery process in the euro government bond markets. How do sovereign yields in the euro area converge in the long run? When considering bonds within the same maturity bucket, which sovereign market contains more information about directions of European interest rates? What determines the speed of yield convergence to the long-term equilibrium relationship? We start the empirical analysis by considering the time series of treasury yields and testing for nonstationarity. Then we estimate VECM models on bonds within the same maturity buckets and test for the presence of cointegration among various yields.

5.1 Unit root and Cointegration tests

In the Treasury markets, bond yields are driven by fundamental factors (e.g. fundamental news on the yield curve) and they are affected by short-term effects (e.g. liquidity effects such as demand and supply dynamics, trade costs, bid-ask bounce and technical trading effects such as auction cycles, re-openings of outstanding issues, repo specialness, etc.). We assume that the fundamental factor follows a random walk and changes as new information arrives. New information shocks are modeled as draws from a stationary independent random variable. Yields are efficient if they reflect all available information about the fundamental value of the bond. Hence, we hypothesize that euro sovereign bond yields are nonstationary.

In the first step of our empirical analysis we test whether the time series of bond yields contain a unit root. The test is performed by using the Augmented Dickey-Fuller test and estimating the following equation:

\[ \Delta p_t = \phi \Delta p_{t-1} + \sum_{i=1}^{l} \varphi_i \Delta p_{t-i} + u_t \]  

where \( \Delta p_t \) is the first difference in yields, \( l \) is the number of lags which we select using the Akaike information criterion (AIC) and \( \varphi_i \) are the coefficients of lagged yield changes. The critical values given by Dickey and Fuller (1979) are used to test the null hypothesis of unit root, \( \phi = 0 \). When the test statistic
is not higher than the critical value, we fail to reject the null hypothesis in which case we say that the yield contains a unit root.

Table 3 presents the test results for the level and first difference of yields in each maturity category in our sample. The second and the fifth columns show the number of lags selected with the Akaike information criterion (AIC) while the fourth and the seventh columns present the $p$-values of the tests. Clearly, when we test yield levels the null hypothesis of unit root is never rejected whereas the null hypothesis is rejected for all the bonds when we test yield changes. This corroborates our initial conjecture that yield levels are $I(1)$ and their first differences are stationary.

[Please insert the Table 3 about here]

Although yields are nonstationary, they do not diverge without bound from one another because they are driven by the same fundamental factors. In our case, bond yields should contain information about interest rates common to all members in the euro area. We expect, therefore, bond yields across different euro area markets to be cointegrated. We use Johansen’s (1988) method to examine the cointegration hypothesis for bond yields in the same maturity category. The number of cointegrating relationships is examined by studying the two test statistics:

$$
\hat{\lambda}_{\text{trace}}(r) = -T \sum_{i=r+1}^{n} \ln(1 - \hat{\lambda}_i)
$$

and

$$
\hat{\lambda}_{\text{max}}(r, r+1) = -T \ln(1 - \hat{\lambda}_{r+1})
$$

where $T$ is the number of observations, $r$ is the tested number of cointegrating relationships, $n$ is the number of bonds in the VECM. If yields are cointegrated, the number of cointegrating relationships should be greater than 0 and less than $n$. The trace statistic tests the null hypothesis that the number of cointegrating vectors is less than or equal to $r$ against the alternative hypothesis that it is greater than $r$. The maximum eigenvalue statistic examines the null hypothesis that the number of cointegrating relationships is $r$ against the alternative hypothesis that it is $r+1$. Table 4 presents the test results for each maturity category. The test specifications include intercepts in the cointegrating equations, no trend in the
level data and 15 lags of yield changes. For all the maturity groups we find that the bonds are cointegrated and there are always three cointegrating vectors.

[Please insert the Table 4 about here]

5.2 Information Shares

Increased financial integration has caused securities markets in the euro area to become more homogenous. The evidence from the cointegration tests shows that bond yields are cointegrated and suggests that they all reflect the same efficient information about the fundamental factors driving the European interest rate. However, due to certain institutional and economic reasons, sovereign markets differ in their capacity to provide timely and informative quotes. We define price leadership as the information contribution of a sovereign security toward the variance of the efficient yield.

In order to produce some benchmark results we follow Hasbrouck (2003) and identify price leadership in all maturity categories by estimating the VECM equation (2) separately for every day over the period Oct 3, 2005 to Sep 29, 2006. Clearly, we cannot present all the daily estimates of the VECM model. However, we can make the following general observations. The yield adjustment coefficients $\beta$ are negative and highly significant at the 1% level, confirming that yields are strongly cointegrated over the trading day. However, the absolute values of these coefficients change from day to day, indicating time-varying adjustments to the long term relationship among these markets. The autoregressive coefficients $a'$s are statistically significant up to five lags. Yield changes are negatively related to their own lags and positively to lags of the other bonds.

Because of the complexity of the estimated models, it is easier to consider the interactions among sovereign yields by analyzing the cumulative impulse response functions. We assume that the system is in equilibrium and, at time 0, it is shocked by an initial innovation specified as one basis point of a particular sovereign yield. Moving from this point forward, we compute the cumulative yield changes at every time step as the averages of daily estimates over the whole sample. We study how the joint yield dynamics will evolve after $n$ periods in the future. We allow a sufficient $n$ to enable yield convergences. We focus on the
long-run cumulative effect of yield shocks which measures the permanent or informational impact on all the yields of the initial shock in a particular market.

Figure 2 shows the cumulative impulse response functions for the 10-year maturity category over the whole sample period. The top-left graph presents the cumulative yield changes caused by an initial shock to the French bond. We observe that an innovation in the French market causes sovereign bond yields to converge to a long-run level after about 100 quote events. Similar convergences are also observed with the other sovereign yields. More importantly, the long-run values differ from zero for all of the bonds. This result indicates that innovations in the quote process cause permanent yield impacts.

Table 5 shows the summary statistics of the information shares in each maturity group. The information share reflects the contribution of each sovereign market to the total efficient yield variance. Because the innovation covariance matrices are not diagonal, we are only able to compute the ranges of the information shares by using the Cholesky decomposition approach as described in Hasbrouck (1995). The lower and upper bounds of information shares are estimated daily and then averaged over the whole sample period. At the 2-year maturity category, we notice that the French bond registers the highest information share with the median value of around 30%. Similarly to the findings of Dunne et al. (2007), the French bonds seem the benchmark instrument for short-term maturities. For the 5-year and 10-year maturities, German bonds lead the price discovery process with the median upper bound information shares of 30% and 27%, respectively. At the 30-year maturity, the Italian bond is the most informative with the median upper bound of the information share of about 31%. The share of the contribution of each market to the price discovery process varies significantly over the maturity categories and over the whole sample period. The standard deviations of information shares range from about 14% for both the 5-year and 10-year to around 20% for the 2-year.

We observe that unlike the U.S. equity markets (Hasbrouck, 1995), there is no absolute venue for price discovery in these sovereign securities markets. The contributions to the efficient yield variances are
often fairly evenly distributed among the four sovereign markets. This pattern is most obvious at the 10-year maturity category, signaling that the competition for price discovery is strongest at this maturity point of the yield curve.

Our findings are consistent with the anecdotal evidence in the IMF (2001) publication with regard to a non-uniform euro government yield curve. Market participants view the French, German and Italian sovereign markets as the three unique segments for trading and hedging financial positions. First, the price leadership of the French sovereign bonds at the short maturities arises because of deep and liquid French repurchase (repo) markets after series of legal and regulatory reforms in France in the 1990s. Biais et al. (2004) note that France is the largest issuer of Treasury bills among the European countries. They find that when markets are highly volatile, bills with a large amount outstanding register lower yields, consistent with the argument that liquidity is valuable during flight-to-quality and flight-to-liquidity events. Second, investors who want to trade the medium term interest rates concentrate on the German market due to active trading in this segment. German bonds are usually characterized by large issuances of more than €10billion to €20billion for one issue. Additionally, the German segment benefits from the established German Bund futures market where the German 5-year and 10-year bonds are the deliverable securities. Third, investors who want to trade cross-country yield spreads rely on the Italian segment. Italian treasury bonds have lower long-term credit rating and higher yields than the bonds of other countries (MTS (2006)). The yield differential remains highest at the very long end of the yield curve such as the 30-year maturity. Market participants expect that as financial integration in Europe proceeds, these spreads will narrow. It is believed that the existence of active convergence trading explains the importance of the Italian segment within the 30-year maturity group.

5.3 Time and Price Discovery

Clearly, given the fast moving nature of the markets and of the information structure the price discovery process varies over time. Even Hasbrouck (1995 and 2003) assumes that the VECM is only valid for a single trading session. When the VECM is estimated over the whole sample period, we
observe a significant gap between the upper and lower bounds of the information shares, suggesting that the static price discovery model is perhaps inappropriate when considering an extended period of time. In order to deal with the above issues we suggest using a dynamic specification for the price discovery process as discussed in section 4.2 above.

With our model we can also investigate the effects of changes in the speed of quote updates on the yield discovery process. In particular, we consider the series of time durations between consecutive quote updates across the four selected bond markets and study the role of time durations in the yield formation model. We decompose the role of time into deterministic time-of-day effects and stochastic effects and extend the VECM by adding these variables into the yield adjustment coefficients. The extended VECM is estimated for each maturity group over the whole sample period.

Because the adjustment coefficients are expected to be negative, an explanatory variable is positively (negatively) related to the yield adjustment if its coefficient is also negative (positive). We divide a trading day into five knots: opening (8:15am-9:00am), morning (9:00am-12:00pm), lunch (12:00pm-3:00pm), U.S. equity opening (3:00pm-4:00pm) and closing (4:00pm-5:30pm). Since the opening knot serves as the benchmark, the coefficients of the other time knots measure how the speed of the yield adjustments differs from the opening at a particular period. As we expect, the coefficients of the opening are all significant and negative. Since the results remain qualitatively similar across different maturities, for brevity we only provide the estimates of the explanatory variables for a representative group.

Table 6 highlights the importance of time in the speed of yield adjustments for the 10-year maturity group. As predicted by Admanti and Pfleiderer (1988), we observe intraday effects in the yield adjustments. The coefficients of the morning knot are negative and significant, indicating an increase in the speed of yield adjustments during the morning trading hours. Moving from this period toward the closing, we observe a reduction in the yield adjustments during the lunchtime. Yields take shorter time to converge when the U.S. equity market opens. The coefficients of the closing are positive and significant, indicating that yield adjustments are slower at the closing.
We notice that the coefficients of the time between quotes are consistently positive and significant for all maturity groups. This finding supports the information argument of time in Easley and O'Hara (1992) and Dufour and Engle (2000). Long durations characterize periods of no news and result in slower yield adjustments.

The previous literature suggests that market liquidity also affects the price discovery process. Particularly, Mizrach and Neely (2007) show that the information share of the spot U.S. Treasury market versus the future market is reduced if the spot market becomes less liquid. Consistent with the previous studies, we observe a positive relation between market liquidity and the speed of yield adjustments. The coefficients for relative spread are positive whereas those of quoted depth are negative. This result indicates that yield adjustments are faster during periods of enhanced market liquidity.

5.4 Macroeconomic news and Price Discovery

After providing evidence of a time-varying price discovery process, we investigate how bond yields adjust to the announcements of macroeconomic news. We conjecture that the informational asymmetry in the market increases around the announcements and this will affect the level of interaction among markets. We consider six periods around the time of announcements and allow the adjustment coefficients to vary before and after the announcements. The extended VECM is also estimated for each maturity over the sample period. For brevity we only present the adjustment coefficients corresponding to the announcement periods for the 10-year maturity group.

Table 7 illustrates how the long-term adjustment coefficients of each sovereign market change around U.S. and the euro-area macroeconomic news releases. In Panel A, consistent with Goldberg and Leonard (2003), we observe that U.S. economic news significantly affect the euro-area sovereign bond yield discovery process. The adjustment coefficients for the half-hour before the announcements tend to be positive and significant for Germany and France, indicating a reduction in interactions between these bond yields. Subsequent to the releases of economic news, the speed of yield adjustments grows
significantly higher and peaks at about twenty to thirty minutes after the announcements except for the Italian bond where the effect dies out more rapidly. The coefficients of the one hour to two hours knot tend to be either positive or insignificant, suggesting that the impacts of macroeconomic news die out about one hour after the announcements. In Panel B, we notice the same patterns in the reactions of bond yields to euro-area news. Yield adjustments are significantly faster after the news releases although this increased activity seems to disappear one hour after the announcements.

6. Conclusion

Increased globalization has generated considerable interests among academics and practitioners to examine how financial integration affects market performance. This paper studies the price discovery process in the euro sovereign securities markets after the introduction of the euro. We identify the price leaders at key points of the euro government yield curve and examine factors that explain the dynamics of the price discovery process over time. The empirical analysis is based on high frequency data extracted from the MTS Time Series database. We consider firm quotes posted by MTS market makers for the most actively traded bonds issued by the German, Italian, French and Spanish governments over the period from October 1, 2005 to September 30, 2006.

We observe a non-uniform benchmark yield curve where no single sovereign market dominates the price discovery process for all maturities. The French market provides price leadership at the 2-year maturity, the German market at the 5-year and 10-year maturities while the Italian market is the most informative at the 30-year maturity of the yield curve. The information shares are most equally divided at the 10-year maturity category, indicating strongest competition for price discovery at this maturity point of the yield curve.

We find that time is important in the price discovery process. Yields take the shortest time to converge in the morning after the opening period and when the U.S. equity markets open. Market liquidity is positively and significantly related to the yield adjustments. Yield adjustments are faster when markets have smaller spreads and larger depth. In addition, our findings indicate that macroeconomic
news releases affect the price discovery process. The speed of yield adjustments is negatively and significantly related to the time between consecutive quote updates. More frequent quote revisions indicate periods of active changes in the information set about the common efficient interest rate, and consequently lead to faster yield convergence.

Furthermore, the increased informational asymmetry around macroeconomic announcements leads to significantly larger yield adjustments to the long-run equilibrium relationships. We find that both U.S. and euro-area news significantly affect the bond yield changes for up to about one hour after the announcements.

References


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MTS. The European bond market: A single market with unique segments, (MTS Group); 2006.
Persaud, AD. Improving efficiency in the European government bond market, (ICAP plc); 2006.
Appendix A: Yield Computation

Because of the absence of yield information in our data, we obtain the bond yield-to-maturity by using the Newton-Raphson procedure and by minimizing the squared yield errors from the equation:

\[ Q_t = \sum_{i=1}^{n} \frac{\text{Coupon}_i}{(1 + y/h)^i} + \frac{\text{ParValue}}{(1 + y/h)^n}, \]

where \( Q_t \) is the bond mid-quote price plus the accrued interest at time \( t \), \( y_t \) is the bond yield-to-maturity, \( h \) is the coupon frequency, \( n \) is the number of remaining coupon periods. Let \( D^* \) denote the bond modified duration which can be described as:

\[ D^* = \left( \sum_{i=1}^{n} \frac{i}{h} \times \frac{\text{Coupon}_i}{(1 + y/h)^i} + \frac{i}{h} \times \frac{\text{ParValue}}{(1 + y/h)^n} \right) \times \frac{1}{Q_t(1 + y/h)}. \]

We compute bond yield-to-maturity and the modified duration for each bond in our sample from the first proposal of a trading day. Given the size of our data, estimating the bond yields at the intraday level is not tractable. Instead, we obtain the bond yields from the mid-quote prices and the estimated modified durations which we assume to remain constant throughout a trading day. In addition, we do not consider the effects of the bond convexity. Because the time between consecutive events is short, changes in interest rates are relatively small, causing the effects of the bond convexity to be dominated by the bond duration. Therefore, yield changes are obtained by using the first-order approximation as:

\[ \Delta y_t \approx \frac{1}{D^* Q_{t-1}} \Delta Q_t. \]
Table 1
Summary Statistics
The data includes trade and quote records for 16 of the most actively traded bonds on the local and EuroMTS markets over the sample period from Oct 1, 2005 to Sep 30, 2006. Quotes outside trading hours (8:15am to 5:30pm) and with relative quoted spread larger than 50 basis points are excluded. Relative spread is the quoted spread divided by the quote midpoint. The quoted depth is the average quantity at the best bid and asks quotes. Averages calculated are the means of the variables.

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<td>82.01</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>255</td>
<td>255</td>
<td>263.3</td>
<td>558</td>
<td>34.7</td>
<td>2.73</td>
<td>70.75</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>227</td>
<td>255</td>
<td>41.04</td>
<td>616</td>
<td>37.4</td>
<td>10.21</td>
<td>14.32</td>
</tr>
</tbody>
</table>
Table 2
Economic News Announcements
The table presents the titles and the indicative release time (Central European Time) of scheduled economic news announcements from the U.S. and the euro-area.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago purchasing manager</td>
<td>03:00 PM</td>
<td>CPI estimate</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>Consumer confidence</td>
<td>03:00 PM</td>
<td>GDP</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>Consumer price index</td>
<td>01:30 PM</td>
<td>Economic confidence</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>Durable goods orders</td>
<td>01:30 PM</td>
<td>PPI</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>Initial jobless claims</td>
<td>02:30 PM</td>
<td>Purchasing manager index</td>
<td>9:00 AM</td>
</tr>
<tr>
<td>New home sales</td>
<td>03:00 PM</td>
<td>Retail sales</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>Nonfarm payrolls</td>
<td>02:30 PM</td>
<td>Unemployment rate</td>
<td>10:00 AM</td>
</tr>
<tr>
<td>U. of Michigan confidence</td>
<td>03:00 PM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unemployment rate</td>
<td>02:30 PM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3
#### Unit Root Tests

The table presents the Augmented Dickey-Fuller unit root tests for yield midpoint and yield changes of German, Italian, French and Spanish bonds in our sample. Lags refer to the number of lags used in the test as determined by the Akaike Information Criterion.

<table>
<thead>
<tr>
<th>Countries</th>
<th>Yield Level</th>
<th>Yield Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Lags</td>
<td>t-statistics</td>
</tr>
<tr>
<td><strong>Panel A: 2-year YTM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>7</td>
<td>-1.65</td>
</tr>
<tr>
<td>Spain</td>
<td>9</td>
<td>-1.70</td>
</tr>
<tr>
<td>France</td>
<td>7</td>
<td>-1.59</td>
</tr>
<tr>
<td>Italy</td>
<td>15</td>
<td>-1.62</td>
</tr>
<tr>
<td><strong>Panel B: 5-year YTM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>5</td>
<td>-2.22</td>
</tr>
<tr>
<td>Spain</td>
<td>5</td>
<td>-1.54</td>
</tr>
<tr>
<td>France</td>
<td>5</td>
<td>-1.94</td>
</tr>
<tr>
<td>Italy</td>
<td>5</td>
<td>-1.94</td>
</tr>
<tr>
<td><strong>Panel C: 10-year YTM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>3</td>
<td>-1.84</td>
</tr>
<tr>
<td>Spain</td>
<td>3</td>
<td>-1.80</td>
</tr>
<tr>
<td>France</td>
<td>3</td>
<td>-1.79</td>
</tr>
<tr>
<td>Italy</td>
<td>4</td>
<td>-1.77</td>
</tr>
<tr>
<td><strong>Panel D: 30-year YTM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>3</td>
<td>-1.58</td>
</tr>
<tr>
<td>Spain</td>
<td>3</td>
<td>-1.29</td>
</tr>
<tr>
<td>France</td>
<td>4</td>
<td>-1.55</td>
</tr>
<tr>
<td>Italy</td>
<td>5</td>
<td>-1.56</td>
</tr>
</tbody>
</table>
Table 4
Cointegration Tests

The table presents the results of Johansen cointegration tests for yields of bonds in the same maturity category. Test specifications include intercepts in cointegrating equations but no trend in the level data and 15 lags of yield changes. We present the trace and maximum eigenvalue value statistics. The trace and maximum eigenvalue value statistics are measured as follows:

\[ \hat{\lambda}_{\text{trace}}(r) = -T \sum_{i=r+1}^{n} \ln(1-i) \text{ test,} \]

\[ \hat{\lambda}_{\text{max}}(r+1) = -T\ln(1-i_{r+1}) \text{ test,} \]

Where \( T \) is the number of observations, \( r \) is the tested number of cointegrating relationships and \( n \) is the number of bonds.

<table>
<thead>
<tr>
<th>Null H₀</th>
<th>Alternative H₁</th>
<th>Trace Statistics</th>
<th>Trace 95% Critical Value</th>
<th>Max Eigenvalue Statistics</th>
<th>Max Eigenvalue 95% Critical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel A: 2-year YTM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r=0 )</td>
<td>( r &gt; 0 )</td>
<td>530.16</td>
<td>47.86</td>
<td>311.01</td>
<td>27.58</td>
</tr>
<tr>
<td>( r≤1 )</td>
<td>( r &gt; 1 )</td>
<td>219.15</td>
<td>29.8</td>
<td>173.65</td>
<td>21.13</td>
</tr>
<tr>
<td>( r≤2 )</td>
<td>( r &gt; 2 )</td>
<td>45.5</td>
<td>15.5</td>
<td>42.78</td>
<td>14.27</td>
</tr>
<tr>
<td>( r≤3 )</td>
<td>( r &gt; 3 )</td>
<td>2.73</td>
<td>3.84</td>
<td>2.73</td>
<td>3.84</td>
</tr>
<tr>
<td>Panel B: 5-year YTM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r=0 )</td>
<td>( r &gt; 0 )</td>
<td>914.58</td>
<td>54.08</td>
<td>592.12</td>
<td>28.59</td>
</tr>
<tr>
<td>( r≤1 )</td>
<td>( r &gt; 1 )</td>
<td>322.46</td>
<td>35.19</td>
<td>173.25</td>
<td>22.30</td>
</tr>
<tr>
<td>( r≤2 )</td>
<td>( r &gt; 2 )</td>
<td>149.21</td>
<td>20.26</td>
<td>145.41</td>
<td>15.89</td>
</tr>
<tr>
<td>( r≤3 )</td>
<td>( r &gt; 3 )</td>
<td>3.80</td>
<td>9.16</td>
<td>3.80</td>
<td>9.16</td>
</tr>
<tr>
<td>Panel C: 10-year YTM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r=0 )</td>
<td>( r &gt; 0 )</td>
<td>650.79</td>
<td>54.08</td>
<td>449.40</td>
<td>28.59</td>
</tr>
<tr>
<td>( r≤1 )</td>
<td>( r &gt; 1 )</td>
<td>201.39</td>
<td>35.19</td>
<td>143.38</td>
<td>22.30</td>
</tr>
<tr>
<td>( r≤2 )</td>
<td>( r &gt; 2 )</td>
<td>58.01</td>
<td>20.26</td>
<td>55.56</td>
<td>15.89</td>
</tr>
<tr>
<td>( r≤3 )</td>
<td>( r &gt; 3 )</td>
<td>2.45</td>
<td>9.16</td>
<td>2.45</td>
<td>9.16</td>
</tr>
<tr>
<td>Panel D: 30-year YTM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r=0 )</td>
<td>( r &gt; 0 )</td>
<td>814.43</td>
<td>54.08</td>
<td>671.45</td>
<td>28.59</td>
</tr>
<tr>
<td>( r≤1 )</td>
<td>( r &gt; 1 )</td>
<td>142.98</td>
<td>35.19</td>
<td>119.88</td>
<td>22.30</td>
</tr>
<tr>
<td>( r≤2 )</td>
<td>( r &gt; 2 )</td>
<td>23.10</td>
<td>20.26</td>
<td>20.18</td>
<td>15.89</td>
</tr>
<tr>
<td>( r≤3 )</td>
<td>( r &gt; 3 )</td>
<td>2.92</td>
<td>9.16</td>
<td>2.92</td>
<td>9.16</td>
</tr>
</tbody>
</table>
Table 5
Contributions to Price Discovery
The table presents the summary statistics of daily estimates of information shares obtained using Hasbrouck's (1995) method for groups of bonds different maturity categories. The Vector Error Correction Model is estimated with five lags and in event time for each day of the sample from October 3, 2005 to September 29, 2006. Bold type indicates the country that provides greater price discovery in each category.

<table>
<thead>
<tr>
<th>YTM</th>
<th>Germany</th>
<th>Spain</th>
<th>France</th>
<th>Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Std</td>
<td>Max</td>
</tr>
<tr>
<td>2Y</td>
<td>0.216</td>
<td>0.170</td>
<td>0.178</td>
<td>0.230</td>
</tr>
<tr>
<td>5Y</td>
<td><strong>0.299</strong></td>
<td><strong>0.254</strong></td>
<td>0.151</td>
<td>0.247</td>
</tr>
<tr>
<td>10Y</td>
<td><strong>0.268</strong></td>
<td><strong>0.226</strong></td>
<td>0.136</td>
<td>0.265</td>
</tr>
<tr>
<td>30Y</td>
<td>0.292</td>
<td>0.237</td>
<td>0.181</td>
<td>0.253</td>
</tr>
</tbody>
</table>
The table presents the adjustment coefficients (with t-statistics in parentheses) for the bonds in the 10-year maturity group of the following Vector Error Correction Model:

$$
\Delta p_{i,t} = \sum_{j=1, j\neq i}^{n} \beta_{i,j,t-1} (p_{i,t-1} - p_{j,t-1} - \mu_{i,j}) + \sum_{s=1}^{m} \sum_{k=1}^{m} a_{i,s,k} \Delta p_{i,t-k} + u_{i,t},
$$

where

$$
\beta_{i,j,t-1} = \gamma_{i,j}^{r} + \sum_{l=2}^{L} \gamma_{i}^{K} K_{i,l,t-1} + \gamma_{i}^{S} S_{i,t-1} + \gamma_{i}^{D} D_{i,t-1} + \gamma_{i}^{T} T_{t-1},
$$

$p$ is the yield of bond $i$ at time $t$, $N$ is the number of bonds and $m$ is the order of lags. $\beta_{i,j,t-1}$ is the adjustment coefficient of bond $i$ to its fundamental relationship with bond $j$. $S_{i,t}$ denotes the relative spread, $D_{i,t}$ the average of the bid and ask size at the best quote and $T_t$ the time duration between the quotes at $t-1$ and $t$. $\gamma_{i}^{S}$, $\gamma_{i}^{D}$ and $\gamma_{i}^{T}$ are the coefficients for the relative spread, the depth and the time duration. We divide a trading day into five knots ($K=4$): 8:15am-9:00am (Opening), 9:30am-12:00pm (Morning), 12:00pm-3:00pm (Lunch), 3:00pm-4:00pm (U.S. Opening) and 4:00pm-5:30pm (Closing) and treat the first knot 8:15am-9:00am as the benchmark. The model is estimated over the full sample from October 3, 2005 to September 29, 2006. All of the estimates are multiplied by 1000. Bold type indicates significance at the 1 percent level.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Germany</th>
<th>Spain</th>
<th>France</th>
<th>Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>-4.63(-4.11)</td>
<td>-4.19(-3.44)</td>
<td>-2.74(-2.61)</td>
<td>-6.74(-6.58)</td>
</tr>
<tr>
<td>Lunch</td>
<td>5.39(4.94)</td>
<td>4.32(3.57)</td>
<td>4.83(4.58)</td>
<td>4.06(3.26)</td>
</tr>
<tr>
<td>U.S. Opening</td>
<td>-2.46(-2.22)</td>
<td>-4.44(-3.6)</td>
<td>-7.53(-7.15)</td>
<td>-10.63(-13.73)</td>
</tr>
<tr>
<td>Closing</td>
<td>5.73(5.32)</td>
<td>1.90(1.60)</td>
<td>8.52(8.36)</td>
<td>9.94(14.03)</td>
</tr>
<tr>
<td>Time Duration</td>
<td>0.13(17.23)</td>
<td>0.21(25.9)</td>
<td>0.07(10.43)</td>
<td>0.13(24.71)</td>
</tr>
<tr>
<td>Spread</td>
<td>0.28(9.14)</td>
<td>3.60(21.31)</td>
<td>2.75(20.03)</td>
<td>0.98(18.46)</td>
</tr>
<tr>
<td>Depth</td>
<td>-0.24(-38.02)</td>
<td>-0.27(-30.99)</td>
<td>-0.41(-43.34)</td>
<td>-0.09(-21.75)</td>
</tr>
</tbody>
</table>
Table 7: Economic News Announcements and Price Discovery

The table presents the adjustment coefficients (with t-statistics in parentheses) for the bonds in the 10-year maturity group of the following Vector Error Correction Model:

\[ \Delta p_{i,t} = \sum_{j=1}^{n} \beta_{i,j,t-1}(p_{j,t-1} - p_{j,t-1} - \mu_{i,j}) + \sum_{s=1}^{m} \sum_{k=1}^{m} \alpha_{s,k} \Delta p_{i,t-k} + u_{i,t}, \]

where

\[ \beta_{i,j,t-1} = \gamma_{i}^{1} + \sum_{l=2}^{L} \gamma_{i}^{l} K_{i,j,t-1} + \gamma_{i}^{S} S_{i,j,t-1} + \gamma_{i}^{D} D_{i,j,t-1} + \gamma_{i}^{T} T_{i,t-1} + \sum_{q=1}^{O} \gamma_{i}^{q} I_{q,t-1}, \]

we use indicator variables \( I_{q,t} \) to allow the adjustment coefficients to vary in six periods (Q=6) before and after the news announcement time: half-hour before the announcements (-30min), from the announcement to ten minutes after the announcements (0-10min), from ten to twenty minutes after the announcements (10min-20min), from twenty to thirty minutes after the announcements (20min-30min), from thirty minutes to 1 hour after the announcements (30min-1hour) and from 1 hour to 2 hours after announcements (1hour-2hour). \( \gamma_{i}^{q} \) measures the sensitivity of yield adjustments in these time periods. The other variables are explained in Table 6. The model is estimated over the entire sample from October 3, 2005 to September 29, 2006. All of the estimates are multiplied by 1000. Bold type indicates significance at 1 percent level.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Germany</th>
<th>Spain</th>
<th>France</th>
<th>Italy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel A: U.S. Economic news</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 30 min.</td>
<td>3.99(2.8)</td>
<td>2.10(1.39)</td>
<td>3.29(2.38)</td>
<td>0.04(0.03)</td>
</tr>
<tr>
<td>0 – 10min.</td>
<td>-5.58(-1.62)</td>
<td>-18.04(-4.53)</td>
<td>-9.49(-3.23)</td>
<td>-5.24(-2.85)</td>
</tr>
<tr>
<td>10min. – 20min.</td>
<td>-6.72(-2.02)</td>
<td>-18.31(-4.76)</td>
<td>-14.21(-4.1)</td>
<td>-0.12(-0.04)</td>
</tr>
<tr>
<td>20min – 30min</td>
<td>-5.4(-1.71)</td>
<td>-23.87(-6.42)</td>
<td>-16.42(-5.11)</td>
<td>-2.04(-0.78)</td>
</tr>
<tr>
<td>30min – 1hour</td>
<td>-15.21(-8.12)</td>
<td>-8.10(-4.05)</td>
<td>-5.19(-2.93)</td>
<td>-1.84(-1.22)</td>
</tr>
<tr>
<td>1hour – 2hour</td>
<td>10.35(18.41)</td>
<td>4.82(7.08)</td>
<td>-0.59(-1.13)</td>
<td>-0.49(-0.87)</td>
</tr>
<tr>
<td>Panel B: Euro-area Economic news</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 30 min.</td>
<td>3.14(2.61)</td>
<td>-3.78(-1.51)</td>
<td>-0.29(-0.20)</td>
<td>-2.80(-1.49)</td>
</tr>
<tr>
<td>0 – 10min.</td>
<td>-2.38(-0.74)</td>
<td>-17.48(-3.85)</td>
<td>-18.3(-5.49)</td>
<td>2.16(0.64)</td>
</tr>
<tr>
<td>10min. – 20min.</td>
<td>-5.13(-2.81)</td>
<td>-10.05(-2.78)</td>
<td>0.23(0.11)</td>
<td>-9.3(-4.68)</td>
</tr>
<tr>
<td>20min – 30min</td>
<td>-1.11(-0.64)</td>
<td>-17.99(-5.34)</td>
<td>-9.19(-5.44)</td>
<td>0.37(0.20)</td>
</tr>
<tr>
<td>30min – 1hour</td>
<td>-26.06(-5.76)</td>
<td>-2.93(-0.65)</td>
<td>-12.19(-3.39)</td>
<td>4.48(1.37)</td>
</tr>
<tr>
<td>1hour – 2hour</td>
<td>0.12(0.05)</td>
<td>-2.25(-0.87)</td>
<td>-0.97(-0.50)</td>
<td>-0.48(-0.21)</td>
</tr>
</tbody>
</table>
Fig. 1. Intraday quote update patterns. This figure presents the average daily pattern for the number of quote updates for each of the four maturity groups. First, we exclude quotes outside trading hours (8:15am-5:30pm) and quotes with relative spreads higher than 50 basis points. Second, we sort quotes in chronological order for each maturity group and track the updates to the quotes vector. Third, we count the number of quote updates for each five minute interval of every trading day and then take the average over the whole sample period from October 3, 2005 to September 29, 2006.
Fig. 2. Cumulative impulse response functions. This figure exhibits the cumulative yield changes for the 10-year maturity group after initial yield shocks to the French, German, Italian and Spanish yield respectively. The VECM model is estimated in event time for each day of the sample period from October 5, 2005 to September 29, 2006. The system is first assumed in equilibrium and then in period zero it is shocked by an initial innovation specified as one basis point in a particular bond yield and zero in other bonds. From this point forward, we compute the cumulative yield changes at every time step as the averages of daily estimates over the whole sample period.