THE ROLE OF U.S. TRADING IN PRICING INTERNATIONALLY CROSS-LISTED STOCKS

by

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Abstract: This paper addresses two issues: 1) where does price discovery occur for firms that are traded simultaneously in the U.S. and in their home markets and 2) what explains the differences across firms in the share of price discovery that occurs in the U.S? The answer to the first question is that the home market is typically where the majority of price discovery occurs, but there are significant exceptions to this rule and the nature of price discovery across international markets during the time of trading overlap is richer and more complex than previously realized. For the second question, the results provide strong support that liquidity is an important factor. For a particular firm, the greater the liquidity of U.S. trading relative to the home market, the greater the role for U.S. price discovery.

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I. INTRODUCTION

When a firm's stock is traded simultaneously in both the United States and another country, what should we expect regarding the role of U.S. trading in price discovery? If the evidence indicates that there is a bigger role for U.S. price discovery for some firms than others or for stocks of some countries than others, what determines this different role for different stocks? There is a small literature on the topic of price discovery for internationally cross-listed firms. The evidence regarding where price discovery occurs is mixed. There is some support for an important role for both the home and foreign market and there is also support for the home market dominating price discovery.[1]

The present study is intended to contribute new evidence on this topic. Specifically, the analysis focuses on the overlap of trading for firms from Canada, France, Germany, and the U.K. with the U.S. Models of the information shares from each market are estimated for the major traded firms. Then a cross-section analysis is

[1] Studies using high-frequency intradaily data include Ding, Harris, Lau, and McInish (1999) who study Singapore and Malaysia trading; Hupperets and Menkveld (2002) who study Dutch firms traded in New York; Eun and Sabherwal (2003) who study Canada and U.S. trading; and Phylaktis and Korczak (2004) who study British and French firms listed in the U.S. All four papers find support for significant price discovery in both markets. Grammig, Melvin, and Schlag (2005) study German and U.S. trading and find support for the home market dominating. Studies based upon lower frequency daily data include Kim, Szakmary, and Mathur (2000) who find a small role for U.S. price discovery in the case of firms from Japan, the Netherlands, the U.K., Sweden, and Australia; Lau and Diltz (1994) who find two-way causality between Japanese and U.S. prices of Japanese firms cross-listed in the U.S.; Lieberman, Ben-Zion, and Hauser (1999) who study Israeli firms also traded in the U.S. and find that price discovery occurs in Israel with the exception of Teva, where the U.S. price leads the Israeli price; Wang, Rui, and Firth (2002) and Agarwal, Liu, and Rhee (forthcoming) who find that for Hong Kong stocks listed in London, Hong Kong is the dominant market; and von Furstenberg and Tabora (2004) who find two-way causality for two Mexican firms also traded in the U.S.

employed to identify the important determinants of price discovery across firms. The time-series evidence on price discovery comes from high-frequency data sampled at 10-second intervals. Preliminary analysis indicated that sampling at lower frequencies, as is commonly done in the literature, results in very wide bounds on the information shares of different markets so that the true causality is blurred and one cannot make any strong statements regarding the origins of price discovery. For instance, daily data are simply too highly aggregated to allow strong evidence of causality. In fact, the evidence indicates that sampling even at 1-minute intervals dramatically weakens the causality in the data.

An additional issue related to internationally cross-listed firms is the incorporation of an exchange rate factor. Many studies examine the home and foreign price of stocks by using the exchange rate to convert one price into the same units as the other price. For instance, if French stocks are quoted in euros in Paris and dollars in New York, one could simply convert the Paris price into a dollar equivalent by multiplying the euro price by the dollar/euro exchange rate. Then the analysis may proceed in terms of just the two stock prices, quoted in a common currency. This approach may introduce some problems in inferring price discovery as the effect of exchange rate change is being ascribed to the stock price incorporating the exchange rate. Grammig, Melvin, and Schlag (2005) produce simulation results that show the severe bias that can result from following such an approach. If the goal is to infer price discovery of the two trading locations, then it is important to allow for an independent exchange rate effect. This means that a three variable system should be modeled: the exchange rate, the home market price, and the foreign market price. We follow such a strategy to allow a clear focus on the contribution of each market to price discovery. A by-product of this estimation strategy is that we can estimate the adjustment of the two market locations to exchange rate shocks. This is an interesting result by itself.

To summarize the findings, the estimated models reveal that for most stocks price discovery largely occurs in the home market with a relatively small role for U.S. trading. However, results differ across firms and some firms cast a larger role for U.S. than home market price discovery. The cross-section models indicate that these differences are driven by differences in the liquidity of the U.S. market for firms. Liquidity is measured by the following variables: NYSE/home turnover, NYSE/home volume, and the NYSE/home spread. The more liquid is U.S. trading in a stock, the larger the role for U.S. price discovery relative to the home market. With respect to the exchange rate effects, it appears that U.S. prices bear more of the burden of adjustment to an exchange rate shock than the home market. This is consistent with the general finding that the home market may be viewed as the primary market and the U.S. is the derivative market. For most firms, U.S. prices follow the home market prices and this leader-follower relationship is reflected in the U.S. price incorporating the exchange rate effect. However, there are important exceptions to this rule so that the dynamics of international price discovery are more complex than previously thought.

The study is organized as follows: section II provides information on each of the stock markets studied and their trading mechanisms along with information on the firms in the sample. Section III describes the data to be used for estimation. Section IV offers a description of hypothesized equilibrium relationships and the econometric methodology employed. Estimation results and discussion are presented in section V. A conclusion and summary is given in the final section VI.

II. TRADING VENUES AND FIRMS

This study involves data on stocks traded on five different exchanges in five different countries. The exchanges and countries are: the New York Stock Exchange (NYSE)/United States; The Toronto Stock Exchange (TSE)/Canada; the Xetra system operated by the Deutsche Börse/Germany; the London Stock Exchange (LSE)/Great Britain; and the Paris Bourse/France. These locations are chosen for analysis because they have trading hours that overlap U.S. trading hours and high-frequency intra-daily quote data are available. The goals of this study require data sampled at very high frequencies to reveal the causality present in the data (if any). Daily data, which is available for all exchanges, would not be useful. In addition, only those firms which are most actively traded can be usefully included in a study of price discovery as infrequent trading would result in either many data holes with high-frequency sampling or else a level of time aggregation that blurs the true causality in the data.

<Table 1 goes here>

A brief summary of each trading venue is provided in Table 1. As indicated in Table 1, trading hours and currencies are as follows:

- *New York Stock Exchange (NYSE)* Trading hours are from 9:30-16:00 New York time and trading occurs in U.S. dollars.

- *Xetra/Deutsche Börse* Until September 17, 1999, Xetra trading hours were from 8:30-17:00 local time. From September 20, 1999 on, trading hours were shifted to 9:00-17:30. Trading occurs in euros.
- *London Stock Exchange (LSE)* Trading hours are from 8:00-16:30 London time. Trading is in British pounds.
- *Paris Bourse* Trading hours are from 9:00-17:30 Paris time. Trading is in euros.
- *Toronto Stock Exchange (TSE)* Trading hours are from 9:30-16:00 Toronto time. Trading occurs in Canadian dollars.

Most firms that list their shares in the United States do so with an American Depositary Receipt (ADR). ADRs are issued by a depositary bank accumulating shares of the underlying foreign stock. ADRs are issued at a fixed multiple relative to the underlying shares (like 5 ADRs per underlying share of Alcatel or 1 ADR per 6 underlying shares of BP Amoco). They tend to trade in a very limited range around the price of the underlying share, exchange-rate adjusted. However, ADRs and underlying shares are close, but not perfect, substitutes. First, they are priced in U.S. dollars and trade and settle just as any other stock in the United States. The dollar price of the ADR will differ from the home market price by a factor incorporating the exchange rate. In addition, foreign exchange risk might influence the differential between the ADR and home market share prices. One can, in principle, arbitrage the price difference between the ADR and underlying shares by new ADR issues or cancellations. This is not a riskless arbitrage due to the time required to convert underlying shares into ADRs or cancel

ADRs and convert into underlying shares. In addition, there are conversion fees, the presence of the intermediary depositary bank, and possible voting and other corporate control rights that may differ between holders of the underlying shares and holders of the ADRs. For these reasons, ADRs are not perfect substitutes for the underlying shares.[2] Beyond the issue of substitutability, there may be "limits to arbitrage" as discussed by Shleifer and Vishny (1997) where noise traders push prices away from fundamental values. However, considering the situation where two stocks are traded simultaneously in real time in different market locations, we expect the law of one price to hold so that the prices of the two assets move closely together over time.

Most of the firms in our sample are traded as ADRs in the United States. However, DaimlerChrysler (DCX) is traded in the United States as a global registered share (GRS), sometimes called a "global ordinary." This is a single security that is traded globally although it is quoted and settled in the respective local currency. GRSs differ from ADRs in that they do not involve a depositary intermediary and have no issues of conversion between different forms since the same security is traded internationally. Since the GRS is quoted in local currency in each market location, prices will differ across markets by an exchange rate factor. In general, global ordinary shares should be very close substitutes across international markets as they allow all stockholders to participate in corporate matters (dividends, distributions, and control issues) regardless of their location. They may not be perfect substitutes since there is local settlement and there may be less than perfect coordination across the multinational settlement

[2] Gagnon and Karolyi (2003) have an extensive discussion of differences between ADRs and underlying shares and the issues involved in arbitraging this market. Moulton and Wei (2005) provide evidence of how NYSE specialist behavior is affected by the presence of the underlying shares in Europe as substitutes for New York trading.

institutions involving transfer and clearance issues. However, we would expect the two prices to move together even more closely than in the case of an ADR and its underlying share.

Canadian firms traded in the United States are listed as ordinary shares. One might think that Canadian ordinary shares trading in the United States may be more fungible with the home market than ADRs since the certificates traded in both countries are identical and there are no conversion fees. Our empirical work below will provide evidence on the degree to which U.S. and Canadian prices move together relative to prices of other countries' shares.

III. DATA

For the purpose of this study, we focus on bid and ask quotes submitted during the period of continuous trading in each market. Table 1 indicates that the intersection of the continuous trading hours of all exchanges is from 9:30-11:00 New York time. As a result, the empirical work will focus on this common interval of time for all markets.

Trading occurs in U.S. dollars in New York, Canadian dollars in Toronto, British pounds in London, and euro in Frankfurt and Paris. As a result, the models of price discovery will require exchange rates to link the U.S. dollar prices to prices in the other countries. Changes in exchange rates require a change in the U.S. and/or home market stock prices in order to preserve the law of one price and avoid arbitrage opportunities.

In order to avoid the problem of infrequent quoting, we focus on the firms from each home market that are most heavily traded on the NYSE. If we employed more thinly traded stocks, then we would have a problem of many "data holes" in our sample which would bias the results due to non-synchronous quoting in the home market and New York. Table 2 lists the firms and number of shares traded on the NYSE in 1999 along with the dollar value of this trade. The sample contains five firms from the TSE, four from the Paris Bourse, three from Xetra/Deutsche Börse, and five from the LSE. These were the top-traded firms from each home market and there was a fairly steep drop-off in trading volume at the next lower firms. In 1999, the total number of firms listed on the NYSE from these countries was: Canada, 70; U.K., 46; France, 16; and Germany, 9.

<Table 2 goes here>

While Canadian trading overlaps the entire New York trading day, the European markets only overlap the New York morning. We use the same sample period for all firms so that we have the same number of observations and hold everything constant other than the firm used for estimation. The New York data are from the TAQ data set available from the NYSE. Frankfurt data are proprietary data from the XETRA trading system of the Deutsche Börse. London data are the tick data set available from the London Stock Exchange. Paris trade and quote data were obtained from Paul Labys, who assembled the data set for other purposes. Toronto data are the Equity Trades and Quotes data set from the Toronto Stock Exchange. The intradaily exchange rates were obtained from Olsen Data in Zurich and are indicative quotes as posted by Reuters.

Table 3 provides basic trading information for each firm. The first column lists the NYSE stock symbols for each firm (Table 2 linked symbols with firm names). The second column provides the conversion ratios between ADRs and the underlying home-market shares at the beginning of our sample. For instance, 12 SAP ADRs are equivalent to 1 share of SAP in Frankfurt during our sample period. Following a 3 to 1 stock split on 1 May, 2000, SAP ADRs now trade at a 4 to 1 ratio against the German shares. Stock splits occurring during our sample period are: Nortel (NT), 1:2 on August 13 on TSE and August 20 on NYSE; Vodafone (VOD), 1:5 on October 1 at LSE and October 4 on NYSE; and BP Amoco (BPA), 1:2 on October 1 on both LSE and NYSE. In the empirical work that follows, the NYSE prices are adjusted by the appropriate conversion rate to be comparable to the underlying share prices. The third column of Table 3 lists the home market of each firm. The next two columns show the average relative spreads at home and on the NYSE. These are computed by taking sample averages of the spreads relative to the mid-quotes over the first 1.5 hours of New York trading. Volume and turnover data are reported in the remaining columns of Table 3. This average daily information is reported for the home market and the NYSE and for the overlap period of the New York morning as well as all day. Turnover is expressed in U.S. dollars using the sample average exchange rates to convert home market trades into dollars. For most firms, home market trading is heavier than New York trading. However, Canadian firms trade more in New York than at home. In addition, STM trades more in New York than Paris during the New York morning, but over the entire trading day, Paris trades STM more than New York.

<Table 3 goes here>

Table 3 provides a portrait of the home market as the primary market (in terms of trading activity) for most firms. However, one can see that the difference between New York and home market trading activity differs greatly across firms. Next we turn to a more detailed description of the sampling methodology.

All asset price series are in logarithms of the average of the bid and ask prices. The asset prices were sampled at 10-second intervals to assemble the basic data set. The choice of sampling interval was made with the issue of contemporaneous correlation in mind. There can be one-way causality existing among variables at a high sampling frequency that dissolves into contemporaneous correlation at higher levels of temporal aggregation. Preliminary analysis was conducted over alternative sampling frequencies and we chose 10 seconds as being suitable relative to lower frequencies like 1 minute or 10 minutes. Estimates using 1-minute sampling revealed an increase in the information share for New York prices that is misleading in that the New York price change includes both the effects of NYSE price shocks as well as the effects of the NYSE price adjusting to exchange rate shocks. At a lower sampling frequency like 10 minutes, the contemporaneous correlation results in estimation bounds on the information shares so wide that one cannot clearly identify where price discovery occurs. At higher sampling frequencies than 10 seconds there was no gain in terms of reducing significant contemporaneous correlation, but there is a tradeoff with microstructural issues like non-synchronous quoting or other sources of microstructure "noise" that makes 10 seconds preferable.

IV. PRICE FORMATION AND DETERMINANTS: METHODOLOGY

IV.A. Liquidity and the price discovery in internationally cross listed stocks

A recent paper by Baruch, Karolyi, and Lemmon (2003) provides a theoretical model and empirical support for trading volume of cross-listed firms to be concentrated in the market with the highest correlation of cross-listed asset returns with other asset returns in that market. As the authors point out, the determination of such asset returns remains to be explained. Our expectation is that the liquidity of each market should be a major factor in determining location of price discovery. As Harris (2003, p. 243) states: "How informative prices are depends on the costs of acquiring information and on how much liquidity is available to informed traders. If information is expensive, or the market is not liquid, prices will not be very informative." The relation between informativeness of price and liquidity is also supported by finance theory as seen in papers like Admati and Pfleiderer (1988) or Hong and Rady (2002). In such models, price innovations are smaller, the deeper or more liquid the market. So any given change has a larger information component in the more liquid market. Models like Foucault (1999) or Foucault, Kadan, and Kandel (2003) have limit orders of liquidity traders priced with wider spreads as the uncertainty regarding information increases. The market location where information is embedded in price should have greater liquidity than the other market. Harris, McInish, and Wood (2003) make a connection between liquidity, information, and home bias in international investment. Domestic investors may be better informed about and better able to monitor local firms than foreign firms. They point to studies by Low (1993), Brennan and Cao (1997), and Coval (1996) as offering support for such information-based home bias.

To set up a simple model in which liquidity influences price discovery in internationally cross listed stocks assume that the log of the exchange rate at time t, E_t, is exogenous with respect to U.S. and home-market shares and evolves as a random walk with white noise innovation ε_t^e :

$$E_t = E_{t-1} + \varepsilon_t^e . \tag{1}$$

The log of the home-market share price, P_t^h, may follow a random walk and, thereby, introduce the innovation or random-walk component in the intrinsic value of the firm. Alternatively, it may follow the last observed log of the U.S. price, P_t^u, adjusted by the exchange rate. In the most general setting, P_t^h represents a weighted average of these two prices, where the weight l_h is determined by the relative liquidity of the two trading venues:

$$P_t^h = l_h P_{t-1}^h + (1 - l_h)(P_{t-1}^u - E_{t-1}) + \varepsilon_t^h . \tag{2}$$

with ε_t^h as the white noise innovation associated with the home market. Similarly, the log of the U.S. price, P_t^u, evolves as:

$$P_t^u = l_h (E_{t-1} + P_{t-1}^h) + (1 - l_h) P_{t-1}^u + \varepsilon_t^u \tag{3}$$

where ε_t^u is the white noise innovation associated with the U.S. market. In the one extreme case where $l_h = 1$ the home market price and the exchange rate are completely determined by their own innovations, and the long run development of the U.S. price depends on the home market and the exchange rate innovations. The U.S. market innovations exert only a transitory effect on the U.S. price. In this situation the home market is the primary and the U.S. market the derivative market. Put differently, price discovery for the stock is exclusively taking place in the home market. In the other extreme case, where $l_h = 0$, the home market is the derivative market, and it is only the U.S. market and the exchange rate innovations which determine the long run development of the home market price.

In our empirical model, we allow the innovations of both home market price, exchange rate, and U.S. market price to exert permanent effects on the two price series and the exchange rate. The magnitude and composition of the permanent effects are allowed to be different and estimated empirically so that the data will reveal where price discovery occurs.

Arbitrage would force the two stock prices, denominated in the same currency, to move closely together over time. Subtracting the log of the U.S. price from the log of the dollar value of a home-market share we get

$$\boldsymbol{E}_t + \boldsymbol{P}_t^h - \boldsymbol{P}_t^u = \varepsilon_t^e + \varepsilon_t^h - \varepsilon_t^u, \tag{4}$$

i.e. the linear combination of the log exchange rate, log home-market price, and log U.S. price is a linear combination of three stationary variables. In other words, E_t, P_t^h, and P_t^u are cointegrated with the single (normalized) cointegrating vector $A = (1, 1, -1)'$.

IV.B. Estimation of information shares for internationally cross listed stocks

In the following we describe the methodology employed to assess the issue of price discovery in internationally cross listed stocks which is based on, but in some important aspects different from, the methodology introduced by Hasbrouck (1995). The differences are caused by the fact that an asset is traded in dollars in the U.S. market and in local currency in the home market, so that the concept of "a single efficient price" for an asset that is traded simultaneously on *n* markets has to be re-thought if there is variation in the exchange rate. For the technical details we refer the reader to the appendix, where we outline the steps of the econometric methodology.

We maintain the (testable) assumption of the existence of a single cointegrating relation between E_t, P_t^h, and P_t^u with normalized cointegrating vector $A = (1, 1, -1)'$ and assume that the dynamics of home market price, U.S. market price and exchange rate can be represented in a non-stationary vector autoregression. The model outlined in equations (1)-(3) is a special case of such a VAR. The Granger Representation Theorem (Engle and Granger, 1987) then implies that we can write the cointegrated three variable system in vector error (or equilibrium) correction form (VECM):

$$\begin{pmatrix} \Delta E_t \\ \Delta P_t^h \\ \Delta P_t^u \end{pmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \begin{bmatrix} 1, & 1, & -1 \end{bmatrix} \begin{pmatrix} E_{t-1} \\ P_{t-1}^h \\ P_{t-1}^u \end{pmatrix} + \zeta_1 \begin{pmatrix} \Delta E_{t-1} \\ \Delta P_{t-1}^h \\ \Delta P_{t-1}^u \end{pmatrix} + \cdots + \zeta_{p-1} \begin{pmatrix} E_{t-p+1} \\ P_{t-p+1}^h \\ P_{t-p+1}^u \end{pmatrix} + \begin{pmatrix} \varepsilon_t^e \\ \varepsilon_t^h \\ \varepsilon_t^u \end{pmatrix}, \qquad (5)$$

where $\Delta E_t = E_t - E_{t-1}$, and ΔP_t^h and ΔP_t^u are defined analogously.

The stationary vector process $\{\varepsilon_t^e, \varepsilon_t^h, \varepsilon_t^u\}$ is assumed to have zero mean, contemporaneous covariance matrix Ω, and to be serially uncorrelated. $\zeta_1, \ldots, \zeta_{p-1}$ are (3×3) parameter matrices and the coefficients b_1, b_2, and b_3 reflect the adjustment of prices to a deviation from the law of one price in the previous period. If the exchange rate is exogenous, we expect b_1 to be small in magnitude. Using Johansen's (1991) maximum likelihood methodology one can estimate the VECM parameters and test for the number of linearly independent cointegrating vectors. We expect only one cointegrating relation, but there could also be either none or two. In both of the latter cases the validity of the model would be questionable. We find it convenient (though computer intensive) to employ the bootstrap methodology for cointegrated systems proposed by Li and Maddala (1997) in order to estimate the standard errors (in fact the whole joint distribution) of the VECM parameter estimates and also of the derived statistics (long run multipliers, information shares) discussed below.

A very useful representation of the cointegrated three variable system is its infinite-order vector moving average (VMA) representation (see appendix). Summing up the VMA weights and adding the identity matrix, we obtain a (3×3) matrix Ψ. The elements of this matrix represent the permanent impact of a one unit innovation in ε^e, ε^h and ε^u on the two price series and the exchange rate. Because of its importance we introduce the following notation that helps to illustrate the interpretation of the elements of Ψ:

$$\Psi = \begin{pmatrix} \psi^{\varepsilon^e \to E} & \psi^{\varepsilon^h \to E} & \psi^{\varepsilon^u \to E} \\ \psi^{\varepsilon^e \to P^h} & \psi^{\varepsilon^h \to P^h} & \psi^{\varepsilon^u \to P^h} \\ \psi^{\varepsilon^e \to P^u} & \psi^{\varepsilon^h \to P^u} & \psi^{\varepsilon^u \to P^u} \end{pmatrix},$$

For example, $\psi^{\varepsilon^u \to P^h}$ denotes the permanent impact a one unit innovation in the log of the U.S. price exerts on the log of the home market price (for the sake of readability we henceforth simply say "price" when we mean "log of the price"). Economic common sense suggests that both $\psi^{\varepsilon^h \to E}$ and $\psi^{\varepsilon^u \to E}$ are small in magnitude, as the exchange rate is expected to be exogenous with respect to price changes of individual stocks.

Most importantly, we can use the Ψ matrix to denote the permanent impacts that period *t* innovations $\varepsilon_t^e, \varepsilon_t^h$ and ε_t^u have on the exchange rate, the home market price and the U.S. price. Denoting these permanent effects by π^e, π^h, and π^u, respectively, we obtain

$$\begin{pmatrix}\pi^e\\ \pi^h\\ \pi^u\end{pmatrix}=\begin{pmatrix}\psi^{\varepsilon^e\to E} & \psi^{\varepsilon^h\to E} & \psi^{\varepsilon^u\to E}\\ \psi^{\varepsilon^e\to P^h} & \psi^{\varepsilon^h\to P^h} & \psi^{\varepsilon^u\to P^h}\\ \psi^{\varepsilon^e\to P^u} & \psi^{\varepsilon^h\to P^u} & \psi^{\varepsilon^u\to P^u}\end{pmatrix}\begin{pmatrix}\varepsilon_t^e\\ \varepsilon_t^h\\ \varepsilon_t^u\end{pmatrix}. \tag{6}$$

It was Hasbrouck's (1995) insight to interpret a variance decomposition of the permanent impact on the efficient price of an asset that is cross-listed in *n* different (national) markets as a means to assign an information share to each of the *n* markets. The transfer of the idea to internationally cross listed stocks using equation (6) is straightforward, once the effect of the exchange rate is properly accounted for. Basic statistics show that the variances of the permanent impacts, $\mathrm{Var}(\pi_t^e), \mathrm{Var}(\pi_t^h)$ and $\mathrm{Var}(\pi_t^u)$ can be read off the main diagonal of the matrix $\Psi\Omega\Psi'$. The basic idea behind the computation of information shares is then easy to understand. If, for example, a large fraction of the variance of the permanent home market price impact π^h is attributable to the U.S. market innovations ε^u then we would conclude that the U.S. market plays an important role for the price discovery of an internationally cross listed stock.

If the innovations ε^e, ε^h and ε^u had zero contemporaneous covariances then assigning information shares would be a straightforward exercise. The variance of, say, the long run impact in the home market would then be given by:

$$\mathrm{Var}(\pi^h)=\left(\psi^{\varepsilon^e\to P^h}\right)^2\mathrm{Var}(\varepsilon_t^e)+\left(\psi^{\varepsilon^h\to P^h}\right)^2\mathrm{Var}(\varepsilon_t^h)+\left(\psi^{\varepsilon^u\to P^h}\right)^2\mathrm{Var}(\varepsilon_t^u)$$

The variance/information share of the U.S. market ($I^{\varepsilon^u\to P^h}$) could then simply be

computed as $I^{\varepsilon^u\to P^h}=\dfrac{\left(\psi^{\varepsilon^u\to P^h}\right)^2\mathrm{Var}(\varepsilon_t^u)}{\mathrm{Var}(\pi^h)}$. Analogous computations would yield the information shares of the home market ($I^{\varepsilon^h \to P^h}$) and the exchange rate ($I^{\varepsilon^e \to P^h}$) innovations. A decomposition of $\text{Var}(\pi^u)$ and $\text{Var}(\pi^e)$ could be conducted in the same fashion. In the presence of contemporaneous correlation of the innovations (i.e. if $\mathbf{\Omega}$ is not a diagonal matrix), however, the computation of information shares is a bit more involved. A Cholesky factorization of the innovation covariance matrix Ω is the standard solution to this problem. The Cholesky factorization basically identifies three orthogonal (contemporaneously uncorrelated) innovations – one for each series - of which the original (correlated) innovations ε^e, ε^h and ε^u are composed. With orthogonal innovations the variance decomposition of the permanent effects can be performed as outlined above (details are given in the appendix). There is a major drawback, however, in that the ordering of the variables can crucially influence the results. When an innovation is ordered first in the Cholesky decomposition its information share will be maximized, while when ordered last, the information share of this innovation will be minimized. The larger the contemporaneous correlation of the innovations, the wider these upper and lower bounds of the information shares. In our empirical application we therefore permute the ordering of the variables in the Cholesky factorization and assess the consequences of the ordering on the results. It turns out that choosing the appropriate sampling frequency is the key to reducing the contemporaneous correlation of the innovations such that the ordering becomes less important. Furthermore, we also report the average of the highest and the lowest information shares which result from the different orderings. The bootstrap methodology adopted in this paper further allows us to compute standard errors for these (averaged) information shares. Collecting the information shares in a matrix yields

$$IS = \begin{pmatrix} I^{\varepsilon^e \to E} & I^{\varepsilon^h \to E} & I^{\varepsilon^u \to E} \\ I^{\varepsilon^e \to P^h} & I^{\varepsilon^h \to P^h} & I^{\varepsilon^u \to P^h} \\ I^{\varepsilon^e \to P^u} & I^{\varepsilon^h \to P^u} & I^{\varepsilon^u \to P^u} \end{pmatrix}.$$

For example, $I^{\varepsilon^u \to P^h}$ denotes the information share (averaged over highest and lowest) of the (orthogonalized) U.S. market innovation with respect to the home market price. By construction, the rows of the matrix *IS* sum to one. If the exchange rate is exogenous, then we expect that the estimates of both $I^{\varepsilon^h \to E}$ and $I^{\varepsilon^u \to E}$ are close to zero. However, it is more interesting to address the relative importance of the innovations in the home and the U.S. market price and those in the exchange rate for the long-run development of the price series (i.e. to compare $I^{\varepsilon^h \to P^h}$ with $I^{\varepsilon^u \to P^h}$ and $I^{\varepsilon^h \to P^u}$ with $I^{\varepsilon^u \to P^u}$). This is one of the key contributions of this paper.

IV.C. Determinants of information shares

Our second main objective is to study, in a cross sectional analysis, the determinants of the information shares, and especially to test the hypothesis that liquidity is an important factor explaining the information share of the U.S. market for internationally cross listed stocks. For this purpose we focus on explaining $I^{\varepsilon^u \to P^h}$, the information share of the U.S. market innovations with respect to the home market price. Having estimated these information shares for a sample of NYSE listed international firms we run a cross sectional logistic regression, where the dependent variable is transformed to take into account the fact that, by construction, the information shares are bounded between zero and one:

$$\ln\left(\frac{I_i^{\varepsilon^u \to P^h}}{1 - I_i^{\varepsilon^u \to P^h}}\right) = x_i'\beta + u_i \,. \tag{7}$$

x_i denotes a vector of explanatory variables serving as proxies for the relative liquidity of the home and the U.S. market of firm *i*. β is a vector of parameters to be estimated, and u_i a firm specific disturbance, where $\mathrm{E}(u_i) = 0$. The variables used to proxy for liquidity are the difference between the U.S. market and home market realized bid-ask spreads and the ratio of U.S. to home market value and volume of traded stocks per day. We are aware that if these variables appear on the right hand side of equation (7) we have to deal with the problem of endogenous regressors, as the information share, in turn, may explain the (relative) liquidity for a stock. Endogeneity implies that OLS estimation would produce inconsistent parameter estimates. We therefore use instruments which are assumed to be uncorrelated with the disturbances u_i, but correlated with the endogenous liquidity proxies. These instruments are a) the number of U.S. analysts following firm *i*, b) the ratio of U.S. to non-U.S. fund holdings of NYSE-listed shares and c) the ratio of foreign to total sales of firm *i*. Standard GMM/IV inference is employed to estimate the parameters β and to compute parameter standard errors. If the hypothesis is true that the more liquid the U.S. market is relative to the home market, the higher the information share of the U.S. market, then we would expect statistically and economically significant parameter estimates for the liquidity proxies and considerable explanatory power of the regressors.

V. ESTIMATION RESULTS

V.A. Information Shares in Price Discovery: Time-Series Evidence

Augmented Dickey-Fuller tests reveal unit roots in the log of each asset price and the variables were identified as being integrated of order one. Johansen cointegration tests are performed and the results clearly support the hypothesis of one cointegrating vector among the 3 variables. With the variables ordered as exchange rate, home-market price, and U.S. price, the estimated cointegrating vectors are close to the vector $A=(1, 1, -1)'$ indicated by theory. Due to the number of firms in the sample, estimates of the cointegration models are not reported. Instead, we focus on the estimates of the VECM equation and the associated information shares. The choice of lag length is determined by the Schwarz Information Criterion (SIC). We start with 18 lags, which represents 3 minutes in a sample with observations at 10-second intervals. Then, using the same set of observations that was used for the estimation of the model with 18 lags, we estimate the VECM at each shorter lag length down to one lag to determine the lag structure that minimizes the SIC. Lag lengths range from 3 for ALA, ELF, DT, and SAP to 7 for VO.

An additional sampling issue is with regard to overnight returns and lags. We created a data set in which no overnight returns were used and no lags reached back to prior days. For instance, if the model calls for 3 lags in the VECM, the dependent variable begins with the fourth observation of each day. The initial observation each day for each stock is determined by the first 10-second interval following the NYSE open containing a quote in both markets.[3] Estimation precision is assessed employing the bootstrap method suggested by Li and Maddala (1997, see appendix for details).

As explained in the appendix, the Cholesky factorization of the innovation variance-covariance matrix results in an upper bound on the estimated information share for the variable that comes first in the ordering and a lower bound on the information share for the variable that comes last in the ordering. We report the averages between the two after permuting the order to obtain both extreme bounds. First, an ordering of exchange rate, home-market price, and U.S. price is used to estimate the information shares and then a reordering with exchange rate, U.S. price, and home-market price is used and the average of the two information shares is reported in Figure 1.

The numbers given in parentheses are the bootstrap standard errors of the estimated information shares. For instance, in the top left figure of Figure 1, we see that the home market information share for TOT is about 0.9 with the standard error of this estimate equal to 0.022. The data plotted in the top left figure shows that the home-market information shares range from about 0.9 for TOT, ALA, ELF, and DT to about 0.4 for BPA. In general, the information shares of home market prices for the U.S. price are greater than 50 percent with only two exceptions, BPA and VO. The top right of the figure contains the estimates and standard errors for the information share of U.S. price innovations on the U.S. price. We can see the close relationship between the two top figures in Figure 1. BPA and VO have information shares that are not significantly

[3] To ensure the integrity of the data set, screening of the time series was performed for each stock. It was determined that ELF shares in Paris experienced an unusual divergence from the New York price for a few days in September 1999. Further research revealed that this was probably due to the forthcoming merger with TotalFina (TOT). The offer period to exchange ELF shares for TOT shares began on September 23 in France and September 29 in the United States. Anyone buying shares of ELF after those dates was not able to participate in TOTs offer (19 TOT shares for 13 ELF shares). We omit all ELF quotes after September 27, 1999 in order to avoid any inferential problems arising from the merger-related price dynamics. Other than this brief period for ELF, no other unusual patterns were found in the data.

different from 50 percent in the top right figure while the other firms are generally much less than 0.5.

<Figure 1 goes here>

The middle row of Figure 1 presents the estimated information shares for the home and U.S. price innovations on the home market price. Once again it is seen that only BPA and VO have home-market price innovation information shares that are not significantly different from 50.

The bottom row of Figure 1 plots the average information shares attributable to exchange rate innovations on the home and U.S. price. It is clear that the exchange rate plays a small role in price discovery for these internationally-listed firms. The bottom left figure shows that the largest information share for exchange rate innovations on the home market price is estimated to be about 3 percent for BPA with much smaller values for the other firms (the average across all firms is 0.006). The bottom right figure shows that the exchange rate information shares are larger for the U.S. price (the average across all firms is 0.026). The U.S. price responds more to an exchange rate shock than does the home-market price.

Figure 1 clearly shows the dominance of the home market price in price discovery. The information shares for U.S. price innovations are seen to be somewhat of a mirror image of the home-price information shares. The higher the information share of the home-market price innovations in explaining home-market price, the lower the U.S. information shares.

We do not report a figure for the information shares related to explaining the variance of innovations in the exchange rate. The exchange rate innovations account for essentially all price discovery in the exchange rate with the stock prices contributing essentially nothing. This is consistent with the exchange rate being exogenous with respect to the two stock prices and is reflected in the information share of the exchange rate in explaining the variance of exchange rate innovations equaling one while the information shares for the home-market and U.S. prices are essentially zero. This exogeneity of the exchange rate is supported across all firms.

The hypothesis that the home market is the primary market and the U.S. the derivative market would be consistent with a larger role for price discovery in the home market than in the United States. Figure 1 indicates that this is clearly true on average for the firms in our sample. However, 9 firms have a sizeable (information share greater than 20 percent) role for U.S. price discovery and 2 firms (BPA and VO) have a larger information share for U.S. price innovations than home-market (London and Toronto) price innovations. The interesting question of what explains the differences across firms will be addressed in the cross-section analysis below.

As already mentioned, the exchange rates appear to be exogenous as there is no economically significant role for the stock prices in exchange rate price discovery. Yet how do the stock prices adjust to exchange rate shocks? To avoid arbitrage and restore the law of one price, the stock prices must change following a change in the exchange rate. Comparing the exchange rate information shares for home-market and U.S. prices underlying the plots in Figure 1, it is clear that generally the U.S. price bears the burden of adjustment to an exchange rate shock as the values of the exchange rate information shares in explaining U.S. prices are significantly greater than those for home-market prices in all but 3 cases. The exceptions for BPA and VO, are consistent with the U.S.

being the primary market for these stocks. In addition, the exchange rate information share in the U.S. price is slightly larger than that for the home-market price for AL.

Summarizing the results so far, price discovery for most firms occurs largely in the home market with a smaller, but statistically and economically significant role for U.S. prices. This is consistent with the home market being the primary market for most stocks with U.S. trading following the home market. However, the U.S. has a greater than 0.5 information share (although not significantly different from 0.5) for 2 firms and has more than a 20 percent information share for 7 more firms. The exchange rate evidence indicates that the exchange rate may be considered to be exogenous with respect to the stock prices. The stock price adjustment to an exchange rate shock occurs largely in the U.S. market. This can be deduced from the larger information share of exchange rate innovations for U.S. market prices than for home market prices. In only three cases, the home market price does most of the adjusting following a shock to the exchange rate. This is additional evidence that the home market is generally the primary market and the derivative market takes the stock price as given in the home market and then follows that price and also accommodates any exchange rate change. So with few exceptions, it is apparent that exchange rate shocks are more important in understanding the intradaily evolution of New York prices of internationally cross-listed firms than the prices of these firms in their home market. An implication of this result is that the notion of buying currency exposure with an ADR is not universally applicable. The cross-section evidence will help to develop this idea further.

V.B. Information Shares in Price Discovery: Cross-Firm Evidence

The striking question that emerges from the results reported in Figure 1 is why firms differ so much in terms of price discovery at home and in the United States. The home market information shares for home market prices range from about 98 percent for DT to about 40 percent for BPA. The associated U.S. information shares for home market prices range from less than 1 percent to about 60 percent, respectively. In between these extremes, we see that in some cases, there is a sizeable role for U.S. price innovations in home market price discovery while in other cases, there is but a small role.

We now analyze the determinants of the cross-firm differences using the logistic-regression model that was described in equation (7). The focus is on assembling a data set that would include measures of liquidity in both stock markets. However, since endogeneity issues arise in a regression of information shares on measures of liquidity we also assembled data on additional variables that could reasonably serve as instruments. An extensive search for data on instrumental variables was undertaken. These variables include the extent to which a firm is mainly a domestic firm rather than a multinational, and the "U.S. following" that firms have. Data on the following measures of liquidity were obtained for the time period of the NYSE and home market trading overlap:

- NYSE and home market turnover (from NYSE and home market)
- NYSE and home market volume (from NYSE and home market)
- NYSE and home market realized bid-ask spreads (from NYSE and home market).

The realized spread is computed as twice the absolute difference between the transaction price at time *t* and the midquote at *t+5 minutes*.[4] Relative realized spreads were then calculated as the realized spread divided by the midquote at time *t*. The realized spread is

[4] The spreads were calculated for medium-sized trades, with a dollar value of $50,000-$300,000, in order to capture "normal" spreads. Small and, particularly, large trades are more subject to idiosyncratic deals.

preferred to the quoted spread at *t* as quoted spreads include an informational aspect that is purged when using realized spreads. As stated in Boehmer (2004, p. 13) "Realized spreads can be interpreted as a market's inherent execution cost, because they exclude the effects of the information content of order flow."[5] To serve as instruments, data on the following variables were obtained:

- the ratio of foreign to total sales (from Worldscope)
- U.S. analysts following (from I/B/E/S)[6]
- U.S. and non-U.S. fund holdings of NYSE listed shares (from Thompson Financial Spectrum).

As stated in section IV, since information shares are truncated at *0* and *1*, a logistic regression model is employed. Specifically, the dependent variable is the information share in home market prices that is attributed to innovations in New York prices. These data are found in the section labeled "Info share attributable to US market innovations (home market))" in Figure 1. Estimation is carried out using Generalized Method of Moments (GMM). The GMM orthogonality conditions are that the instruments are uncorrelated with the residuals of the specified model of information shares as a linear function of a constant and the liquidity indicators. The weighting matrix used is White's heteroskedasticity-consistent covariance matrix. Initial analysis indicates that, not surprisingly, there is considerable collinearity among the three measures of liquidity. In particular, turnover and volume essentially convey the same information.

[5] Since November 2000, the U.S. Securities and Exchange Commission requires market centers to publish monthly data on realized spreads and effective spreads along with execution speed as indicators of market quality. See Boehmer (2004) and the American Stock Exchange website www.amex.com/amextrader/tradingdata for further discussion of realized spreads.

[6] Specifically, this is the number of U.S. analysts making a recommendation on a stock in 1999. Jennifer Juergens provided valuable advice in identifying the firms and locations of analysts.

Since turnover has marginally greater explanatory power, it is employed (in logs) in the reported estimations along with the difference of the realized relative spreads.

Estimation results are reported in Table 4. Both measures of liquidity have the expected effect on information shares and both have statistically significant coefficient estimates. The results support the following inference: the greater the NYSE trading activity relative to the home market, the greater the share of price discovery in New York; and the larger the realized spread on a firm's shares in New York trading relative to the home market, the lower the New York price discovery. The evidence is consistent with liquidity playing an important role in understanding the link between U.S. trading and price discovery for internationally cross-listed firms. In addition, the model developed here is able to explain a large proportion of the cross-firm variation in information shares as reflected in the R^2 of 0.989. Finally, the J-statistic of 0.21 reported in Table 4 has an associated p-value of 0.64. Therefore, we cannot reject the null hypothesis that the moment conditions are correct at any reasonable significance level.

<Table 4 goes here>

VI. SUMMARY AND CONCLUSIONS

This paper addresses two issues: 1) Where does price discovery occur for firms that are traded simultaneously in New York and in other markets in other countries and 2) what explains the differences across firms in the share of price discovery that occurs in New York? The short answer to the first question is that most firms have the largest fraction of price discovery occur at home with New York taking a relatively small role.

However, the data reveal important exceptions to this finding. It is simply not true that New York trading always lags the home market and there is no significant role for price discovery to occur in New York. The answer to the second question is found by modeling the information share of New York trading in price discovery of home-market prices across firms as a function of variables related to New York liquidity relative to liquidity in the home market. The data strongly support liquidity as an important factor in understanding the role of the U.S. in price discovery. For a particular firm, the greater the liquidity of U.S. trading relative to the home market, the greater the role for NYSE price discovery for that firm.

An additional issue of interest arises from our modeling strategy of allowing an independent effect for the exchange rate. Past studies have typically used the exchange rate to convert prices of one market into the same currency units of another market and then proceeded to analyze the link between the prices in both markets. For instance, rather than model a three variable system of, say, the price of STM in Paris in euros, the price in New York in dollars, and the dollar/euro exchange rate, it is typical for researchers to convert the dollar price into euros with the exchange rate and then model the links between the Paris and New York price. However, this then allows the New York price to include the exchange rate innovations and may bias the results regarding true causality. In earlier work, not reported here, we found that the bias is increasing in exchange rate volatility. Such bias does not enter into the results reported in this study. These results indicate strong support for the exchange rate as an exogenous variable in the cross-country pricing of a firm’s stock. Furthermore, our results indicate that the NYSE price usually bears the burden of adjustment to the law of one price following an exchange rate shock. This is interpreted as further evidence that the NYSE is typically the derivative market for non-U.S. firms and the home market is the primary market. However, it is important to realize that this is not a universal truth. For those firms where the NYSE has the dominant price discovery role, the exchange rate adjustment comes more from the home market than the NYSE. Thus, it is not always true that an ADR provides exposure to currency fluctuations. For those ADRs with greater liquidity in U.S. trading than at home, we would find little price response to an exchange rate change.

Overall, the results indicate that the nature of price discovery across international markets during the time of trading overlap is richer and more complex than previously realized. While the home market is typically where the majority of price discovery occurs, there are significant exceptions to this rule.

Appendix: Methodological details

Variance decomposition/Information shares

From a time series perspective, modelling price discovery in internationally cross listed stocks starts with a pth order three variable vector autoregression:

$$\begin{pmatrix} E_t \\ P_t^h \\ P_t^u \end{pmatrix} = \Phi_1 \begin{pmatrix} E_{t-1} \\ P_{t-1}^h \\ P_{t-1}^u \end{pmatrix} + \Phi_2 \begin{pmatrix} E_{t-2} \\ P_{t-2}^h \\ P_{t-2}^u \end{pmatrix} + \cdots + \Phi_p \begin{pmatrix} E_{t-p} \\ P_{t-p}^h \\ P_{t-p}^u \end{pmatrix} + \begin{pmatrix} \varepsilon_t^e \\ \varepsilon_t^h \\ \varepsilon_t^u \end{pmatrix}. \tag{A1}$$

$\Phi_1, \Phi_2, \ldots, \Phi_p$ are (3×3) parameter matrices. The stationary vector process $\{\varepsilon_t^e, \varepsilon_t^h, \varepsilon_t^u\}$ is assumed to have zero mean, contemporaneous covariance matrix $\mathbf{\Omega}$, and to be serially uncorrelated. Given that the three variables are cointegrated (here with the single normalized cointegrating vector $A = (1,1,-1)$) the Granger Representation Theorem implies that the above system can be written in vector error (or equilibrium) correction form (VECM):

$$\begin{pmatrix} \Delta E_t \\ \Delta P_t^h \\ \Delta P_t^u \end{pmatrix} = BA' \begin{pmatrix} E_{t-1} \\ P_{t-1}^h \\ P_{t-1}^u \end{pmatrix} + \zeta_1 \begin{pmatrix} \Delta E_{t-1} \\ \Delta P_{t-1}^h \\ \Delta P_{t-1}^u \end{pmatrix} + \cdots + \zeta_{p-1} \begin{pmatrix} E_{t-p+1} \\ P_{t-p+1}^h \\ P_{t-p+1}^u \end{pmatrix} + \begin{pmatrix} \varepsilon_t^e \\ \varepsilon_t^h \\ \varepsilon_t^u \end{pmatrix}.$$

$\zeta_1, \ldots, \zeta_{p-1}$ are (3×3) parameter matrices and B (given that only a single cointegrating relation exists) is a (3×1) parameter vector. For the purpose of this paper it is useful to rewrite the cointegrated three variable system in its infinite order vector moving average (VMA) representation:

$$\begin{pmatrix} \Delta E_t \\ \Delta P_t^h \\ \Delta P_t^u \end{pmatrix} = \begin{pmatrix} \varepsilon_t^e \\ \varepsilon_t^h \\ \varepsilon_t^u \end{pmatrix} + \psi_1 \begin{pmatrix} \varepsilon_{t-1}^e \\ \varepsilon_{t-1}^h \\ \varepsilon_{t-1}^u \end{pmatrix} + \psi_2 \begin{pmatrix} \varepsilon_{t-2}^e \\ \varepsilon_{t-2}^h \\ \varepsilon_{t-2}^u \end{pmatrix} + \cdots, \tag{A2}$$

where $\psi_1, \psi_2, \ldots$ are (3×3) parameter matrices. Summing up the VMA parameter matrices and adding the identity matrix we obtain a (3×3) matrix $\psi = \mathrm{I} + \sum_{i=1}^{\infty} \psi_i$ upon which cointegration imposes the restriction that $A'\psi = 0$. The elements of ψ give the permanent impact that one unit innovations in ε^e, ε^h and ε^u exert on the two price series and the exchange rate. With cointegrating vector $A = (1, 1, -1)'$ and assuming that the permanent impact of the stock price innovations on the exchange rate are zero, i.e. $\psi^{\varepsilon^h \to E} = \psi^{\varepsilon^u \to E} = 0$, the restriction $A'\psi = 0$ implies that $\psi^{\varepsilon^h \to P^h} = \psi^{\varepsilon^h \to P^u}$. In words, a one unit innovation in the log of the U.S. price has the same permanent impact on the log home price and the log U.S. price. By the same token $\psi^{\varepsilon^u \to P^h} = \psi^{\varepsilon^u \to P^u}$.

The permanent impacts on the two price series and the exchange rate $\pi = (\pi^e, \pi^h, \pi^u)'$ that time *t* innovations $\varepsilon_t = (\varepsilon_t^e, \varepsilon_t^h, \varepsilon_t^u)'$ exert is given by $\pi = \psi \varepsilon_t$. The simple idea behind the computation of information shares is to decompose the variances of these permanent impacts which are found on the diagonal of the variance-covariance matrix $\mathrm{Var}(\pi) = \psi \mathbf{\Omega} \psi'$, i.e. $\mathrm{Var}(\pi^e) = [\psi \mathbf{\Omega} \psi']_{11}$, $\mathrm{Var}(\pi^h) = [\psi \mathbf{\Omega} \psi']_{22}$ and $\mathrm{Var}(\pi^u) = [\psi \mathbf{\Omega} \psi']_{33}$. As outlined in the main text, the decomposition would be straightforward if the innovations $\varepsilon_t^e, \varepsilon_t^h$ and ε_t^u were uncorrelated which is, however, often not the case. A Cholesky factorization of the variance covariance matrix $\mathbf{\Omega}$ can partially solve this problem. Since Ω is a positive definite matrix we can represent it via $\mathbf{\Omega} = \mathbf{CC}'$ with *C* as a lower-diagonal (3×3) matrix:

$$\mathbf{C} = \begin{pmatrix} c_{11} & 0 & 0 \\ c_{21} & c_{22} & 0 \\ c_{31} & c_{32} & c_{33} \end{pmatrix}.$$

Denote by $e_t = (e_t^e, e_t^h, e_t^u)'$ a vector of uncorrelated zero mean unit variance random variables . We refer to e_t^e, e_t^h, and e_t^u as *orthogonalized* innovations. The vector of *correlated* innovations $\varepsilon_t = (\varepsilon_t^e, \varepsilon_t^h, \varepsilon_t^u)'$ is then constructed from the orthogonalized residuals as follows:

$$\begin{pmatrix} \varepsilon_t^e \\ \varepsilon_t^h \\ \varepsilon_t^u \end{pmatrix} = \begin{pmatrix} c_{11} & 0 & 0 \\ c_{21} & c_{22} & 0 \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \begin{pmatrix} e_t^e \\ e_t^h \\ e_t^u \end{pmatrix} \tag{A3}$$

Equation (A3) makes clear that the correlated innovations are generated as linear combinations of the orthogonalized innovations and that the ordering of the variables plays an important role: Only the variable ordered first is determined by its own orthogonalized innovation, $\varepsilon_t^e = c_{11} e_t^e$. The variable ordered last is a linear combination of all three orthogonalized innovations: $\varepsilon_t^u = c_{31} e_t^e + c_{32} e_t^h + c_{33} e_t^u$.

We can write the permanent impacts as a function of the orthogonalized innovations:

$$\pi = \boldsymbol{\psi} \mathbf{C} e_t \ . \tag{A4}$$

Using the orthogonalized innovations, the variance decomposition can be performed as outlined in Section IV. In the following we focus on a decomposition of $\mathrm{Var}(\pi^h) = [\boldsymbol{\psi\Omega\psi}']_{22} = [\boldsymbol{\psi}\mathbf{CC}'\boldsymbol{\psi}']_{22} = [\boldsymbol{\psi}\mathrm{Var}(\mathbf{C}e_t)\boldsymbol{\psi}']_{22}$. The decomposition of $\mathrm{Var}(\pi^e)$ and $\mathrm{Var}(\pi^u)$ is conducted in the same way. Writing the second row of (A4) in detail, and using the notation introduced in section IV we have:

$$\pi^h = \left(\psi^{\varepsilon^e \to P^h} c_{11} + \psi^{\varepsilon^h \to P^h} c_{21} + \psi^{\varepsilon^u \to P^h} c_{31} \right) e_t^e + \left(\psi^{\varepsilon^h \to P^h} c_{22} + \psi^{\varepsilon^u \to P^h} c_{32} \right) e_t^h + \left(\psi^{\varepsilon^u \to P^h} c_{33} \right) e_t^u .$$

As the innovations $e_t = (e_t^e, e_t^h, e_t^u)'$ are uncorrelated we can decompose the variance of π^h into the contributions of the three orthogonal innovations as follows:

$$\mathrm{Var}(\pi^h) = [\boldsymbol{\psi\Omega\psi}']_{22} = \left(\psi^{\varepsilon^e \to P^h} c_{11} e_t^e + \psi^{\varepsilon^h \to P^h} c_{21} + \psi^{\varepsilon^u \to P^h} c_{31} \right)^2 \mathrm{Var}(e_t^e) + \left(\psi^{\varepsilon^h \to P^h} c_{22} + \psi^{\varepsilon^u \to P^h} c_{32} \right)^2 \mathrm{Var}(e_t^h) + \left(\psi^{\varepsilon^u \to P^h} c_{33} \right)^2 \mathrm{Var}(e_t^u).$$

By construction we have $\mathrm{Var}(e_t^e) = \mathrm{Var}(e_t^h) = \mathrm{Var}(e_t^u) = 1$. Hence, the variance/information share of, say, the U.S. market with respect to the home market price is given by [7]

$$I^{\varepsilon^u \to P^h} = \frac{\left(\psi^{\varepsilon^u \to P^h} c_{33}\right)^2}{\left[\boldsymbol{\psi\Omega\psi}'\right]_{22}}.$$

Analogous computations yield the information shares of home market ($I^{\varepsilon^h \to P^h}$) and the exchange rate ($I^{\varepsilon^e \to P^h}$) innovations. Given the matrix of information shares as defined in section IV

$$IS = \begin{pmatrix} I^{\varepsilon^e \to E} & I^{\varepsilon^h \to E} & I^{\varepsilon^u \to E} \\ I^{\varepsilon^e \to P^h} & I^{\varepsilon^h \to P^h} & I^{\varepsilon^u \to P^h} \\ I^{\varepsilon^e \to P^u} & I^{\varepsilon^h \to P^u} & I^{\varepsilon^u \to P^u} \end{pmatrix},$$

it is easily seen that the general formula to compute the information shares is given by:

$$\left[IS\right]_{ij} = \frac{(\left[\boldsymbol{\psi}\mathbf{C}\right]_{ij})^2}{\left[\boldsymbol{\psi\Omega\psi}'\right]_{ii}}.$$

Bootstrap methodology

To compute standard errors and quantiles for the VECM parameter estimates as well as for the information shares we employ the bootstrap method for cointegrated systems proposed by Li and Maddala (1997).[8] The bootstrap procedure amounts to first determining the number of cointegrating relations and estimating the VECM parameters (we employ the Johansen (1991) methodology) and computing the sequence of estimated

[7] Note that we introduce a slight abuse of notation since we measure the information share of the orthogonalized and not the correlated innovation.

[8] For an analytic solution see Paruolo (1997a,1997b). Paruolo derives the distributions of the estimates using asymptotic results. The bootstrap procedure has the advantage of a finite sample distribution and does not have to rely on asymptotic approximations.

residuals $\hat{\varepsilon}_t = (\hat{\varepsilon}_t^e, \hat{\varepsilon}_t^h, \hat{\varepsilon}_t^u)'$. Using these initial estimates we generate artificial series of the three system variables $\{\widetilde{E}_t, \widetilde{P}_t^h, \widetilde{P}_t^u\}_{t=1}^T$ with the same number of observations T as the original data, by simulating the VECM with estimated parameters and independent draws with replacement from the sample of estimated residuals. Based on the generated data, the VECM parameters and the information shares are estimated again. The process is then repeated K=1000 times. The sample distribution of VECM parameters, cointegrating vectors and the information shares can then be used for statistical inference without having to rely on asymptotic results.

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Table 1

A Comparison of Trading Venues

	New York	**Frankfurt**	**London**	**Paris**	**Toronto**
Major Index	S&P 500	DAX	FTSE 100	CAC 40	S&P TSX Composite
Currency	U.S. dollar	euro	British pounds	euro	Canadian dollar
Price Increments	Now \$0.01 for 1999 sample period: \$ 1/16	€0.01	Stock price: 0-9.9999, £0.0001 10-499.75, £0.25 500-999.50, £0.5 ≥ 1000, £1	Stock price: 0.01-49.99, €0.01 50-99.95, €0.05 100-499.90, €0.10 ≥ 500, €0.50	Stock price: < 0.50, C\$0.005 ≥ 0.50, C\$0.01
Trading System	Market maker specialists	XETRA electronic order book	SETS electronic order book	Euronext electronic order book	Market maker specialists
Trading Hours (local time)	9:30-16:00	Now 9:00-17:30 for 1999 sample period: 9:00-17:00	8:00-16:30	9:00-17:30	9:30-16:00
Trading Hours (New York time)	9:30-16:00	3:00-11:00	3:00-11:30	3:00-11:30	9:30-16:00

Table 2

Most active firms for NYSE trading in 1999

	Shares traded (millions)	Value (million $)
Toronto:		
Nortel (NT)	607	41,645
Seagram (VO)	257	12,644
Barrick Gold Corp (ABX)	381	7,325
Newbridge Networks (NN)	272	7,156
Alcan Aluminum (AL)	182	5,775
Paris:		
STMicroelectronics (STM)	124	11,589
Alcatel (ALA)	174	4,871
TOTALFina (TOT)	71	4,482
Elf Aquitaine (ELF)	52	3,996
Frankfurt:		
DaimlerChrysler (DCX)	170	14,794
SAP (SAP)	196	6,800
Deutsche Telekom (DT)	38	1,655
London:		
Vodafone (VOD)	383	43,858
BP Amoco (BPA)	476	41,443
SmithKline Beecham (SBH)	152	10,027
Glaxo Wellcome (GLX)	111	6,537
AstraZeneca (AZN)	98	4,085

Table 3
Descriptive Statistics for Firms and Markets

Summary statistics are reported for German, Canadian, British, and French companies with the largest NYSE trading volume. The sample period ranges from August 1, 1999 to October 31, 1999. Relative spreads are computed by taking sample averages of the ratio of spread to mid-quotes at the 10 second sampling interval considering only the spreads and mid-quotes during the daily trading overlap period of the first 1.5 hours of New York trading. Trade volume and turnover are reported both for the New York morning and all day. The trade turnover is expressed in US $ by using the sample average of the respective exchange rate to convert from local currencies. Trade volumes were computed by converting the NYSE traded ADRs into home-market equivalents. The column *ADR ratio* reports the conversion rate from ADRs into home-market stock. These ADR ratios refer to the beginning of the sample periods, before any stock splits. Stock splits occurred for NT (1:2 implemented August 13, 1999 on TSE and August 20, 1999 on NYSE), for VOD (1:5, implemented after October 1, 1999 at LSE and after October 4, 1999 at NYSE) and for BPA (1:2, implemented after October 1, 1999 at LSE and NYSE). DCX is traded as a globally registered share (GRS), i.e the unit of stock is the same at both the home market and the NYSE. Similarly, TSE stocks trade on the NYSE as ordinary shares, not ADRs. Trade volumes refer to units of stocks at the beginning of the sample period, before eventual stock splits.

					First 1.5 hours of overlap				Whole trading day			
Stock	ADR ratio	Home market	Relative spread home market	Relative spread NYSE	Trade volume home market	Trade volume NYSE	Turnover home market	Turnover NYSE	Trade volume home market	Trade volume NYSE	Turnover home market	Turnover NYSE
DCX	*	Xetra	0.107%	0.197%	694,046	191,814	51,528,693	14,228,694	2,905,670	484,184	215,366,677	35,799,818
DTE	1:1	Xetra	0.166%	0.361%	875,623	46,698	37,580,050	1,994,945	3,747,518	100,964	161,125,301	4,307,691
SAP	12:1	Xetra	0.175%	0.392%	78,682	27,317	33,602,328	11,859,883	330,121	76,542	141,447,885	33,199,945
ABX	*	TSE	0.280%	0.397%	656,598	678,708	13,657,798	14,108,793	1,811,664	1,882,666	37,454,097	38,959,813
AL	*	TSE	0.272%	0.290%	247,325	345,109	8,211,594	11,462,946	701,569	854,338	23,174,438	28,329,124
NN	*	TSE	0.335%	0.484%	176,210	240,555	4,381,832	6,046,260	562,857	723,956	13,799,781	17,966,281
NT	*	TSE	0.193%	0.221%	701,799	947,341	36,256,367	51,326,652	2,043,588	2,870,513	105,966,209	154,431,852
VO	*	TSE	0.348%	0.303%	156,979	309,328	7,495,220	14,617,631	558,623	993,028	26,677,862	46,833,469
AZN	1:1	LSE	0.191%	0.299%	646,448	154,541	32,646,959	6,315,050	2,975,335	395,723	136,066,262	16,264,166
BPA	1:6	LSE	0.193%	0.129%	3,684,905	3,123,947	48,988,226	45,092,071	13,807,599	8,356,922	194,712,299	121,570,006
GLX	1:2	LSE	0.193%	0.266%	1,193,917	326,431	39,243,013	8,950,115	5,496,750	841,888	162,460,030	23,002,738
SBH	1:5	LSE	0.277%	0.261%	1,999,612	1,241,117	29,828,594	15,472,396	9,394,953	3,154,039	127,110,541	39,114,665
VOD	1:10	LSE	0.216%	0.166%	7,109,291	6,309,281	69,158,792	69,300,596	32,780,446	19,087,688	301,014,118	203,257,944
ALA	5:1	Paris	0.154%	0.424%	188,520	30,942	27,447,956	4,507,972	650,620	105,683	94,607,842	15,459,105
ELF	2:1	Paris	0.140%	0.205%	192,174	50,030	34,867,412	9,088,520	767,866	120,663	138,353,741	21,829,475
STM	1:1	Paris	0.182%	0.249%	333,169	354,409	25,394,057	27,514,187	959,302	790,316	73,398,025	61,093,536
TOT	2:1	Paris	0.142%	0.229%	407,985	52,551	52,684,674	6,775,357	1,640,752	155,484	213,098,811	20,101,310

Table 4
Cross-Firm Estimation Results: Information Shares as a Function of Liquidity Indicators

This table summarizes logistic-regression results for a model where the dependent variable is the information share of U.S. price innovations in explaining home-market prices for a cross-section of the most heavily traded firms on the NYSE from the following locations: Frankfurt, London, Paris, and Toronto. Data are for 1999. Explanatory variables are NYSE/Home market turnover and the difference of realized relative spreads averaged over the sample period for each firm. Estimation is via GMM with the White heteroskedasticity-consistent covariance matrix used as the weighting matrix. Instruments are the ratio of foreign to total sales, U.S. analysts following, and the ratio of U.S. to non-U.S. fund holdings of NYSE-listed shares.

Variable	**Coefficient**	**Standard Error**	**P-value**
Constant	-0.862	0.042	0.000
NYSE/Home Turnover	0.820	0.031	0.000
NYSE spread-Home spread	-255.78	71.84	0.003

R^2 = 0.989

J-statistic = 0.21 (p = 0.64)

Figure 1: Information shares: estimates and standard errors.

The estimated information shares represent averages of two alternative orderings FX→home→US and FX→US→home. The values in parentheses are the standard errors of these averaged information shares. The standard errors are obtained by applying the procedure for bootstrapping cointegrating relations suggested by Li and Maddala (1997). We conduct 1000 bootstrap replications. In each replication the VECM is estimated and the $\psi(1)$ Matrix computed. In each replication the pairs of information share vectors resulting from the orderings FX→home→US and FX→US→home are averaged. The standard errors are obtained by computing the sample standard deviation (based on the sample of 1000 bootstrap replications) of the averaged information shares.