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PRICE DISCOVERY IN INTERNATIONAL EQUITY TRADING

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Abstract

This study addresses two questions: where does price discovery occur for internationally-traded firms and how do international stock prices adjust to an exchange rate shock? These questions are answered by analyzing quotes originating in New York and Frankfurt for three large German firms, DaimlerChrysler, Deutsche Telekom, and SAP, during overlapping trading hours. A high-frequency sample of quotes from both locations along with the dollar/euro exchange rate yields evidence of one cointegrating relation among the three variables. Vector error correction models are estimated for each firm and the associated vector moving average representations are utilized to infer the share of price discovery coming from the exchange rate, New York, and Frankfurt quotes. The evidence suggests a structure of the international equity market that has the home-market largely determining the random walk component of the international value of a firm along with an independent role for exchange rate shocks to affect prices in the U.S. markets. However, there is a significant information share for New York in the case of DaimlerChrysler and an even bigger role for New York with respect to SAP. Following a shock to the exchange rate, we find that almost all of the adjustment comes through the New York price.

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1 Introduction

Stocks of many non-U.S. firms are traded in the United States. The issue of where price discovery occurs for such firms is surprisingly understudied. For instance, we lack evidence that yields a firm answer to the question of whether U.S. trading follows the home market or the home market follows the U.S. Furthermore, how do the prices in both markets adjust to an exchange rate shock? Does arbitrage avoidance require both markets to simultaneously adjust to a new exchange rate or does the adjustment tend to occur all in one market?

While there is no paper that attempts to address both of these issues as will be done here, there is a literature that addresses the relationship between prices of foreign equities and their U.S. listings. This literature is overwhelmingly focused on low-frequency daily returns so that issues of non-synchronous prices are potentially important. Exceptions include Ding, Harris, Lau, and McInish(1999), who examine the links between Singapore and Malaysia trading for one Malaysian firm and Eun and Sabherwal (2001) who examine the links between U.S. and Canadian trading for a sample of Canadian firms. These studies show significant price discovery in both the home and foreign market. While these papers are innovative and instructive, they use much lower frequency intradaily data than our study so that it may be difficult to sort out the true causality from the contemporaneous correlation created by time aggregation. Harris, McInish, and Wood (2001) examine high-frequency spread and transaction price dynamics for Daimler-Chrysler, before and after the creation of the global ordinary DCX shares.

While analysis in an intra-day setting is required to provide hard evidence, there is suggestive evidence from lower-frequency studies of an independent effect of the U.S. market. For instance, Kim, Szakmary, and Mathur (2000) use daily data to estimate VAR models of the impact of the underlying shares, the exchange rate, and the U.S. market index on ADR prices. They find that the underlying shares appear to be most important, but there is a significant independent role for the U.S. market index in pricing ADRs. While their paper does not specifically address the issue of price discovery, their findings of a role for the U.S. factor suggest that the issue of price discovery requires a more detailed analysis. One goal of this paper is to provide evidence on the information shares of U.S. and home market trading using contemporaneously sampled, high-frequency data. A second goal is to provide evidence on the equity price response at home and in the U.S. of an exchange rate change. There is a large literature on the effect of exchange rate changes on equity prices, but this literature has focused on the foreign exchange exposure effect of exchange rate changes for a single firm in its home country. Such studies have (quite properly) conducted analyses at a low time series frequency as they were concerned with issues related to the management of foreign exchange risk exposure. Ours is the first study to examine the high-frequency response of pairs of internationally cross-listed equity prices to exchange rates at the time resolution relevant for arbitrageurs.

One might think of price discovery for shares of, say, Deutsche Telekom stock to be determined in the following way. News in Germany is most important for this stock, so during German business hours, the price fluctuates with public and private information revelation. Once New York trading begins in the ADR,[1] the price of the stock may include relevant information coming from the North American market as inventory and information-based trading occurs during the New York morning period of the overlap between European and American trading hours. In addition, dollar/euro exchange rate fluctuations will have implications for the stock prices in both Europe and America. In order for the ADR price to equal the home market price, with both measured in a common currency, as the exchange rate varies, so will the stock prices. For instance, dollar depreciation would tend to increase the dollar price of the ADR and/or lower the euro price of the underlying home-market shares. Since there has been no intra-daily analysis of how international stock prices adjust to exchange rate shocks, we do not know if adjustment is symmetric in both the home country and the U.S. markets or if most or all of the adjustment to an exchange rate shock occurs in one market location. Our analysis will provide a first look at this issue.

The use of high-frequency, intra-day data allows a view of the market dynamics that simply cannot be achieved in daily data or lower-frequency intra-day data. Besides the issue of non-synchronous quotes that arises in using closing prices from different international markets, one cannot make meaningful inferences regarding price discovery except at the high-frequency relevant for actual trading. Furthermore, the pattern of adjustment of stock prices to exchange rate shocks would be lost due to time aggregation. Traders respond quickly to new information, so to infer the stock price response to an exchange rate shock one must examine the data immediately after the change in the exchange rate. At a low frequency, there will be many reasons why stock prices change so that one cannot clearly identify the link between a change in the exchange rate and a consequent change in the price of a stock. The gain from using high-frequency data is essentially that there may be one-way causality existing among variables at a high sampling frequency that dissolves into contemporaneous correlation at a lower sampling frequency.

We investigate the issue of price discovery for three large German blue-chip firms that are traded on the XETRA system in Germany and the New York Stock Exchange (NYSE) in the United States: Daimler-Chrysler, Deutsche Telekom, and SAP. The paper is organized as follows: Section 2 presents a brief overview of relevant institutional detail regarding the trading venues, trading mechanisms, and firms studied. Section 3 introduces the basic equilibrium relationships in the context of a simple microstructure model of the market. Section 4 provides the framework for analysis and discusses issues of methodology. Section 5 presents and discusses the data and estimation results. Finally, a summary and conclusion is provided in Section 6.

2 Institutional Details

Deutsche Telekom (DT) and SAP are both traded in the United States in the form of ADRs listed on the NYSE. This dollar-denominated U.S. trading is not an exchange of actual shares of the firms, but rather trade in negotiable instruments

[1] Foreign firms typically list in the United States in the form of American Depositary Receipts (ADRs).

issued by a depositary bank that represent ownership of the underlying shares as issued in Germany. DT ADRs trade one-for-one against the underlying home-market shares in Germany and SAP ADRs trade at a 12 to 1 ratio against the underlying shares, or 12 ADRs are issued for each share of the underlying stock held by the depositary.[2] 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 U.S. dollars in New York and euros in Frankfurt.[3] DCX is traded on the NYSE in the United States. German trading in these firms occurs via the electronic trading network known as XETRA. XETRA is an order-driven system with no designated market makers. Banks and institutional investors are main providers of liquidity through the limit orders they submit to the market.

ADRs are issued by a depositary bank accumulating shares of the underlying foreign stock. Since ADRs are issued at a fixed multiple relative to the underlying shares, 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, there is foreign exchange risk priced in 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. The time lag coupled with foreign exchange risk, results in no riskless arbitrage opportunities. 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. Still, we expect the prices of the two assets to move closely together over time. 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 security 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 institutions involving transfer and clearance issues.[4]

[2]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.

[3]See Karolyi (1999) for a detailed analysis and discussion of the DaimlerChrysler global ordinary stock.

[4]Karolyi (1999) provides a good review of the differences between ADRs, GRSs, and home market shares.

3 International Equity Trading and Equilibrium Relationships

Equilibrium in the market for U.S.-traded shares and the underlying home-market shares involves the dollar price of the ADR or GRS, the home-market price of the underlying shares, and the exchange rate. We motivate the empirical analysis by first presenting a relatively simple microstructure model where price discovery is assumed to occur in the home market. We 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 innovation u_t:

$$E_t = E_{t-1} + u_t \tag{1}$$

The log of the home-market share price, P_t^h, follows a random walk and introduces the innovation or random-walk component in the intrinsic value of the firm as v_t:

$$P_t^h = P_{t-1}^h + v_t \tag{2}$$

The log of the U.S. price, P_t^u, adjusts to the last observed exchange rate and home-market price and also includes a random term, w_t, to reflect any U.S.-based randomness that may be due to tick-size, liquidity orders, or any other idiosyncratic source:

$$P_t^u = E_{t-1} + P_{t-1}^h + w_t \tag{3}$$

If the exchange rate is defined in terms of dollars per foreign currency, then from a dollar basis, arbitrage would result in the U.S. price closely following the exchange-rate-adjusted home market price during the time of day when the two markets overlap. It is not necessary that the two values be equal at every point in time as there should be a no-arbitrage band due to transaction costs, and for ADRs, time lags and associated exchange rate risk involved in conversions of home-market shares into ADRs or the flow-back conversions in the opposite direction.[5] However, the two values should move closely together over time. If we subtract the log of the U.S. price from the log of the dollar value of a home-market share we have:

$$\begin{aligned} E_t + P_t^h - P_t^u &= E_{t-1} + u_t + P_{t-1}^h + v_t - E_{t-1} - P_{t-1}^h - w_t \\ &= u_t + v_t - w_t \end{aligned} \tag{4}$$

where u, v, and w are i.i.d. and uncorrelated with zero mean. So this linear combination of the exchange rate, home-market price, and U.S. price is stationary, i.e. E_t, P_t^h, and P_t^u are cointegrated with cointegrating vector $A' = [1, 1, -1]$. The empirical work below will verify the presence of one cointegrating vector, so with the three-variable system, we have two common trends, which one may attribute to the independent information associated with exchange rate innovations and innovations in the home-market price.

[5] Miller and Morey (1996) study the price of Glaxo-Wellcome stock during the overlap of trading between London and New York and show that the differences that exist between the ADR and the London price do not exceed the transaction costs that would be associated with arbitrage.

If the vector of the logs of prices and the exchange rate, P_t, can be represented by a nonstationary vector autoregression of the form:

$$P_t = \beta + \phi_1 P_{t-1} + \phi_2 P_{t-2} + \ldots + \phi_q P_{t-q} + \epsilon_t \tag{5}$$

where ϵ_t is white noise with covariance matrix Ω, and $\Delta P_t = P_t - P_{t-1}$ has the Wold representation

$$(1 - L)P_t = \delta + \psi(L)\epsilon_t \tag{6}$$

where L is the lag operator, then if there are cointegrating relations among the elements of P, the Granger Representation Theorem (Engle and Granger, 1987) shows that there exists an error correction model of the form:

$$\Delta P_t = \alpha + BZ_{t-1} + \delta_1 P_{t-1} + \delta_2 P_{t-2} + \ldots + \delta_{t-q+1} P_{t-q+1} + \epsilon_t \tag{7}$$

where $Z_{t-1} = A'P_{t-1}$. This is the error correction representation for a cointegrated system that we will employ in the empirical work below.

4 Contributions to Price Discovery

Our goal is to estimate the contribution of each asset price — the U.S. price, the home-market price, and the exchange rate — to price discovery. This requires a framework that can decompose the total variance in the three-variable system into meaningful parts. We note that since, in our theoretical framework, each of our asset prices is $I(1)$ and covariance stationary in first differences, we can write the three-equation system as a vector moving average (VMA):

$$\Delta P_t = \Psi(L)\epsilon_t = \epsilon_t + \psi_1 \epsilon_{t-1} + \psi_2 \epsilon_{t-2} + \ldots \tag{8}$$

Cointegration of the variables in P with cointegrating vector A' implies that $A'\Psi(1) = 0$, where $\Psi(1) = I + \psi_1 + \psi_2 + \ldots$.

The econometric methodology involves several steps. First, the Schwarz Information criterion (SIC) is employed to identify the appropriate lag length. The fitted VEC model is tehn used in a dynamic simulation to estimate the VMA parameters in 8) and the elements of the $\Psi(1)$ matrix.[6]

Once the $\Psi(1)$ matrix is estimated, we can infer the share of information associated with innovations to each variable by using a method similar to Hasbrouck (1995). However, we have two random walk components common across markets or two common trends originating in the exchange rate and home-market price innovations, compared to only one in Hasbrouck's study.

From Stock and Watson's (1988) common trends representation of a cointegrated system it can be seen that the permanent impact of innovations on the three asset prices is given by the vector $\Psi(1)\epsilon_t$. In order to provide a simple discussion of related issues, we write the components of this vector explicitly as:

$$\Psi(1)\epsilon_t \begin{bmatrix} \psi_{11} & \psi_{12} & \psi_{13} \\ \psi_{21} & \psi_{22} & \psi_{23} \\ \psi_{31} & \psi_{32} & \psi_{33} \end{bmatrix} \begin{bmatrix} \epsilon_t^e \\ \epsilon_t^h \\ \epsilon_t^u \end{bmatrix} \tag{9}$$

[6]See Hamilton (1994) p. 318-323 for a discussion of this method.

For example, with the elements in P_t being ordered as E_t, P_t^h, and P_t^u, then $\psi_{11}\epsilon_t^e + \psi_{12}\epsilon_t^h + \psi_{13}\epsilon_t^u$ gives the long-run component of the innovations that is permanently impounded in the exchange rate random walk. Given our prior beliefs regarding the structure of the system, we expect the $\Psi(1)$ matrix to have a specific form. In particular, we expect: $\psi_{12} = \psi_{13} = 0$, $\psi_{22} = \psi_{32}$, and $\psi_{23} = \psi_{33}$. Intuitively, ψ_{12} and ψ_{13} equaling zero means that the exchange rate is unaffected by innovations in the two stock prices. Then given this prior based upon economics, the fact that the two stock prices behave symmetrically to innovations coming from Frankfurt or New York follows from the restrictions imposed by cointegration, i.e., $A'\Psi(1) = 0$ and and a cointegrating vector of $A' = [1, 1, -1]$. We have no prior belief with regard to ψ_{21} and ψ_{31}, as the two stock prices may have different responses to exchange rate innovations. The estimation results reported below will provide an empirical test of these priors.

The impact of an innovation in price j on price i is determined by ψ_{ij}. For instance, $\psi_{12}\epsilon_t^h$ is the long-run impact of an innovation in the home-market price on the exchange rate random walk. To find the information shares, we decompose the variance of long-run innovations in each asset i, $var(\psi_{i1}\epsilon_t^e + \psi_{i2}\epsilon_t^h + \psi_{i3}\epsilon_t^u)$. These variances can be found on the diagonal of $\psi'\Omega\psi$. The information shares are then found as the share of total variance explained by each asset.

Since there is contemporaneous correlation among the innovations, i.e. Ω is not diagonal, it is not possible to identify an independent information share for each asset without further restrictions. To find each individual asset's contribution to that variance, we must impose a triangularization of the Ω matrix to deal with the presence of contemporaneous correlation. We follow the standard approach to this problem by using the Cholesky factorization of Ω. This provides a lower triangular matrix C, where $\Omega = C'C$. The Cholesky factorization is creating an orthogonalization where, in our application, we first isolate the impact of the exchange rate innovation, then the home-market innovation conditioned on the exchange rate innovation, and then the U.S. innovation, conditioned on both of the other markets. In this recursive setting, one may think of the orthogonalized innovation in the U.S. market as being the residual of a regression of the U.S. innovation on the innovations in the exchange rate and home-market price.[7] We now may compute a unique measure of the contribution of each asset to the total variance.

The information share of asset j with respect to asset i, S_{ij}, can be computed as:

$$S_{ij} = \frac{[\psi C]_{ij}}{(\psi\Omega\psi')_{ii}}. \tag{10}$$

This normalization guarantees that the information shares sum to unity for each asset. Since the resulting information shares will depend upon the ordering of the variables, it is important to demonstrate that the qualitative results are robust across alternative orderings. The Cholesky factorization will result in providing an upper bound on the share for the variable ordered first and a lower bound on the share of the variable ordered last. There are a couple of ways in which this issue may be addressed. We could appeal to directed acyclic graph analysis as discussed

[7]Hamilton, p. 321-323 has a good discussion of this issue.

in Swanson and Granger (1997) to motivate a particular ordering of the variables (which would support a choice of the order we actually use: exchange rate, home-market price, and U.S. price). However, given our high frequency sample, we demonstrate that the estimated upper and lower bounds for the information shares lie in a very tight range regardless of the ordering so that the issue is relatively unimportant in our case.

5 Data and Estimation Results

We study the relationship between U.S. and German trading over the common trading time overlap each day for the period August 1 to October 31, 1999. The overlap between Frankfurt and New York trading is from 14:30 to 16:00 GMT (or 9:30-11:00 New York time) until September 20, 1999. On this day, XETRA trading was extended an additional 30 minutes so that the overlap is from 14:30 to 16:30 GMT for the remainder of the sample. The exchange rate data are tick-by-tick quotes on the dollar price of the euro as reported on the Reuters indicative quoting screen.[8] The NYSE quote data are taken from the TAQ data set available from the NYSE. The XETRA quote data are proprietary data provided by the Frankfurt Stock Exchange for this study. Table 1 lists summary statistics for each firm and each market. The first two columns provide average bid and ask prices. XETRA quotes are in euro while NYSE quotes are in dollars. The dollar price of the euro was greater than 1 during this period, with a mean of 1.0607 for the bid price, so dollar prices exceed euro prices on the same firm. The SAP ADR represents 1/12 of a share of SAP stock as issued in Germany. In Table 1 and the empirical work that follows, the NYSE prices are multiplied by 12 to be comparable to the home-market shares. The third column shows that XETRA quoting is more intense than NYSE. XETRA quotes range from 3.4 times the NYSE quotes for DCX to 3.9 times the NYSE quotes for DT. Number of shares traded is also higher on XETRA than for the NYSE. The fourth column shows the average daily trading volume in each market and it is seen that the ratio of XETRA volume to NYSE volume ranges from 1.8 for DT to 3.9 for DCX. The last column reports the average daily turnover as measured in euro for XETRA and dollars for the NYSE. In German trading, DCX generates the highest volume, followed by DT and then SAP. In U.S. trading, DT has the highest average volume, followed by DCX and SAP.

Figure 1 plots the log of stock prices and the exchange rate over the 3-month period we study. The difference between the two prices reflects the exchange rate, which is seen in the final graph to move in a fairly narrow range over the sample period. The actual dollar/euro exchange rate traded within a range of 1.0355 to 1.0889 over the August – October period studied. The fact that the exchange rate was close to 1 over the period results in the XETRA euro price and the NYSE dollar price moving closely together over time.

The volume and turnover data presented in Table 1 tend to confirm the notion that XETRA provides the primary market and U.S. trading is in the derivative asset. Additional informal evidence may be seen in plots of the quoting intensity

[8]The data were obtained from Olsen & Associates, Zurich.

of each market. Figure 2 presents plots of the average number of quotes per second for each 5-minute interval over the trading day. The period of overlap between New York and Frankfurt is the peak period of activity during the day. Note how quoting intensity rises in Frankfurt with the New York opening and how quoting intensity falls in New York with the Frankfurt close. This effect seems most pronounced for DT and we shall see below how the information shares indicate that DT seems much more a German firm than an international firm. Overall, Figure 2 is consistent with the New York trading being derived from Frankfurt, but it is also suggestive of synergies between the two markets as quoting intensity in Frankfurt rises when New York opens.

The informal evidence presented in Table 1 and Figure 2 is useful and provocative, but is only suggestive of the interdependencies between the markets. We now turn to the formal econometric evidence regarding the relationship between U.S. and home-market trading. First, we discuss additional issues related to data and sampling and then we develop the estimates in line with the discussion in Sections 3 and 4.

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.[9] We examined partial correlations among the residuals of our three-equation VEC system over alternative sampling frequencies and chose 10 seconds as being suitable relative to lower frequencies like 1 minute, as the 1 minute frequency yielded much more evidence of significant partial correlation. At higher sampling frequencies than 10 seconds there was no gain in terms of reducing significant contemporaneous correlations, but there is a tradeoff with microstructural issues like non-synchronous quoting or other sources of microstructure "noise" that makes 10 seconds preferable. An additional sampling issue is with regard to overnight returns and lags. We created a data set that started each day with observations on the dependent variables and lags so that no overnight returns were used and no lags reached back to prior days. For instance, if the model calls for 3 lags in the VEC, the dependent variable begins with the fourth observation of each day. The initial observation each day for each stock was determined by the first 10-second interval following the NYSE open containing a quote in either market.

Augmented Dickey-Fuller tests revealed unit roots in the log of each asset price and the variables were identified as being $I(1)$. Johansen cointegration tests were performed and the results clearly support the hypothesis of one cointegrating vector among the 3 variables. The next step is to estimate the VEC equation (7). The choice of lag length was determined by the Schwarz Information Criterion (SIC). We started with 18 lags, which is 3 minutes in a sample with observations at 10-second intervals. Then, holding the number of observations constant, we estimated the VEC at each shorter lag length down to 1 lag to determine the lag structure that minimized the SIC. This revealed 3 lags as optimal for SAP and

[9] See Granger (1988) for discussion of related issues.

DT and 4 lags as optimal for DCX. The cointegrating relations of the estimated VECs are reported in Table 7. The cointegrating vectors are all about 1,1, and -1 with the variables ordered as exchange rate, home-market price, and U.S. price. For each security, summary statistics are given on the order of cointegration.[10] In all 3 cases, the data support 1 cointegrating vector.

Standard errors in Table 7, and all following tables, were computed employing a bootstrap method suggested by Li and Maddala (1997). In order not to distort the dynamic properties of the cointegrated system we choose to bootstrap from the residuals of our estimated VEC models rather from than the actual data.[11] More precisely, the estimated residuals are re-sampled by drawing observations randomly with replacement and then building a new vector of observations on the data from the innovations and the lagged values of the dependent variables. From the new set of observations, parameters are re-estimated. This process is repeated 1,000 times to generate the empirical distributions for the parameters of interest.

The VECMs are dynamically simulated to find the VMA parameter matrices in equation (8). As discussed in Section 4, this provides estimates of dynamic multipliers associated with unit shocks to the innovations in each variable. The resulting $\Psi(1)$ estimates are given in Table 3. The reported matrices meet our prior expectations as discussed in the previous section: the exchange rate appears to be unaffected by innovations in the stock prices; the long-run impact of a shock to the XETRA price is about the same on both XETRA and NYSE prices; and the long-run impact of a shock to the NYSE price is about the same on both XETRA and NYSE prices. In addition, Table 3 reports estimates of parameters for which we had no prior beliefs: the long-run impact of a shock to the XETRA price is greater than the long-run impact of a shock to the NYSE price and shocks to the exchange rate have a greater impact on the NYSE price than the XETRA price. The greater impact of XETRA prices compared to NYSE prices is consistent with a view that price is discovered in Frankfurt and then New York follows with the derivative market.

The fact that the NYSE price appears to accommodate most of the adjustment to an exchange rate shock while the XETRA price is relatively unaffected by such shocks is important new evidence on how international equity prices evolve. One might think that, given a shift in the exchange rate, both prices would tend to adjust to a new equilibrium defined by the new exchange rate. For instance, if the dollar depreciates against the euro, we might expect arbitrage forces to result in a rise in the NYSE price and a simultaneous fall in the XETRA price in order for the "law of one price" to hold in the international equity market. Instead, the evidence indicates that almost all of the adjustment to a new exchange rate comes through changes in the NYSE price. There is a small and statistically significant negative effect of the exchange rate innovation on the XETRA price that is roughly the same magnitude for DCX and SAP but much smaller for DT. However, the NYSE effect is about 3 times the XETRA effect for DCX and SAP and about 12 times the XETRA effect in the case of DT.[12] The fact that the NYSE price does

[10] See Johansen (1991) for a discussion of the test statistics.

[11] See Sapp (2000) for a similar bootstrap application to high-frequency exchange rate data.

[12] The exchange rate evidence is also indicative that our overall results are not driven by the fact that there is more frequent quoting on XETRA than the NYSE. It does not appear to be the

most of the adjustment to an exchange rate shock is additional evidence that the ADR is priced as the derivative asset. Given the home-market price, a change in the exchange rate requires a change in the NYSE price in order to follow the XETRA price. In order to prevent arbitrage opportunities, it is no surpirce that there is a very quick adjustment in the stock prices following an exchange rate change. This dynamic pattern of adjustment to an exchange rate change across international equity markets would be lost in an analysis at the daily level.

As explained above, the triangularization 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 will later address this issue by estimating the upper and lower bounds on information shares. First, an ordering of exchange rate, home-market price, and U.S. price is used to estimate the information shares. We use this order in computing the information shares reported in Table 4.

Table 4 contains the contribution of innovations in the variables listed at the top row to explaining the variance in innovations of variables listed in the first column. For instance, consider the first row of information shares for DCX. 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. The same pattern is seen for the other two stocks as well.

The information shares related to explaining innovation variance for the XETRA prices indicates that the exchange rate information shares are less than 1 percent for all three firms. The XETRA price innovations are shown to be most important with information shares ranging from 0.991 for DT to 0.798 for SAP. The NYSE innovations have an information share of approximately zero for DT, about 9 percent for DCX, and about 20 percent for SAP.

The information shares related to NYSE price innovations indicate that the exchange rate accounts for shares ranging from about 5 percent for DT to about 7 percent for DCX. XETRA price innovations have the largest information share of about 84 percent for DCX, 94 percent for DT, and 75 percent for SAP. The NYSE price innovations account for an information share of about zero for DT, 9 percent for DCX, and 19 percent for SAP.

An overview of the results reported in Table 4 offers a clear interpretation of the findings: a) the exchange rate is exogenous with respect to the stock prices; b) exchange rate innovations are more important in understanding the evolution of NYSE prices than XETRA prices; and c) most of the fundamental or random walk component of the value of the 3 firms is determined in Frankfurt.

There are striking differences across the three firms, especially between the DT and SAP results. The XETRA price innovation share is above 99 percent

case that XETRA seems to be the "first mover" just because they have more frequent quotes. The NYSE quotes do most of the adjusting to the exchange rate while XETRA quotes appear to be relatively unaffected by exchange rate changes. The differences in our estimates across firms (even though all three have about the same ratios of XETRA to NYSE quotes) is corollary evidence that the results reflect real economic phenomena and are not just an artifact of quote frequency.

for the XETRA price of DT. The same information share for SAP is about 75 percent. There is almost a 20 percent information share for the NYSE innovation in both the XETRA and NYSE prices for SAP. Why does DT have such a large information share for XETRA relative to SAP and DCX? In contrast to DCX and SAP, DT appears to be more of a German firm than a multinational firm. This is borne out in the revenue data as U.S.-based revenue accounts for less than 1 percent of DT revenue, a little more than 50 percent of DCX revenue, and a little less than 50 percent of SAP revenue.[13] Even more descriptive of the differences between the multinational nature of SAP shares realtive to DT is the U.S. versus the non-U.S. location of mutual fund holders of each stock. The shares of NYSE traded stocks held by U.S. versus non-U.S. mutual funds in January, 2001 are: DCX 9,152,343/132,084,720; DT 693,933/24,173,898; and SAP 7,969,826/958,013.[14] U.S. mutual funds own around 8 times as many SAP ADRs as non-U.S. funds. However, only 3 percent of DT ADRs are owned by U.S. mutual funds. The largest owners of SAP tend to be large U.S. institutions (the top 5 being INVESCO Funds Group, Inc., INVESCO Capital Management, Inc., MFS Investment Management, Smith Barney Asset Management, and Kayne Anderson Rudnick Investment Management, LLC) while the largest owners of DT tend to be non-U.S. funds (the top 5 includes Brandes Investment Partners, LP, Frankfurt Trust, Union Bank of Switzerland-Asset Management, Citadel Investment Management, LP, and UBS Warburg). It is clear that SAP has a much stronger follwoing in the United States than DT. DCX, on the other hand, lies between the results found for DT and SAP. While DCX and SAP both have similar U.S. revenues, their ownership patterns are quite different. DCX ADR ownership is more similar to DT with U.S. mutual funds holding only about 7 percent of the shares. So DCX lies in between SAP and DT in terms of the strength of its U.S. following. Beyond the obvious differences in terms of the geographic distribution of ownership, there may be some additional factors that help explain the fact that SAP has a larger share of price discovery for the NYSE than DT or DCX. First, SAP is considered a "new economy stock" and the U.S. market focus on those firms may account for the larger information share of the NYSE. Second, SAP's biggest rivals are U.S. firms. So U.S. news may be more relevant for SAP than DCX, who has major rivals in Europe or Asia, or DT, who essentially does business in Europe only.

Figure 3 contains estimates of the kernel densities associated with the information shares for the two stock prices. The figure provides a more detailed look at the differences across the firms than the standard errors reported in Table 4. One can see in the top two figures the fact that the exchange rate innovations have an effect on NYSE prices that is markedly different than the effect on the XETRA prices. If one superimposed the XETRA figure on the NYSE, not even the extreme tails would overlap. On the other hand, it is seen in the four lower figures that the effects of XETRA price innovations and NYSE price innovations

[13]An examination of each firm's web homepage indicated the following recent data: DCX, total revenue in the 3rd quarter of 1999 was 36.3 billion euro with 19.3 billion euro from the U.S.; DT, total revenue in 1999 was 35.5 billion euro with 161 million euro from the U.S.; SAP, total revenue in the 3rd quarter of 1999 was 1.1 billion euro with 492 million euro from the U.S.

[14]Mutual fund ownership is listed on the J.P. Morgan ADR web site: www.adr.com.

are similar for stocks in both trading locations. The kernel densities look quite similar for XETRA innovation effects on XETRA and NYSE prices and NYSE innovation effects on XETRA and NYSE prices.

The ordering of variables underlying Table 4 was motivated by our priors on the likely recursive ordering of the contemporaneous correlation. However, one can further explore the sensitivity of results over the alternative possible orderings. We do so in order to demonstrate that the bounds for information shares are quite small. By permuting the order of variables in the Cholesky decomposition, we find the bounds for information shares given in Table 5. In many cases, the bounds are so tight that the upper and lower values round to the same 3 decimal places. In other cases, there is less than 1 percentage point difference. Given the tight bounds that exist over alternative orderings, it is clear that the information shares and associated inferences are unaffected in any substantive manner by the ordering of variables.

6 Summary and Conclusions

We now return to the initial questions that motivated this study: where does price discovery occur for internationally-traded firms and how do international stock prices adjust to an exchange rate shock? Our approach to answering these questions involves an analysis of the high-frequency quotes on three blue-chip German firms during the daily overlap of trading in Frankfurt on XETRA and New York on the NYSE. While the results support the notion that price discovery occurs largely in Frankfurt, results differ across our three firms. In order of the information shares attributed to Frankfurt trading in explaining XETRA (NYSE) price innovations we have DT, with 99 (94) percent; DCX, with 91 (84) percent; and SAP, with 80 (75) percent. The high share for DT is likely a result of the fact that almost all DT revenue is earned in Germany and DT ADR ownership is concentrated outside the U.S. DCX and SAP both have substantial U.S. revenue sources and SAP ownership is concentrated inside the U.S. It makes intuitive sense that multinational firms would have more room for international price discovery than firms that are essentially operating only in their home market.

An additional question of interest related to the first question is: how do international stock prices adjust to an exchange rate shock? We find that the New York prices bear almost all of the adjustment to exchange rate changes. For each of our firms, the information shares attributed to the exchange rate in explaining XETRA prices are approximately zero. For NYSE prices, the exchange rate innovations have an information share of at least 5 percent.

The evidence suggests a structure of the international equity market that has the home-market largely determining the random walk component of the international value of a firm along with an independent role for exchange rate shocks to affect prices in the derivative markets. This is not to say that the NYSE does not contribute to price discovery in the case of New York trading in foreign firms. In fact, we find that for SAP the information share of the NYSE in explaining XETRA and NYSE price innovations is about 20 percent. So while there may be some role for derivative market price discovery, the evidence is strongly supportive of prices largely being determined in the home market.

References

[1] Bacidore, Jeffrey M. and Sofianos, George, 2000, "NYSE Specialist Trading in Non-U.S. Stocks," NYSE Working Paper #2000-05, May.

[2] Chen, S. X.,1999,"Beta kernel estimators for density functions", *Computational Statistics & Data Analysis*, 31, 2, 131-145.

[3] Ding, David K., Frederick H. deB. Harris, Sie Ting Lau, and Thomas H. McInish, 1999, "An Investigation of Price Discovery in Informationally-Linked Markets: equity trading in Malaysia and Singapore," Journal of Multinational Financial Management, 9, 317-329.

[4] Engle, Robert F. and Clive W.J. Granger, 1987, "Co-integration and error correction: Representation, estimation, and testing," *Econometrica*, 55, 251-276.

[5] Eun, Cheol S. and Sanjiv Sabherwal, 2001, "Price Discovery for Internationally Traded Securities: evidence from the U.S.-listed Canadian stocks," Georgia Tech Working Paper, July.

[6] Granger, Clive W.J., 1988, "Some Recent Developments in a Concept of Causality," *Journal of Econometrics*, 39, 199-211.

[7] Hamilton, James D., 1994, *Time Series Analysis*, Princeton University Press.

[8] Harris, Frederick H. deB., Thomas H. McInish, and Robert A. Wood, 2001, "DCX Trading in New York and Frankfurt: Home bias insights from intraday data," University of Memphis Working Paper, June.

[9] Hasbrouck, Joel, 1995, "One Security, Many Markets: Determining the Contributions to Price Discovery," *Journal of Finance*, September, 50,1175-1199.

[10] Johansen, Søren, 1991, "Estimation and Hypothesis Testing of Cointegrating Vectors in Gaussian Vector Autoregressive Models", *Econometrica*, 59, 1551-80.

[11] Karolyi, G. Andrew, 1999, "DaimlerChrysler AG, The First Truly Global Share," Ohio State University Working Paper, September.

[12] Kim, Minho, Andrew C. Szakmary, and Ike Mathur, 2000, "Price Transmission Dynamics Between ADRs and Their Underlying Foreign Securities," *Journal of Banking and Finance*, August, 24, 1359-1382.

[13] Li, Hongyi and G.S. Maddala, 1997, "Bootstrapping Cointegrating Regressions," *Journal of Econometrics*, October, 80, 297-318.

[14] Miller, Darius P. and Matthew R. Morey, 1996, "The Intraday Pricing Behavior of International Dually Listed Securities," *Journal of International Financial Markets, Institutions, and Money*, January, 6, 79-89.

[15] Sapp, Stephen, 2000, "Price Leadership in the Spot Foreign Exchange Market", Working Paper, University of Western Ontario.

[16] Silverman, B. W., 1986, *Kernel density estimation for statistics and data analysis*, Chapman & Hall, London.

[17] Stock, James H., and Mark W. Watson, 1997, "Testing for Common Trends", *Journal of the American Statistical Association*, 83, 1097-1107.

[18] Swanson, Norman R. and Clive W.J. Granger, 1997, "Impulse Response Functions Based on a Causal Approach to Residual Orthogonalization in Vector Autoregressions," *Journal of the American Statistical Association*, March, 92, 357-367.

[19] Watson, Mark W.,1994, "Vector Autoregression and Cointegration," in R.F. Engle and D.L. McFadden, eds, *Handbook of Econometrics*, Volume IV, Elsevier Science, p. 2844-2915.

Table 1:

Descriptive Statistics for Firms and Markets

Summary statistics are reported for three firms: DaimlerChrysler (DCX), Deutsche Telekom (DT), and SAP. Trading in the U.S. occurs on the NYSE and trading in Germany occurs on the XETRA system. The data are for the period of trading overlap each day: 14:30-16:00 (or 16:30 from September 20, 1999) over the period from August 1 to October 31, 1999. XETRA prices are quoted in euro and NYSE prices are quoted in dollars (the mean bid quote for the exchange rate over the sample period was 1.0607 dollars per euro). DCX and DT shares in the U.S. trade at a 1 to 1 ratio against German shares. SAP shares in the U.S. trade at a 12 to 1 ratio against the German shares, but the table adjusts the NYSE prices and volume by a factor of 12 to make the SAP numbers for each market comparable.

Firm	Avg. bid price	Avg. ask price	Avg. daily no. of quotes	Avg. daily trading volume	Avg. daily turnover
DCX					
XETRA	69.72	69.79	731	794,523	55,478,987
NYSE	73.80	73.96	215	203,909	15,102,534
DT					
XETRA	40.60	40.67	593	1,024,785	41,579,511
NYSE	42.97	43.14	151	572,902	28,491,202
SAP					
XETRA	402.00	402.70	563	92,917	37,657,635
NYSE	429.24	430.92	162	30,749	13,388,669

Table 2:

VEC Estimation Results

Vector error correction models are estimated for each firm. The form of the equation is:

$$\Delta P_t = \alpha + BZ_{t-1} + \delta_1 P_{t-1} + \delta_2 P_{t-2} + \ldots + \delta_{t-q+1} P_{t-q+1} + \epsilon_t$$

where ΔP_t contains the change in the logs of the exchange rate, the home-market price, and the U.S. price; Z_{t-1} is the lagged log-levels of each variable in the cointegrating equation estimated by the Johansen method. The table reports the cointegating vector that applies to Z. a, B, and d are coefficients to be estimated and are not reported to conserve space. The bootstrap standard errors are in parentheses. Each table contains the number of observations for that firm (each day, the time of the first observation is defined by the first quote), the log likelihood associated with the estimated system, and summary statistics associated with the Johansen test for the order of cointegration, where h = number of cointegrating relations, LR = likelihood ratio statistic, crit. 5 %: critical values of LR statistics taken from Hamilton (1994), pp. 767-768. In each case, the results support 1 cointegrating vector. TR is Johansen's trace statistic, MEV is Johansen's maximum Eigenvalue statistic.

Table 2a: DCX Estimation results

Cointegrating Equation							
E	1.00000	(0.00000)		Number of obs.	38704		
P^h	1.01520	(0.01683)		Log Likelihood	812177.0		
P^u	-1.01512	(0.01615)					
	H_0 H_A	LR	crit. 5%		H_0 H_A	LR	crit. 5%
TR	$h=0$ $h=3$	437.51	24.31	MEV	$h=0$ $h=1$	433.18	17.89
	$h=1$ $h=3$	4.33	12.53		$h=1$ $h=2$	4.25	11.44
	$h=2$ $h=3$	0.08	3.84		$h=2$ $h=3$	0.08	3.84

Table 2b: DT Estimation results

Cointegrating Equation							
E	1.00000	(0.00000)		Number of obs.	38300		
P^h	1.01516	(0.01754)		Log Likelihood	772688.2		
P^u	-1.01507	(0.01725)					
TR	H_0 H_A	LR	crit. 5%	MEV	H_0 H_A	LR	crit. 5%
	$h=0$ $h=3$	684.36	24.31		$h=0$ $h=1$	677.29	17.89
	$h=1$ $h=3$	7.07	12.53		$h=1$ $h=2$	6.86	11.44
	$h=2$ $h=3$	0.20	3.84		$h=2$ $h=3$	0.20	3.84

Table 2c: SAP Estimation results

Cointegrating Equation							
E	1.00000	(0.00000)		Number of obs.	38754		
P^h	1.00538	(0.02204)		Log Likelihood	785231.2		
P^u	-1.00523	(0.02182)					
TR	H_0 H_A	LR	crit. 5%	MEV	H_0 H_A	LR	crit. 5%
	$h=0$ $h=3$	435.32	24.31		$h=0$ $h=1$	433.20	17.89
	$h=1$ $h=3$	2.12	12.53		$h=1$ $h=2$	2.12	11.44
	$h=2$ $h=3$	0.01	3.84		$h=2$ $h=3$	0.01	3.84

Table 3:

Vector Moving Average Coefficients

The matrices below are estimates of the $\Psi(1)$ matrix associated with the vector moving average (VMA) models:

$$\Psi(1)\epsilon_t = \begin{bmatrix} \psi_{11} & \psi_{12} & \psi_{13} \\ \psi_{21} & \psi_{22} & \psi_{23} \\ \psi_{31} & \psi_{32} & \psi_{33} \end{bmatrix} \begin{bmatrix} \epsilon_t^e \\ \epsilon_t^h \\ \epsilon_t^u \end{bmatrix}$$

The reported coefficients indicate that the exchange rate appears to be unaffected by innovations in the stock prices. The long-run impact of a shock to the home-market stock price appears to be similar for both XETRA and NYSE prices. Similarly, the long-run impact of a shock to the U.S. stock price appears to be the same for both XETRA and NYSE prices. The long-run impact of a shock to the home-market price is larger than the impact of a shock to the U.S. price in all cases. Shocks to the exchange rate appear to have a larger impact on the NYSE price than the XETRA price. Bootstrap standard errors are in parentheses.

DCX

$$\begin{bmatrix} 0.576(0.010) & -0.005(0.011) & 0.011(0.012) \\ -0.132(0.025) & 0.822(0.031) & 0.250(0.033) \\ 0.435(0.027) & 0.818(0.032) & 0.261(0.034) \end{bmatrix}$$

DT

$$\begin{bmatrix} 0.594(0.006) & -0.004(0.007) & 0.004(0.008) \\ -0.046(0.026) & 0.879(0.030) & 0.081(0.031) \\ 0.539(0.027) & 0.875(0.030) & 0.085(0.031) \end{bmatrix}$$

SAP

$$\begin{bmatrix} 0.596(0.007) & -0.005(0.008) & 0.001(0.008) \\ -0.149(0.021) & 0.689(0.024) & 0.287(0.026) \\ 0.444(0.023) & 0.685(0.025) & 0.288(0.026) \end{bmatrix}$$

Table 4:

Information Shares of the Exchange Rate, Home-Market Price, and U.S. Price in Price Discovery of Internationally-Traded Equities

The information shares are the proportion of the innovation variance in the value of asset i that can be attributed to innovations in the price of asset j. The estimates are drawn from a VEC model involving the dollar/euro exchange rate, the home-market (XETRA) price, and the U.S. (NYSE) price. That particular order of the three variables is utilized in the triangularization of the covariance matrix. Elements of each row may not sum exactly to 1 due to rounding to 3 decimal places. Bootstrap standard errors are in parentheses.

	Exchange Rate Innovation	XETRA Innovation	NYSE Innovation
DCX			
Exchange Rate	0.999 (0.005)	0.000 (0.002)	0.001 (0.004)
XETRA Price	0.007 (0.003)	0.906 (0.029)	0.087 (0.027)
NYSE Price	0.073 (0.007)	0.838 (0.024)	0.089 (0.027)
DT			
Exchange Rate	0.999 (0.004)	0.000 (0.002)	0.000 (0.002)
XETRA Price	0.000 (0.001)	0.991 (0.007)	0.009 (0.007)
NYSE Price	0.049 (0.005)	0.942 (0.008)	0.009 (0.007)
SAP			
Exchange Rate	1.000 (0.004)	0.000 (0.002)	0.000 (0.002)
XETRA Price	0.006 (0.002)	0.798 (0.041)	0.196 (0.039)
NYSE Price	0.059 (0.006)	0.752 (0.036)	0.189 (0.039)

Table 5:

Bounds for Information Shares

Permuting the order of the variables in the Cholesky decomposition of the covariance matrix allows the computation of the upper and lower bounds on information shares. The variable going first in the order has its share maximized and the variable listed last has its share minimized. The table gives the upper and lower bounds for each innovation pair. Only a single value is reported when the upper and lower bounds round to the same number at 3 decimal places.

	Exchange Rate Innovation	XETRA Innovation	NYSE Innovation
DCX			
Exchange Rate	0.998	0.000	0.001-0.003
XETRA Price	0.007	0.906-0.901	0.086-0.093
NYSE Price	0.072-0.081	0.833-0.838	0.089-0.097
DT			
Exchange Rate	0.999	0.000	0.000
XETRA Price	0.000	0.988-0.991	0.009-0.012
NYSE Price	0.049-0.050	0.938-0.941	0.009-0.012
SAP			
Exchange Rate	1.000	0.000	0.000
XETRA Price	0.006-0.007	0.794-0.797	0.196-0.199
NYSE Price	0.057-0.058	0.750-0.758	0.189-0.191

Figure 1:

Time-Series Plots of the XETRA and NYSE Stock Prices and the Dollar/Euro Exchange Rate

The data plotted in the figures shows the stock prices in Frankfurt trading (XETRA) and New York trading (NYSE) for 3 firms, DaimlerChrysler (DCX), Deutsche Telekom (DT), and SAP. In addition, the dollar/euro exchange rate is plotted. The sample period is August 1, 1999 to October 31, 1999.

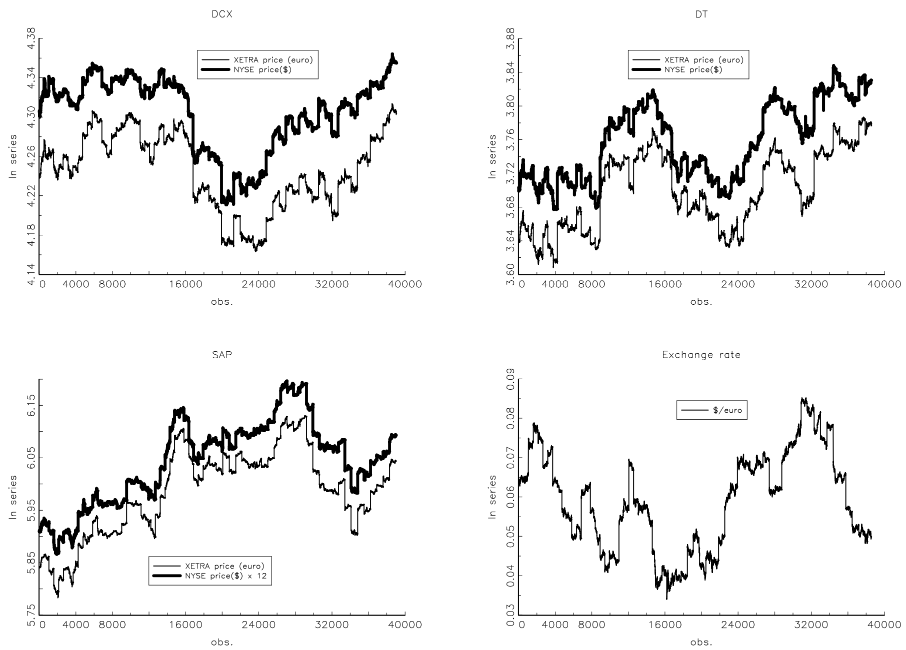

Figure 2:
Intra-daily Quoting Intensities

The figures show the average number of quotes per second for each 5-minute interval over the XETRA and NYSE trading day for the period August 1 - September 19, 1999 when XETRA closed at 16:00 GMT.

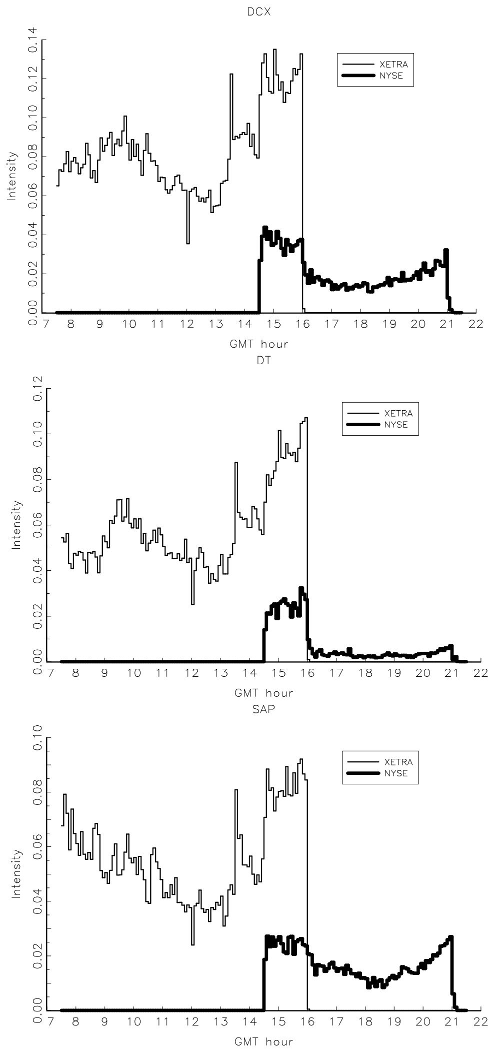

Figure 3:
Kernel Density Estimates of Estimated Information Shares

The figures show the density estimates of the estimated information shares with respect to XETRA and NYSE price innovations based on a sample of 1,000 bootstrap replications. The figures show the density estimates of the estimated information shares with respect to XETRA and NYSE price innovations based on a sample of 1,000 bootstrap replications. To account for the bounded support of the data, the beta kernel proposed by Chen (1999) with Silverman's (1986) bandwidth selector, adjusted for variable kernels, was employed.