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Information processing and measures of integration: New York, London and Tokyo

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Information processing and measures of integration: New York, London and Tokyo

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Information processing and measures of integration: New York, London and Tokyo

ABSTRACT

Equity markets do not pass all overnight information into prices instantaneously at the opening of trade. The New York market takes up to 30 minutes after the opening time to absorb overnight foreign news, Tokyo takes about 90 minutes, and London about 120 minutes on average. These delays in information absorption are not commercially significant but do have implications for measures of market integration. We adjust intra-daily return series for non-instantaneous news absorption and then use adjusted series to predict opening price variation in three major equity markets. Because the adjusted daytime returns series are uncorrelated, we can accurately measure the size, and identify the sources, of transmissions. Overnight news, as represented by foreign daytime returns, explains 12% of opening price variation (close-open returns) in New York, 14% in Tokyo and 30% in London. For New York and Tokyo, the largest influences come from the market that trades immediately prior (London and New York respectively) whereas opening price variation in London is linked closer with New York than Tokyo. Foreign volatility spillovers are also significant, and subject to asymmetry effects.

JEL Codes: G14 G15

Keywords: GARCH, spillover, integration, transmission, efficiency

1. Introduction

Studies of equity market integration aim to map the transmission of common information from one market to another through time.[1] If news arrival is random and opening prices exhibit the full impact of overnight news, sequences of open-close returns from efficient markets should be uncorrelated, with the remaining day's trade responding to independent innovations. However, really precise mapping of information transmission is made difficult by the fact that continuous random news arrival must be tracked using the non-synchronous and/or overlapping returns processes which we actually observe.[2]

In this study we show that variations in opening prices in three major equity markets, Tokyo, London and New York, are significantly predicted by the returns and volatility patterns of earlier foreign trade. This predictability does not contradict market efficiency (since there is no opportunity to trade between the close and opening of a market) but it does identify the information flows which are common to all three markets. Using intra-daily data on the S&P 500, the Nikkei 225 and the FTSE 100 indices, we search the early hours of trade in each market for the point of

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[1] The degree of integration between international stock markets has implications for portfolio allocation (Ang and Bekaert 2002, Gerard, Hillion and de Roon 2002), risk management (Bookstaber 1997) and asset pricing (Diermeier and Solnik 2001). Highly integrated markets offer reduced opportunities for diversification and may make the global financial system more susceptible to crisis.

[2] See, for example, Becker et. al. (1990), Becker et. al. (1992), Susmel and Engle (1994), Burns, Engle and Mezrich (1998), Martens and Poon (2001).

zero correlation with lagged foreign and domestic open-close returns. We make this the reference point for measuring the arrival of truly new information, and the starting point for adjusting returns calculations. We can then use the resulting zero-correlation open-close returns as orthogonal explanators for opening price variation (close to open returns).

This new method improves the quality of integration measures by isolating the early-trade ‘opening’ price which fully reflects prior news. By contrast, estimates based on raw opening prices are likely to mismeasure the size of transmissions between markets. In addition, since the adjusted daytime returns are orthogonal explanatory variables in the model of opening price variation, we can now for the first time identify both the *size* and the *source* of foreign market effects on price change and volatility.

In fact, about 12 per cent of the log change in close to opening price in New York, 14 per cent in Tokyo and 30 per cent in London is explained by foreign daytime returns. The strongest impact on New York and Tokyo is from the markets that trade immediately prior to them, that is London and New York respectively. London, however, appears to be much more dependent on New York’s daytime return than on Tokyo’s, despite the fact that New York news is older. Spillovers from foreign daytime volatility explain 9 per cent of opening price conditional variance in New York, 3 per cent in Tokyo and 2 per cent in London. We also find evidence in all three markets of asymmetric effects in returns and volatility spillovers associated with negative foreign returns.

Past research into the transmission of shocks from one market to another has highlighted the importance of a careful treatment of returns timing, since results can be contaminated by non-synchronous or overlapping measurement of returns (Burns, Engle and Mezrich 1998, and Martens and Poon 2001). Hamao et.al. (1990, 1991) and Becker et.al. (1990) approach the problem by dividing close to close returns (which confuse predictive and contemporaneous effects) into close to open and open to close returns. These studies highlight transmission of return and volatility spillovers into the Tokyo market from New York: Becker et. al. (1990) put the impact of the lagged US return at about 7 per cent of the variation in Tokyo open to close returns. In addition, using hourly data, Becker et. al. (1992) confirm that inter-market correlations can persist into the trading day beyond the initial opening, a feature which they attribute to a 'sticky' opening index value for Tokyo. However, filter tests indicate that the degree of return predictability uncovered in these studies was not sufficient to generate a profit net of trading costs.[3] Similarly, while Engle et. al. (1990) and Lin (1989) show that volatility transmissions are significant, they do not find evidence that mean returns could be predicted from one market to another.

Susmel and Engle (1994) concentrate on the hours when the London and New York markets trade simultaneously, searching for returns and volatility spillovers between contiguous segments of trade. Using hourly data from two years spanning

[3] According to Jensen's (1978) version of the Efficient Markets Hypothesis (EMH), predictability in daily prices is consistent with the EMH as long as the patterns do not permit abnormal profits. Fama (1970) provides an alternative version of the EMH that does not take into account transaction and information costs and thus precludes existence of any discernable patterns.

the 1987 stock market crash, they find weak evidence of volatility spillovers, but no evidence of returns predictability.

Consistent with Susmel and Engle (1994), our results confirm the weak and transitory nature of open-close returns spillovers between Tokyo, London and New York, and we reinforce (using filter trading rules) the fact that any predictability between daytime returns series is not commercially interesting. Nevertheless, we contend that the impact of lagged daytime returns and volatilities on *opening prices* (overnight returns) is important, and is best measured using returns series that fully embed prior information according to statistical, rather than commercial, significance.

We approach this problem in two stages. First we establish the half-hour interval after opening where the index price embeds all information accumulated during the close, by modelling six sets of non-overlapping daytime ('open'-close) returns in a VAR-GARCH system.[4] (The sample runs over a nine year period January 5, 1996 – March 22, 2005.[5]) We measure non-overlapping daytime ('open'-close) returns firstly at the initial opening price index value, and then in a sequence of five half-hour increments after the opening. We estimate the VAR-GARCH system using each returns series, and test for significant information transmission from market to market. Once a market has absorbed preceding news, estimated coefficients on all

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[4] Our models allow for sensitivity of returns and variances to both the sign and size of shocks, following the method of Glosten Jagannathan and Runkle (1993). See also Black (1976), Christie (1982), Erb, Harvey and Viskanta (1994) and Longin and Solnik (2001) on asymmetric effects in equity markets.
[5] This was the largest sample of intra-daily data available from SIRCA.

foreign returns and volatility spillovers will be statistically insignificant. Consequently, we can use significance tests to identify the point of time into the trading day (within a 30 minute band) when news from earlier trade in other markets is fully reflected in the domestic market price index.

We find that although the markets are efficient (according to Jensen's (1978) definition)[6] they do not process all prior information instantaneously at opening. Returns from the previous day's trade in the other markets have explanatory power for domestic open-close returns for about 30 minutes in New York, about 90 minutes in Tokyo and for about 120 minutes in London. Volatility spillovers take longer to clear in all three markets.

At the second stage, having identified the average full-absorption 'opening' price in each market, we can measure information linkages and market integration by modelling the variation in 'opening' prices explained by foreign market news. Here we specify similar mean and variance equations as before, but the dependent variables are now the overnight (close-open) returns, and daytime returns are explanatory variables. For example, we measure the effects of foreign news on the NYSE by estimating the explanatory power of London and Tokyo daytime returns and volatility for the US overnight return. A decomposed R-squared for each opening price equation gives the proportion of variation that is due to earlier daytime returns from each foreign city, and one-step-ahead variance decompositions likewise set out the impact of volatility spillovers.

[6] Appendix B sets out results of tests for the profitability of filter rules based on significant predictability in the estimated models. Gains do not exceed even modest transactions costs.

2. Data

We proxy returns to well-diversified portfolios of stocks on the New York, Tokyo and London exchanges using intra-daily[7] (half-hour interval) data for the S&P 500, Nikkei 225 and FTSE 100 over the period January 5th, 1996 – March 22nd, 2005. All prices are measured in domestic currency.[8] The S&P 500 and FTSE 100 are market capitalisation-weighted and the Nikkei 225 is a price-weighted index.

These major equity exchanges trade consecutively in time (apart from a two hour overlap between London and New York), a feature which we can exploit to map transmissions between the markets. The Tokyo exchange, which opens first on any calendar day, has no concurrent trading with the other two exchanges. Tokyo trades from 7:00 p.m.– 9:00 p.m. and from 10:30 p.m.-1:00 a.m. US Eastern Standard Time (EST). London trades from 3:00 a.m.-11:30 a.m. EST, and the New York Stock Exchange (NYSE) trades from 9:30 a.m.-4:00 p.m. EST. The NYSE and London share two hours of simultaneous trading between 9:30 a.m. and 11:30 a.m. (EST). We remove the effects of common trading hours between the London and New York markets by artificially ending the London day at 9:00 a.m. EST (2:00 p.m. London time), one half hour before the NYSE opens.[9] Figure 1 gives a representation of the sequence of trading hours.

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[7] Intra-daily time series data were provided by SIRCA, http://www.sirca.com.au.
[8] Becker, Finnerty and Gupta (1990) find that choice of currency is not important to results.
[9] Hamao, Masulis and Ng (1990) use a similar procedure.

[INSERT FIGURE 1 HERE]

Using the trading sequence shown in Figure 1, we calculate six series of daytime (open-close) returns for each market as: $r_t^{(o+i)-c} = \ln\left(P_t^c / P_t^{(o+i)}\right) \times 100$ where $i = \{0, 0.5, 1.0, 1.5, 2.0, 2.5\}$ hours. The first daytime return series is based on the initial opening price (i=0), and we then generate five additional series of daytime returns by moving the opening price forward in five half-hour increments (i.e. 30 minutes past the opening, 60 minutes past the opening, …, 150 minutes past the opening) while holding the closing price fixed. Table 1 presents summary statistics for the daytime returns.

[INSERT TABLE 1 HERE]

Table 1 reveals two patterns in daytime returns. Firstly, returns based on the initial opening price are the most volatile, but volatility declines at a non-linear rate as the day progresses. Conventional models of asset pricing, which assume regular, random news arrival, predict a linearly decreasing variance of returns as the time interval over which the return is calculated shortens. However the pattern of returns variance in Table 1 does not fit with regular news arrival: it is more consistent with a bunching of news at the opening of trade, followed by a short period of increased activity while the market processes overnight information. Secondly, of the six series of daytime returns, the initial open-close returns are smallest in all three markets, while average returns increase as the day progresses. In other words, the opening price index value is higher on average than price index values later in the day. The skewness coefficient is smallest for initial open-close returns in all three markets, which also confirms a relatively high average opening price. [10]

Overnight (close-open) returns are the opening price over the previous day's closing price: $r_t^{c-(o+i)} = \ln\left(P_t^{o+i} / P_{t-1}^{c}\right) \times 100$. We again move the opening price (now the numerator of the ratio) forward through the day by 30 minute steps, generating six overnight returns series for each market. Table 2 presents summary statistics for overnight returns. In the reverse patterns to the daytime returns series, volatility increases non-linearly with time, particularly early in the day, as is consistent with a backlog of overnight news being processed by the market in the first few hours of trade. Again, close-to-initial-open returns are generally larger that subsequent values, suggesting higher average prices at initial opening than further into the day.

[INSERT TABLE 2 HERE]

Figure 2 shows the relationship between the markets' trading sequence, the daytime returns and the overnight returns conditioning on one value of *i* the increment to the opening time. Daytime (open-close) returns correspond to separate, consecutive information flows, whereas overnight (close to open) returns should encompass information embedded in the daytime returns of the two markets which conduct business immediately prior to the opening of the third. In efficient markets, we would expect all daytime returns to have zero covariance with other daytime returns, but overnight returns to co-vary with the daytime returns of the markets

[10] Although all series exhibit excess kurtosis, this coefficient does not vary much across the first 150 minutes of trading.

which are operating immediately prior. The strength of return covariance and volatility spillovers into opening prices gives an indication of market integration.

[INSERT FIGURE 2 HERE]

3. Econometric Method

Summary statistics presented in Tables 1 and 2 indicate that overnight news is not always instantly and fully reflected in the first opening index value of a major market. Here we do not propose reasons for possible lags or frictions in daily information processing – we leave that to the extensive literature on microstructure – except to say that the lags prove to be commercially insignificant. Our aim to measure (to the nearest 30 minutes) how long after opening it takes for the daytime market index return to reach zero covariance with the news generated just prior to opening. Once we have an estimate of this time, we can more accurately measure integration between markets.

3.1. Modelling daytime returns linkages

If the markets adjust sluggishly and take time to absorb international news, then daytime (open-close) returns will be correlated across the markets. To test this hypothesis, we estimate a standard VAR-GARCH model with Glosten, Jagannathan and Runkle (1993) (GJR) asymmetry terms:

$$\begin{aligned} \mathbf{r_t} &= \mathbf{c} + \left(\Phi + \boldsymbol{\gamma}\mathbf{I_{t\text{-}1}}\right)\mathbf{r_{t\text{-}1}} + \boldsymbol{\theta}\mathbf{x_t} + \boldsymbol{\varepsilon}_\mathbf{t} \\ \boldsymbol{\varepsilon}_\mathbf{t} &= \mathbf{H}_\mathbf{t}^{1/2}\boldsymbol{\eta}_\mathbf{t}. \end{aligned} \qquad (1)$$

Elements of the daytime returns vector $\mathbf{r_t} = \begin{bmatrix} r_{1,t} & r_{2,t} & r_{3,t} \end{bmatrix}'$ are ordered by calendar time, so that Tokyo comes first, followed by New York and London. Φ and $\boldsymbol{\gamma}$ are (3×3) coefficient matrices that reflect information spillovers in returns. An asymmetric spillover coefficient vector $\boldsymbol{\gamma}$ is included in order to capture dynamics associated with negative shocks, where $\mathbf{I_t}$ is a (3×1) indicator function vector whose elements are equal to one when the news shock is negative and zero otherwise:

$$\mathbf{I}_{it} = \begin{cases} 1 | r_{it} < 0 \\ 0 | r_{it} \geq 0 \end{cases} \quad \text{for } i = \{1, 2, 3\}. \tag{2}$$

The innovation vector $\boldsymbol{\varepsilon_t} = \begin{bmatrix} \varepsilon_{1t} & \varepsilon_{2t} & \varepsilon_{3t} \end{bmatrix}'$ follows a multivariate GJR variance process with volatility spillovers. The standardised innovations $\boldsymbol{\eta_t}$ are normal white noise $\boldsymbol{\eta_t} \sim N(\mathbf{0}, \mathbf{I}_3)$. The (2×3) coefficient matrix $\boldsymbol{\theta}$ captures weekday seasonality given by a (2×1) dummy vector $\mathbf{x_t}$ where:

$$x_{1t} = \begin{cases} 1 \text{ if Monday} \\ 0 \text{ otherwise} \end{cases}$$

$$x_{2t} = \begin{cases} 1 \text{ if Tuesday} \\ 0 \text{ otherwise} \end{cases} \tag{3}$$

We estimate the elements of $\boldsymbol{\theta}$ associated with Monday dummies for the New York and London markets and the element related to the Tuesday dummy for the Tokyo market and set the other elements of $\boldsymbol{\theta}$ to zero.[11] Time subscripts in (1) indicate the temporal ordering in trading hours of the three exchanges. The daytime return for each market is explained by the immediately preceding daytime returns for the other two markets, and its own lagged return:

$$\begin{aligned}
r_{1,t} &= c_1 + \sum_{i=1}^{3}\left(\phi_{1i} + \gamma_{1i} I_{i,t-1}\right) r_{i,t-1} + \theta_{12} x_{2t} + \varepsilon_{1t} \\
r_{2,t} &= c_2 + \left(\phi_{21} + \gamma_{21} I_{1,t}\right) r_{1,t} + \sum_{i=2}^{3}\left(\phi_{2i} + \gamma_{2i} I_{i,t-1}\right) r_{i,t-1} + \theta_{21} x_{1t} + \varepsilon_{2t} \\
r_{3,t} &= c_3 + \sum_{i=1}^{2}\left(\phi_{3i} + \gamma_{3i} I_{i,t}\right) r_{i,t} + \left(\phi_{33} + \gamma_{33} I_{3,t-1}\right) r_{3,t-1} + \theta_{31} x_{1t} + \varepsilon_{3t}
\end{aligned} \tag{4}$$

The conditional variance vector $(diag\mathbf{H}_t)$ $\mathbf{h_t} = \left[h_{1t} \quad h_{2t} \quad h_{3t}\right]'$ is an asymmetric vector GJR (1, 1, 1) process with volatility spillovers:

$$\mathbf{h_t} = \boldsymbol{\omega} + \left(\boldsymbol{\alpha} + \boldsymbol{\delta}\boldsymbol{\Im}_{\mathbf{t-1}}\right)\left[\boldsymbol{\varepsilon}_{\mathbf{t-1}} \circ \boldsymbol{\varepsilon}_{\mathbf{t-1}}\right] + \boldsymbol{\beta}\mathbf{h}_{\mathbf{t}-1} + \boldsymbol{\chi}\mathbf{x_t}. \tag{5}$$

The '$\circ$' operator is the element by element multiplication operator, $\boldsymbol{\omega}$ is a (3×1) vector of intercepts, $\boldsymbol{\alpha}$ and $\boldsymbol{\delta}$ are (3×3) matrices of symmetric and asymmetric volatility spillover coefficients and $\boldsymbol{\beta}$ is a diagonal (3×3) matrix of GARCH coefficients. We define the indicator function $\Im_{\mathbf{t}}$ as

$$\Im_{it} = \begin{cases} 1 | \varepsilon_{it} < 0 \\ 0 | \varepsilon_{it} \geq 0 \end{cases} \quad \text{for } i = \{1,2,3\}, \tag{6}$$

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[11] While the Monday effect is studied in Engle, Ito, Lin (1990), French (1980) and Gibbons and Hess (1981), the so called Japanese-Tuesday effect has been studied in Kato (1990) who reports that Japanese returns are, on average, negative on Tuesdays.

and day of the week dummies for Monday and Tuesday in $\mathbf{x_t}$, and coefficients $\boldsymbol{\chi}$, as for (3). Time indexing corresponds to temporal ordering of trading. Individual conditional variance processes are:

$$\begin{aligned}
h_{1,t} &= \omega_1 + \sum_{i=1}^{3}\left(\alpha_{1i} + \delta_{1i} I_{i,t-1}\right)\varepsilon_{i,t-1}^2 + \beta_1 h_{1,t-1} + \chi_{12} x_{2t} \\
h_{2,t} &= \omega_2 + \left(\alpha_{21} + \delta_{21} I_{1,t}\right)\varepsilon_{1,t}^2 + \sum_{i=2}^{3}\left(\alpha_{2i} + \delta_{2i} I_{i,t-1}\right)\varepsilon_{i,t-1}^2 + \beta_2 h_{2,t-1} + \chi_{21} x_{1t} \\
h_{3,t} &= \omega_3 + \sum_{i=1}^{2}\left(\beta_{3i} + \delta_{3i} I_{i,t}\right)\varepsilon_{i,t}^2 + \left(\beta_{33} + \delta_{33} I_{3,t-1}\right)\varepsilon_{3,t-1}^2 + \beta_3 h_{3,t-1} + \chi_{31} x_{3t}
\end{aligned} \tag{7}$$

We estimate this model for each of the six daytime returns series, beginning with initial open-close returns and moving through to later periods of the day. Series with the same increment to opening time appear on both sides of the equations. After estimation, we can test for significant spillovers in returns, and then isolate, for each market, the point in each day where information from earlier international trade is fully processed into the price. For example, if estimated coefficients on the returns from prior trade in New York and London are insignificant explanators for the open + 60 minutes Tokyo return, but significant for the initial open and open + 30 minutes returns, then we can infer that information from international overnight news takes about 60 minutes to be fully reflected in the Tokyo price index.

3.2 Integration

Identifying the time when most overnight news is absorbed into the price index helps us measure integration more accurately. We measure integration by regressing lags of international and domestic market *daytime* returns on domestic market *opening price change* as captured by overnight returns. Because we choose the 'opening' price index that corresponds to complete information absorption for both daytime and overnight returns series, we can fully account for the impact of that previous news. By contrast, if we choose an 'opening' price that does not correspond to full information absorption, we may underestimate market integration.[12] Another advantage of this measurement technique is that since the explanatory variables in the returns equations have covariance that is insignificantly different from zero by construction, we can decompose the explained sum of squares into approximate proportions arising from each of the explanatory variables. We are then able to identify the source and size of spillover effects between markets.

Overnight returns follow a vector GJR (1, 1, 1) process where the explanatory variables are daytime returns:

$$\begin{aligned} \mathbf{r}_{\mathbf{t}}^{\mathbf{c\text{-}o*}} &= \mathbf{k} + \left(\boldsymbol{\psi} + \boldsymbol{\lambda}\mathbf{I}_{\mathbf{t\text{-}1}}\right)\mathbf{r}_{\mathbf{t\text{-}1}}^{\mathbf{o*\text{-}c}} + \boldsymbol{\rho}\mathbf{x}_{\mathbf{t}} + \mathbf{u}_{\mathbf{t}} \\ \mathbf{u}_{\mathbf{t}} &= \mathbf{G}_{\mathbf{t}}^{1/2}\boldsymbol{\upsilon}_{\mathbf{t}}. \end{aligned} \tag{8}$$

$\mathbf{r}_{\mathbf{t}}^{\mathbf{c\text{-}o*}}$ is a (3×1) vector of close-open returns which is specified in the temporal order of trading: Tokyo, London, New York. The asterisk in the superscript indicates that we have chosen returns corresponding to the full-absorption opening price for each market. Explanatory variables, $\mathbf{r}_{\mathbf{t\text{-}1}}^{\mathbf{o*\text{-}c}}$ are lagged values of daytime returns for each

[12] In addition, since the previous day's closing price appears as the denominator of the independent variable, our full-absorption daytime returns avoid a potential endogeneity problem.

market, again corresponding to the full-absorption opening price in each market, and $\mathbf{x_t}$ are day of week dummies, as defined in (3).[13]

The innovations vector $\mathbf{u_t}$ is an asymmetric vector GJR (1, 1, 1) process with volatility spillovers from daytime returns shocks. The standardised innovations $\boldsymbol{\upsilon}_\mathbf{t}$ are normal white noise $\boldsymbol{\upsilon}_\mathbf{t} \sim N\left(\mathbf{0}, \mathbf{I}_3\right)$. We model a vector of overnight conditional variances $(diag\mathbf{G}_t)$, $\mathbf{g}_\mathbf{t}^{\mathbf{c\text{-}o^*}} = \left[g_{1t}^{c-o^*}, g_{2t}^{c-o^*}, g_{3t}^{c-o^*}\right]'$ as:

$$\mathbf{g}_\mathbf{t}^{\mathbf{c\text{-}o^*}} = \boldsymbol{\mu} + \left(\boldsymbol{\gamma} + \boldsymbol{\sigma}\mathbf{I}^*_{\mathbf{t\text{-}1}}\right)\left[\mathbf{u}_\mathbf{t\text{-}1}^{\mathbf{c\text{-}o^*}} \circ \mathbf{u}_\mathbf{t\text{-}1}^{\mathbf{c\text{-}o^*}}\right] + \mathbf{b}\mathbf{g}_\mathbf{t\text{-}1}^{\mathbf{c\text{-}o^*}} + \left(\boldsymbol{\pi} + \boldsymbol{\xi}\Im_{\mathbf{t\text{-}1}}\right)\left[\boldsymbol{\varepsilon}_\mathbf{t\text{-}1}^{\mathbf{o^*\text{-}c}} \circ \boldsymbol{\varepsilon}_\mathbf{t\text{-}1}^{\mathbf{o^*\text{-}c}}\right] + \boldsymbol{\varsigma}\mathbf{x_t}, \qquad (9)$$

where $\boldsymbol{\mu}$ is a (3×1) vector of constants, $\boldsymbol{\gamma}$, and $\boldsymbol{\sigma}$ are diagonal matrices of symmetric and asymmetric ARCH terms, $\mathbf{b}$ is a diagonal matrix of GARCH coefficients, and $\boldsymbol{\pi}$ and $\boldsymbol{\xi}$ are (3×3) coefficient matrices of symmetric and asymmetric daytime volatility spillovers respectively. $\mathbf{x_t}$ in (8) and (9) is a vector of day of the week dummies as defined in (3), while $\boldsymbol{\rho}$ and $\boldsymbol{\varsigma}$ are coefficient matrices that multiply the week-day dummies in the mean and variance equations respectively. The indicator function $\mathbf{I}^*_{\mathbf{t\text{-}1}}$ isolates negative close-open returns as:

$$\mathbf{I}^*_{it} = \begin{cases} 1 \middle| u_{it}^{c-o^*} < 0 \\ 0 \middle| u_{it}^{c-o^*} \geq 0 \end{cases} \quad \text{for } i = \{1,2,3\}. \qquad (10)$$

[13] We also fit an MA(1) term in the mean equations (8).

We judge the effects of international financial integration by the size and statistical significance of estimated spillover coefficients: $\boldsymbol{\psi}$ and $\boldsymbol{\lambda}$ in returns and $\boldsymbol{\pi}$ and $\boldsymbol{\xi}$ in volatility.

4. Results

Firstly we identify the point after initial market opening at which daytime returns in the domestic market are not significantly explained by prior daytime returns from international or domestic sources. Once we find this point for each market, we use the corresponding daytime returns to better estimate the size and source of international market spillovers in mean and variance.

4.1 Estimating predictability in daytime returns

We begin by estimating the model in (1) to (7). Tables A.1-A.3 in Appendix A give detailed estimation results for Tokyo, London and New York, along with the usual diagnostics. In each case we use Bollerslev-Wooldridge (1992) robust standard errors in reported test statistics. Table 3 presents a summary of results.

[INSERT TABLE 3 HERE]

Tokyo receives information spillovers in daytime return from both London and New York as well as influences from its own previous day's return. The news from prior trade in London, represented by the lagged London daytime return, has predictive power for the Tokyo daytime return up to 30 minutes after opening. The lagged New York daytime return has predictive power for up to 90 minutes after the opening. Tokyo's own lagged daytime return has a statistically significant negative coefficient, which increases in magnitude about 90 minutes after the opening time in Tokyo and does not dissipate within the first 150 minutes of trading.

In conditional volatility, Tokyo appears to receive volatility spillovers from New York but not London. Further, volatility spillovers from New York are stronger when associated with negative news, and influence Tokyo's conditional volatility for up to one hour after opening.

Although the Tokyo market takes longer than 150 minutes of trading to fully process all available information, including its own lagged daytime return, it does process all *overnight* information within the first 90 minutes of trading. Therefore, for the purposes of evaluating effects of financial integration, we use a price recorded 90 minutes after the opening time to represent the daily return for Tokyo.

The previous period's New York daytime return has predictive power for London returns with a significant asymmetric component, whereas the Tokyo return does not. The symmetric impact of the New York returns on London becomes insignificant after 60 minutes of trading, whereas the asymmetric impact holds predictive power for another hour. Negative news contained in London's own lagged return is also significant for returns based on the first 120 minutes of trade.

Volatility spillovers from Tokyo and New York are significant for conditional volatility predictions in London. The volatility spillover from New York becomes insignificant within the first 30 minutes of trading and effects from Tokyo work through after about 120 minutes.

On the basis of these findings we judge the London market to have processed all overnight news within 120 minutes after opening and so we use the index value recorded at this time for the integration analysis that follows.

New York returns are predicted by overnight news for the least length of time of any of the three markets. Returns on the S&P 500 are predicted by overnight news emanating from London and Tokyo, but only for the first 30 minutes of trading. On the other hand, there appears to be a persistent negative autocorrelation with the previous day's domestic trade. Volatility spillovers from Tokyo and London are predictive for the New York conditional variance, and the predictive power still persists 150 minutes into the day.

Overall, the S&P 500 index absorbs foreign news quickly, and for the purposes of studying international financial integration, we select the open+30 minutes price index as an opening price reflecting overnight news.

On the face of it, results that indicate that stock market returns can be predicted using historical information appear to offer opportunities for arbitrage, and contradict the efficient markets hypothesis. However a simple application of filter rules using the predictability of returns from our model shows these results are of no commercial interest, a fact which at least partly explains their existence. Appendix B gives a complete description of the filtering test we applied and details of the results. Any small gains, where they exist, are almost certainly less than transactions costs.

4.2 Estimating opening price variation

If national stock markets are financially integrated then news shocks generated during the course of a trading day in one market, while the other markets are closed, will have a significant effect on early trading prices in the other markets. Here we measure the information transfer between markets through the impact of foreign daytime returns and variances on domestic opening price variation. Table 4 sets out unconditional correlation estimates between adjusted daytime returns. We can use the feature of zero correlation between explanatory variables to show the relative importance of one market for another, by decomposing the R-squared in returns regressions, and the news impact in conditional variance equations.

[INSERT TABLE 4 HERE]

Table 5 presents estimates of the model described by equations (8) and (9). Overnight news conveyed by foreign daytime returns significantly affects the adjusted opening price in each market.

[INSERT TABLE 5 HERE]

London and Tokyo daytime returns have a significant impact in New York, the stronger effect associated with the London return. The overnight return from New York also exhibits a negative moving average coefficient, reflecting the negative first order autocorrelation reported in daytime returns. New York also imports overnight volatility from Tokyo and London. The London daytime volatility shock produces a larger effect than Tokyo volatility, but New York variance responds more to negative news from Tokyo. (Domestic volatility associated with negative returns shocks also persists.) R-squared indicates that about 13 percent of the total variation in the New York opening price is explained by the right-hand-side variables.[14]

Opening price variation in Tokyo is related to prior returns from New York and London, as well as domestic market lags. Effects from New York are particularly strong for negative returns shocks. Asymmetric volatility spillovers from New York and London are also significant (at 10 percent) in the conditional variance estimates. About 15 percent of the total variation in overnight return in Tokyo is explained by the model.

The London stock market has the most predictable opening price variation: about 30 percent is explained by the model. Predictive power comes mainly from Tokyo and New York daytime returns.[15] London's conditional variance responds to asymmetric daytime volatility shocks from New York and domestic prior daytime volatility.

Diagnostic tests on residuals and squared residuals (D-W and Ljung-Box Q) are satisfactory in all three markets' equations. All three equations fail the Jarque-Bera normality test which justifies the use of Bollerslev-Wooldridge (1992) robust standard errors throughout this paper (Susmel and Engle 1994).

[14] New York is also the only market of the three that exhibits a statistically significant day of the week effect. A positive coefficient in the close-open return implies that, on average, the opening price increased following a weekend.

[15] London overnight return is also dependent on its negative first order moving average term. This may indicate that London over-reacts to overnight news initially but corrects the following day.

4.3 Decomposing the explained sum of squares

When explanatory variables are correlated it is difficult to attribute shares of the explanatory power of a model between regressors, however in this case, because we use full-absorption 'opening' index values which embed prior information, regressors are uncorrelated. (See Table 4 above.) By estimating equations (7) and (8) in stages, adding regressors at each stage, we can unpack the sources of explanation among the right hand side variables.[16] For precision and clarity we decompose the regression in stages, however our results are largely insensitive to the order at which explanatory variables are added.

Table 6 outlines the relative importance of information from each news source. Of the R-squared of 12.98 per cent for New York, 10.57 per cent is explained by the daytime return in London, or just over 81 per cent of the total. Of the remainder, 13.29 per cent of the R-squared is attributable to the daytime return in Tokyo and 5.29 per cent to New York's own daytime return, a moving average term and a Monday dummy.

[INSERT TABLE 6 HERE]

The strongest influence on Tokyo's overnight return is also the market that trades immediately prior to Tokyo, that is, New York. About 81 per cent of the total 15 per cent of variation is attributed to daytime return in New York. The daytime

[16] In principle, building up the regression in steps in not necessary, since where regressors are uncorrelated, the proportion of explained sum of squares (ESS) attributable to any regressor x_i is equal to $b_i^2 \sum_t \left(x_{it} - \overline{x}_i \right)^2$ where b_i is the estimated coefficient on x_i, and $\overline{x}_i$ is the sample mean.

return in London accounts for about 14 per cent of R^2, while the remaining explanatory power is due to Tokyo's daytime return and a moving average term.

Unlike New York and Tokyo, London's overnight return is best explained by a market that does not trade immediately prior. About 28 per cent of the variation in its return is explained by the daytime return in New York and only 2 per cent by the daytime return in Tokyo. This result suggests that Anglosphere linkages may be more influential for London than the timing of news arrival.

We now turn to influences on conditional variance for each market.

Domestic market factors are the major influence on conditional returns variances in all three markets. In terms of international volatility spillovers, New York exhibits the largest amount of predictability from foreign daytime volatility shocks. The volatility shock from London explains about 9 per cent of New York's one-step-ahead conditional variance, while the volatility shock from Tokyo explains only 0.5 per cent.

[INSERT TABLE 7 HERE]

Tokyo's conditional variance is largely unaffected by foreign daytime volatility shocks. New York's and London's volatility spillovers respectively account for only 2 per cent and 1.5 per cent of Tokyo's overnight conditional variance. London's overnight conditional volatility is mainly determined by its own volatility shocks, both overnight and daytime. New York volatility explains about 2 per cent of London's conditional variance. All statistically significant daytime volatility spillovers in both London and Tokyo are associated with negative market news.

5. Conclusions

We apply a new approach to gauging equity market linkages which takes into account non-instantaneous adjustments to overnight news. The approach has several advantages over previously used methods. Firstly, we explicitly test the data and ensure that preceding news has been absorbed by the market price on which returns are computed, before estimating financial market linkages, thus creating more accurate measures of return and volatility spillovers. Secondly, this adjustment process means that daytime returns from domestic and international markets within the one 24 hour period are uncorrelated, a property which allows us to break down the incremental impact of news from each market.

The New York market takes about 30 minutes of trade to absorb overnight news, while Tokyo and London take about 90 minutes and 120 minutes respectively. After accounting for non-instantaneous adjustment to overnight news we find significant amounts of predictability in the opening prices of the New York, Tokyo and London stock markets based on information provided by foreign daytime returns. In New York about 12 per cent of the close-open price change and about 9 per cent of conditional variance is explained by news which has come out of the London and Tokyo exchanges in the intervening period. London seems to be the most dependent on news out of international markets, with spillovers accounting for 29.5 per cent of the opening price variation. On the other hand, only 2 per cent of the London's overnight one-step ahead forecast variance is explained by daytime spillovers from New York and Tokyo. Lastly, Tokyo exhibits medium levels of dependence in both returns and volatility: 14 per cent of the return is explained by news embedded in the New York and London daytime returns, while 3 per cent of its conditional variance is explained by the foreign daytime volatility spillovers. Information transmission is mutual between all three markets; however the strongest effects emerge from New York, followed by London (which explains more than 10.5 percent of New York's overnight return). Tokyo accounts for only 1.7 per cent of New York and 2.1 per cent of London. Similar patterns hold for volatility: larger mutual interdependence between New York and London and only marginal spillovers from Tokyo.

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Table 1. Summary statistics: daytime (open-close) stock index returns (%).

	Opening Times	Std. Dev.	Mean	Skewness	Kurtosis
New York	Open	1.145	0.025	-0.092	5.480
	Open + 30min	0.971	0.025	0.239	8.255
	Open + 60min	0.896	0.037	0.196	7.277
	Open + 90min	0.834	0.029	0.044	6.990
	Open + 120min	0.789	0.034	0.061	5.784
	Open + 150min	0.757	0.036	0.016	6.231
Tokyo	Open	1.228	-0.065	0.028	4.915
	Open + 30min	1.044	-0.042	0.208	5.053
	Open + 60min	0.987	-0.058	0.344	5.606
	Open + 90min	0.909	-0.050	0.096	5.219
	Open + 120min	0.838	-0.032	0.134	4.960
	Open + 150min	0.837	-0.035	0.120	4.960
London	Open	0.862	-0.019	-0.671	8.602
	Open + 30min	0.696	-0.026	-0.375	6.146
	Open + 60min	0.626	-0.018	-0.304	5.397
	Open + 90min	0.563	-0.011	-0.381	6.098
	Open + 120min	0.506	-0.008	-0.368	6.081
	Open + 150min	0.461	-0.004	-0.440	6.186

Daytime returns are calculated as $r_t = 100\ln(p_t^c / p_t^o)$ where the opening price p_t^o is the index value recorded at the 'Opening Time' reported in column 2, sampling 5 January 1996 to 22 March 2005.

Table 2. Summary statistics: overnight (close-open) stock index returns (%).

	Opening Times	Std. Dev.	Mean	Skewness	Kurtosis
New York	Open	0.469	0.007	-0.749	64.750
	Open + 30min	0.783	0.008	-0.328	11.725
	Open + 60min	0.848	-0.004	-0.345	11.258
	Open + 90min	0.885	0.004	-0.222	8.969
	Open + 120min	0.928	-0.001	-0.267	8.523
	Open + 150min	0.958	-0.003	-0.150	7.551
Tokyo	Open	0.751	0.038	-0.089	20.428
	Open + 30min	1.098	0.016	-0.047	8.495
	Open + 60min	1.156	0.031	0.010	9.098
	Open + 90min	1.241	0.023	-0.113	8.385
	Open + 120min	1.307	0.006	-0.123	7.556
	Open + 150min	1.307	0.008	-0.106	7.385
London	Open	0.947	0.033	0.047	11.481
	Open + 30min	1.139	0.040	-0.450	13.490
	Open + 60min	1.149	0.032	-0.375	11.225
	Open + 90min	1.171	0.025	-0.400	10.828
	Open + 120min	1.202	0.023	-0.363	10.452
	Open + 150min	1.211	0.018	-0.271	9.567

Overnight returns are calculated as $r_t = 100\ln(p_t^o / p_{t-1}^c)$ where the opening price p_t^o is the index value recorded at the 'Opening Time' reported in column 2, sampling 5 January 1996 to 22 March 2005.

Table 3. Duration of information spillovers in daytime returns and volatility.

From/To:	**Tokyo**	**London**	**New York**
Spillover in Mean			
Tokyo	> 150 min	-	0 min – 30 min
London	0 min – 30 min	-	0 min – 30 min
New York	60 min – 90 min	30 min – 60 min	-
Tokyo Asymmetric	-	-	-
London Asymmetric	-	90 min – 120 min	-
New York Asymmetric	-	90 min – 120 min	> 150min
Spillover in Variance			
Tokyo	> 150 min	90 min – 120 min	90 min – 120 min
London	-	> 150 min	> 150min
New York	30 min – 60 min	-	0 min – 30 min
Tokyo Asymmetric	90 min – 120 min	60 min – 90 min	> 150 min
London Asymmetric	-	>150 min	> 150 min
New York Asymmetric	30 min – 60 min	0 min-30 min	> 150 min
GARCH (1)	> 150 min	>150min	> 150 min

Period after the opening at which spillover coefficients become insignificant at the 10% level. Grey shaded areas correspond to spillover coefficients that do not become insignificant within the first 2 ½ hours of trading.

Table 4. Unconditional (sample) correlation coefficients between daytime returns.

	New York	Tokyo	London
New York	**1.00**	**-0.04**	**0.03**
p-value	-	*0.14*	*0.19*
Tokyo	**-0.04**	**1.00**	**0.04**
p-value	*0.14*	-	*0.14*
London	**0.03**	**0.04**	**1.00**
p-value	*0.19*	*0.14*	-

Daytime returns are calculated as the log difference of closing price and a price recorded at 30 minutes after open for New York, 90 minutes after open for Tokyo and 120 minutes after open for London.

Table 5. Information spillovers from *daytime* to *overnight* returns and volatility

	New York		Tokyo		London	
	Coeff.	*p-value*	Coeff.	*p-value*	Coeff.	*p-value*
Spillover in return from:						
Tokyo	0.11	*0.000*	0.14	*0.010*	0.12	*0.001*
London	0.46	*0.000*	0.25	*0.009*	0.03	*0.717*
New York	0.03	*0.330*	0.34	*0.000*	0.52	*0.000*
Tokyo Asymmetric	0.00	*0.992*	-0.32	*0.000*	0.03	*0.592*
London Asymmetric	0.00	*0.974*	0.20	*0.191*	0.03	*0.805*
New York Asymmetric	0.00	*0.979*	0.21	*0.025*	0.13	*0.074*
Const.	0.02	*0.515*	0.02	*0.702*	0.08	*0.014*
MA(1)	-0.05	*0.057*	0.03	*0.129*	-0.09	*0.000*
Monday	0.07	*0.030*	-	-	0.02	*0.603*
Tuesday	-	-	0.00	*0.973*	-	-
Spillover in variance from:						
Tokyo	-0.02	*0.000*	0.04	*0.164*	-0.01	*0.357*
London	0.19	*0.057*	-0.06	*0.171*	0.00	*0.971*
New York	-0.01	*0.192*	-0.01	*0.673*	-0.01	*0.282*
Tokyo Asymmetric	0.05	*0.002*	-0.02	*0.642*	0.01	*0.607*
London Asymmetric	-0.04	*0.724*	0.14	*0.066*	0.27	*0.002*
New York Asymmetric	0.05	*0.003*	0.05	*0.085*	0.05	*0.073*
Const.	0.01	*0.04*	0.01	*0.07*	0.01	*0.01*
ARCH(1)	0.03	0.50	-0.01	0.20	0.01	0.39
ARCH(1) - Asymmetric	0.03	*0.55*	0.08	*0.00*	0.08	*0.00*
GARCH(1)	0.84	*0.00*	0.93	*0.00*	0.89	*0.00*
R-squared	12.90%		14.99%		30.12%	
Diagnostics on standardized residuals						
Durbin-Watson stat	2.04		2.04		2.03	
Ljung-Box (20)	15.17	*0.712*	16.09	*0.651*	17.41	*0.562*
Ljung-Box (20) squared residuals	6.75	*0.995*	15.56	*0.687*	10.69	*0.934*
Jarque-Bera	7802.32	*0.000*	528.60	*0.000*	580.48	*0.000*

The p-values reported are based on Bollerslev-Wooldridge (1992) robust standard errors. Grey areas mark statistical significance at 10 percent level. Estimation time period covered is 6 January 1996 to 22 March 2005, a total of 2037 observations. (Insignificant day of the week dummies were dropped from the variance equations without major changes to the estimation results.)

Table 6. Sequential build-up of R-squared in overnight returns

Dependent Variable:	New York		
Source of Variation	*Explained SS*	*R-squared*	% of R-squared explained
London	132.08	10.57%	81.42%
Increment due to Tokyo	21.56	1.73%	13.29%
Tokyo and London	153.64	12.29%	94.71%
Increment due to Other	8.59	0.69%	5.29%
London, Tokyo and Other	162.22	12.98%	100.00%
Dependent Variable:	**Tokyo**		
Source of Variation	*Explained SS*	*R-squared*	% of R-squared explained
New York	379.91	12.11%	80.64%
Increment due to London	66.15	2.11%	14.04%
New York and London	446.06	14.22%	94.68%
Increment due to Other	25.08	0.80%	5.32%
New York, London and Other	471.14	15.02%	100.00%
Dependent Variable:	**London**		
Source of Variation	*Explained SS*	*R-squared*	% of R-squared explained
Tokyo	44.26	1.50%	4.98%
Increment due to New York	822.89	27.97%	92.58%
Tokyo and New York	867.15	29.47%	97.56%
Increment due to Other	21.65	0.74%	2.44%
Tokyo, London and Other	888.80	30.21%	100.00%

Incremental Sums of Squares and R-squared are calculated by estimating equations (8) and (9) on a market that traded immediately before the dependent variable market first and then incrementing the information set to account for other markets and variables in a chronological order. For example, the New York overnight return is first regressed on London's daytime return, secondly on London's and Tokyo's daytime returns and lastly by all explanatory variables including New York's daytime return and day-of-the-week dummies. Explanatory variable "Other" refers to an ma(1) term, dependent variable's own daytime return and day of the week dummies (where statistically significant at 10 percent).

Table 7. One-step ahead opening price conditional variance decompositions

	New York	**Tokyo**	**London**
Daytime volatility shock from:			
New York	4.46%	1.94%	2.13%
Tokyo	0.53%	0.00%	0.00%
London	8.79%	1.45%	12.24%
Domestic	86.23%	96.61	85.63
Total	100.00%	100.00%	100.00%

We decompose the unconditional fitted variance by setting all conditional variance terms to their unconditional values and calculating the proportion of the total variance contributed by each spillover effect and domestic ARCH and GARCH effects. For example, if the model from (8) is given by $g_{it} = \mu_i + \gamma_i u_{it-1}^2 + b_i g_{it-1} + \sum_{j=1}^{3} \pi_j \varepsilon_{jt-1}^2$, where π_j represents an international volatility spillover coefficient, the unconditional variances (means of one-step-ahead residual variances for equations (5) and (9)) are denoted by h_i, and g_i respectively, and the daytime volatility spillover contribution to the total unconditional variance is $100 \times \pi_j \frac{1}{T} \sum_{t=2}^{T} \varepsilon_{j,t-1}^2 \Big/ g_i$. We sum the symmetric and asymmetric volatility spillovers into one spillover quantity for each market when calculating these proportions.

Figure 1: Trading hours of the Tokyo, London and New York Stock Exchanges (Eastern Standard Time)

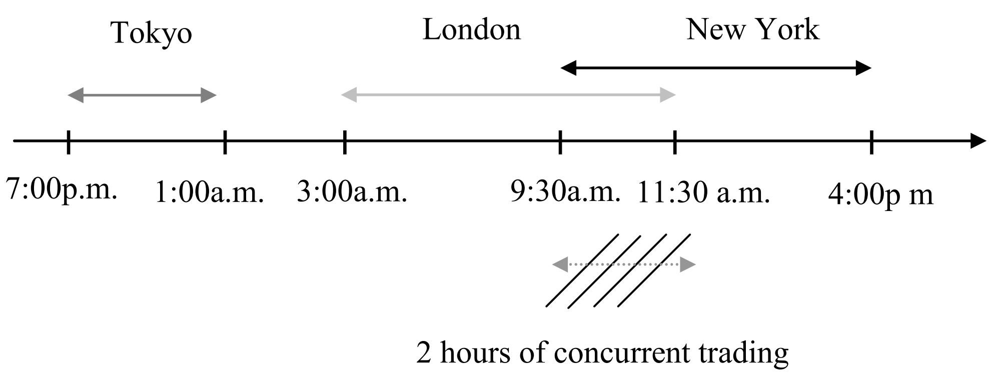
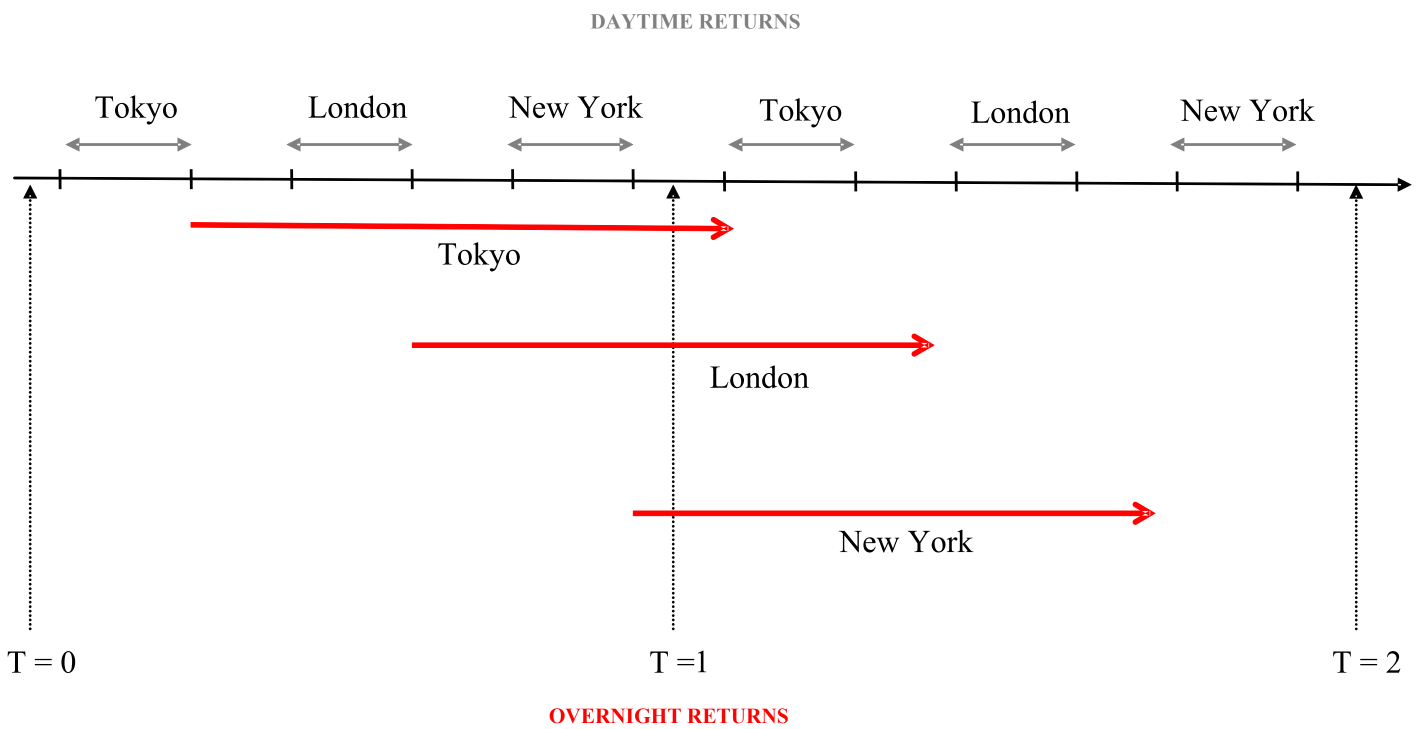


Figure 2: Sequence of trading hours: Daytime and Overnight returns.



Appendix A:Table A1. Spillovers to Tokyo's open-close returns and volatility

	Opening index value recorded at the ***opening*** time plus:											
Dependent Variable: **daytime Tokyo return**	**-**		**30 minutes**		**60 minutes**		**90 minutes**		**120 minutes**		**150 minutes**	
Spillover in Return from:	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*
Tokyo	-0.07	*0.095*	-0.03	*0.523*	-0.04	*0.350*	-0.09	*0.046*	-0.11	*0.012*	-0.11	*0.021*
London	0.13	*0.045*	0.10	*0.149*	0.10	*0.140*	0.05	*0.545*	0.07	*0.319*	0.04	*0.603*
New York	0.11	*0.014*	-0.07	*0.100*	-0.08	*0.060*	-0.04	*0.391*	-0.03	*0.494*	-0.04	*0.398*
Tokyo Asymmetric	-0.06	*0.409*	-0.06	*0.357*	-0.03	*0.689*	0.01	*0.880*	0.00	*0.973*	-0.02	*0.838*
London Asymmetric	-0.01	*0.936*	0.02	*0.886*	0.00	*0.975*	0.01	*0.932*	-0.02	*0.864*	0.04	*0.752*
New York Asymmetric	0.10	*0.170*	0.11	*0.131*	0.14	*0.048*	0.03	*0.637*	0.00	*0.949*	0.02	*0.725*
Spillover in Variance from:												
Tokyo	0.02	*0.134*	0.03	*0.018*	0.04	*0.010*	0.05	*0.012*	0.06	*0.001*	0.06	*0.002*
London	0.01	*0.590*	0.04	*0.274*	0.03	*0.496*	0.07	*0.354*	0.05	*0.240*	0.07	*0.218*
New York	-0.02	*0.062*	-0.03	*0.089*	-0.01	*0.617*	0.01	*0.760*	0.00	*0.919*	0.01	*0.483*
Tokyo Asymmetric	0.07	*0.004*	0.04	*0.053*	0.07	*0.016*	0.07	*0.017*	0.04	*0.183*	0.04	*0.185*
London Asymmetric	0.05	*0.250*	0.01	*0.861*	0.03	*0.721*	0.01	*0.951*	0.02	*0.743*	0.00	*0.993*
New York Asymmetric	0.04	*0.029*	0.05	*0.037*	0.03	*0.274*	0.01	*0.789*	0.01	*0.828*	-0.01	*0.719*
GARCH(1)	0.90	*0.000*	0.90	*0.000*	0.87	*0.000*	0.83	*0.000*	0.86	*0.000*	0.86	*0.000*
R Squared	4.82%		1.16%		0.84%		0.72%		1.17%		1.18%	
Diagnostics on standardized residuals												
Ljung-Box (20)	16.38	*0.693*	24.74	*0.212*	29.34	*0.081*	24.35	*0.227*	25.94	*0.168*	21.31	*0.379*
Ljung-Box squared residual (20)	9.32	*0.979*	11.20	*0.941*	21.66	*0.359*	13.08	*0.874*	13.48	*0.856*	14.18	*0.821*
Jarque-Bera	33.48	*0.000*	144.40	*0.000*	158.79	*0.000*	191.00	*0.000*	168.63	*0.000*	189.60	*0.000*

Daytime returns are calculated as open-close logarithmic returns, where the closing price was held constant and the opening index value recorded at times as indicated in the column headings. Bollerslev-Wooldridge (1992) standard errors used to calculate p-values. Estimation time period covered is 6 January 1996 to 22 March 2005, a total of 2037 observations.

Table A.2. Spillovers to London's open-close returns and volatility

Dependent Variable: **daytime London return**	Opening index value recorded at the ***opening*** time plus: **-**		**30 minutes**		**60 minutes**		**90 minutes**		**120 minutes**		**150 minutes**	
Spillover in Return from:	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*
Tokyo	0.02	*0.519*	-0.01	*0.822*	0.02	*0.473*	0.03	*0.252*	0.02	*0.298*	0.02	*0.410*
London	0.04	*0.340*	0.05	*0.239*	0.06	*0.199*	0.05	*0.199*	0.03	*0.452*	0.03	*0.515*
New York	-0.03	*0.340*	-0.05	*0.092*	-0.03	*0.196*	-0.03	*0.319*	0.00	*0.849*	0.02	*0.442*
Tokyo Asymmetric	0.05	*0.232*	0.04	*0.271*	0.01	*0.869*	-0.01	*0.859*	-0.03	*0.405*	-0.02	*0.479*
London Asymmetric	-0.19	*0.005*	-0.15	*0.035*	-0.12	*0.091*	-0.13	*0.059*	-0.04	*0.579*	0.01	*0.918*
New York Asymmetric	0.15	*0.003*	0.11	*0.021*	0.10	*0.024*	0.09	*0.027*	0.04	*0.303*	0.00	*0.945*
Spillover in Variance from:												
Tokyo	0.00	*0.366*	0.00	*0.153*	-0.005	*0.006*	0.00	*0.088*	0.00	*0.710*	0.00	*0.325*
London	0.05	*0.003*	0.04	*0.005*	0.04	*0.005*	0.05	*0.001*	0.06	*0.000*	0.06	*0.000*
New York	0.00	*0.470*	0.00	*0.869*	0.00	*0.911*	0.00	*0.719*	0.00	*0.531*	0.00	*0.346*
Tokyo Asymmetric	0.01	*0.094*	0.01	*0.029*	0.01	*0.008*	0.00	*0.194*	0.00	*0.777*	0.00	*0.516*
London Asymmetric	0.04	*0.031*	0.01	*0.489*	0.00	*0.777*	0.00	*0.743*	-0.03	*0.048*	-0.03	*0.095*
New York Asymmetric	0.03	*0.005*	0.03	*0.012*	0.01	*0.105*	0.01	*0.223*	0.01	*0.305*	0.00	*0.461*
GARCH(1)	0.91	*0.000*	0.92	*0.000*	0.94	*0.000*	0.94	*0.000*	0.94	*0.000*	0.94	*0.000*
Monday	-0.07	*0.000*	-0.07	*0.000*	-0.06	*0.000*	-0.05	*0.000*	-0.04	*0.000*	-0.04	*0.000*
R Squared	4.11%		0.67%		0.54%		0.84%		0.16%		0.12%	
Diagnostics on standardized residuals												
Ljung-Box (20)	19.80	*0.470*	22.69	*0.304*	11.84	*0.921*	15.47	*0.749*	13.54	*0.853*	14.22	*0.819*
Ljung-Box squared residual (20)	18.83	*0.533*	18.22	*0.573*	17.20	*0.640*	19.48	*0.491*	15.39	*0.754*	10.28	*0.963*
Jarque-Berra	109.91	*0.000*	116.22	*0.000*	132.78	*0.000*	240.02	*0.000*	353.05	*0.000*	426.75	*0.000*

Daytime returns are calculated as open-close logarithmic returns, where the closing price was held constant and the opening index value recorded at times as indicated in the column headings. Bollerslev-Wooldridge (1992) standard errors used to calculate p-values. Estimation time period covered is 6 January 1996 to 22 March 2005, a total of 2037 observations.

Table A3. Spillovers to New York's open-close returns and volatility

Dependent Variable: **daytime New York return**	Opening index value recorded at the ***opening*** time plus: **-**		**30 minutes**		**60 minutes**		**90 minutes**		**120 minutes**		**150 minutes**	
Spillover in Return from:	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*	coeff.	*p-value*
Tokyo	0.07	*0.04*	0.04	*0.36*	0.00	*0.92*	0.01	*0.80*	-0.02	*0.57*	0.01	*0.84*
London	0.32	*0.00*	0.04	*0.53*	0.01	*0.86*	-0.01	*0.83*	0.06	*0.42*	0.01	*0.83*
New York	0.06	*0.15*	0.04	*0.36*	0.01	*0.85*	0.00	*0.98*	-0.01	*0.72*	-0.04	*0.37*
Tokyo Asymmetric	-0.01	*0.86*	-0.04	*0.47*	0.00	*0.95*	-0.03	*0.57*	0.00	*0.94*	-0.01	*0.86*
London Asymmetric	0.05	*0.55*	0.00	*0.97*	0.06	*0.52*	0.09	*0.37*	-0.05	*0.62*	-0.02	*0.82*
New York Asymmetric	-0.13	*0.07*	-0.09	*0.27*	-0.11	*0.12*	-0.16	*0.03*	-0.15	*0.03*	-0.14	*0.04*
Spillover in Variance from:												
Tokyo	-0.01	*0.44*	0.00	*0.95*	-0.01	*0.01*	-0.01	*0.04*	-0.01	*0.17*	0.00	*0.59*
London	-0.02	*0.07*	0.03	*0.17*	0.06	*0.05*	0.08	*0.02*	0.06	*0.06*	0.07	*0.07*
New York	-0.03	*0.08*	-0.01	*0.42*	-0.01	*0.40*	-0.01	*0.39*	-0.01	*0.41*	-0.01	*0.63*
Tokyo Asymmetric	0.03	*0.04*	0.01	*0.28*	0.04	*0.00*	0.04	*0.00*	0.04	*0.00*	0.03	*0.02*
London Asymmetric	0.16	*0.00*	0.09	*0.02*	0.10	*0.04*	0.08	*0.11*	0.07	*0.19*	0.14	*0.06*
New York Asymmetric	0.18	*0.00*	0.15	*0.00*	0.13	*0.00*	0.13	*0.00*	0.10	*0.00*	0.11	*0.00*
GARCH(1)	0.87	*0.00*	0.86	*0.00*	0.86	*0.00*	0.85	*0.00*	0.89	*0.00*	0.85	*0.00*
R Squared	6.69%		0.60%		0.95%		1.71%		2.09%		2.41%	
Diagnostics on standardized residuals												
Ljung-Box (20)	31.39	*0.050*	18.37	*0.563*	21.44	*0.372*	25.94	*0.168*	27.91	*0.111*	27.67	*0.118*
Ljung-Box squared residual (20)	10.84	*0.950*	8.15	*0.991*	12.93	*0.880*	17.29	*0.634*	15.93	*0.721*	12.86	*0.884*
Jarque-Berra	26.51	*0.000*	81.44	*0.000*	56.95	*0.000*	104.52	*0.000*	116.36	*0.000*	120.84	*0.000*

Daytime returns are calculated as open-close logarithmic returns, where the closing price was held constant and the opening index value recorded at times as indicated in the column headings. Bollerslev-Wooldridge (1992) standard errors used to calculate p-values. Estimation time period covered is 6 January 1996 to 22 March 2005, a total of 2037 observations.

Appendix B: Filter rule test for profitable arbitrage

Where statistically significant return spillovers are detected, we perform a filter rule profitability test. For example, if the estimated New York return equation from (1) is found to have statistically significant positive spillovers from Tokyo and London, we implement a filter rule that buys S&P 500 following a positive return in Tokyo and London. Alternatively, we sell short S&P 500 if Tokyo and London markets registered a negative daytime return. The trigger to buy (or short sell) is defined as an up or down movement of pre-specified size observed in all variables included in the filter rule. For, example, for the London and Tokyo positive daytime returns to indicate a buying signal for New York, then both of these markets will need to increase by more than a specified filter amount (e.g., 0.25 %). Markets show semi-strong form inefficiency where the filter generates abnormal returns (after transaction costs are taken into account) in excess of the buy and hold strategy.

Table B reports average daytime returns based on four filter rule strategies. In the New York market, the filter trading strategies fail to predict market direction resulting in negative average daytime returns in many cases. In fact, any transaction cost greater than 0.11% (0.22% round trip cost) of the amount invested results in a negative average filter rule daytime return in New York. In London, we use a filter rule which initiates trade when negative daytime returns are recorded in Tokyo (same day) and New York (previous day). The rule results in negative returns if transaction costs exceed 0.12 percent.

Tokyo offers the highest returns, with the filter rules producing mostly positive average returns. The buy-and-hold strategy on the other hand results in negative average returns. Further, the filter generates larger average returns when it is associated with negative news in other markets, (i.e. short-selling of Nikkei 225) than with positive. However, if transaction costs exceed 0.33%, the average filter rule returns turn negative. We conclude that the filter rules applied here frequently predict market direction correctly, but generate negative profits after transaction costs are taken into account. Our results are consistent with the findings of Becker, Finnerty and Gupta (1990).

Table B1. Filter rule profitability tests of daytime ("open"-close) returns

"Opening" price recorded at:	Market	-0.50% FILTER (% mean return)	-0.25% FILTER (% mean return)	0.25% FILTER (% mean return)	0.50% FILTER (% mean return)	Buy and Hold Strategy (% mean return)
Opening time	**New York**	**-0.31**	**-0.17**	**-0.08**	**-0.59**	0.02
	no. of signals	*(39)*	*(76)*	*(78)*	*(25)*	
	Tokyo	**0.66**	**0.46**	**0.40**	**0.44**	-0.06
	no. of signals	*(47)*	*(104)*	*(142)*	*(59)*	
	London	**-**	**-**	**0.21**	**0.13**	-0.02
	no. of signals	-	-	*(205)*	*(98)*	
½ hours after the open	**New York**	**-0.06**	**0.03**	**-0.01**	**-0.18**	0.02
	no. of signals	*(49)*	*(106)*	*(90)*	*(24)*	
	Tokyo	**0.07**	**0.07**	**-0.03**	**-0.06**	-0.04
	no. of signals	*(579)*	*(805)*	*(733)*	*(528)*	
	London	**-**	**-**	**-0.01**	**0.02**	-0.03
	no. of signals	-	-	*(240)*	*(124)*	
1 hour after the open	**New York**	**-0.25**	**-0.17**	**0.09**	**-0.14**	0.04
	no. of signals	*(38)*	*(101)*	*(75)*	*(21)*	
	Tokyo	**0.07**	**0.07**	**-0.08**	**-0.08**	-0.06
	no. of signals	*(563)*	*(806)*	*(706)*	*(487)*	
	London	**-**	**-**	**-0.03**	**-0.03**	-0.02
	no. of signals	-	-	*(226)*	*(109)*	
1 ½ hours after the open	**New York**	**-0.01**	**0.01**	**0.11**	**0.12**	0.03
	no. of signals	*(522)*	*(786)*	*(694)*	*(456)*	
	Tokyo	**0.14**	**0.11**	**0.00**	**0.03**	-0.05
	no. of signals	*(486)*	*(716)*	*(800)*	*(583)*	
	London	**-**	**-**	**-**	**-**	-0.01
	no. of signals	-	-	-	-	
2 hours after the open	**New York**	**0.02**	**0.01**	**0.10**	**0.17**	0.03
	no. of signals	*(493)*	*(737)*	*(673)*	*(423)*	
	Tokyo	**0.15**	**0.12**	**0.03**	**0.07**	-0.03
	no. of signals	*(474)*	*(696)*	*(779)*	*(528)*	
	London	**-**	**-**	**-**	**-**	-0.01
	no. of signals	-	-	-	-	
2 ½ hours after the open	**New York**	**0.03**	**0.03**	**0.12**	**0.21**	0.04
	no. of signals	*(472)*	*(740)*	*(653)*	*(412)*	
	Tokyo	**0.14**	**0.12**	**0.03**	**0.07**	-0.03
	no. of signals	*(466)*	*(695)*	*(781)*	*(529)*	
	London	**-**	**-**	**-**	**-**	0.00
	no. of signals	-	-	-	-	

Filter rules are formed from results presented in Table 4.3 and A4.1 – A4.3. If a return spillover is found statistically significant and positive a filter rule is formed by making a buy decision when the spillover is greater than 0.25 or 0.50 percent and a sell decision if the spillover is less than -0.25 and 0.50%. A rule is implemented only when all spillovers exceed a specified threshold. The "-" symbol indicates that no statistically significant spillovers are estimated for the corresponding return and hence no filter rule constructed.