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The Contribution of a Satellite Market to Price Discovery: Evidence from the Singapore Exchange

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The contribution of a satellite market to price discovery: Evidence from the Singapore exchange

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The Singapore Exchange (SGX), a small satellite market, successfully competes with a large home market, the Osaka Securities Exchange (OSE), in trading the Nikkei 225 futures index. In this paper, we investigate the contribution of the SGX to price discovery and shed light on the reasons for its continued success. Evidence is provided from information revelation and price discovery of three competing but informationally linked markets of the Nikkei 225 index-domestic spot (Tokyo Stock Exchange), domestic futures (OSE), and foreign futures (SGX), which represents the satellite market. Overall, the futures market contributes 77% to price discovery, with the satellite market contributing 42% of the futures and 33% of the total price discovery. These figures, surprisingly, far exceed the satellite market's share of trading volume. Support is provided for the extended trading hours on the SGX for three of the four non-overlapping trading sub-periods.

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INTRODUCTION

When a security is traded on multiple markets that are open contemporaneously, market participants may choose where to trade to exploit information. An investor who wants to trade the Nikkei 225 stock index, for example, can do so on the spot market in Tokyo and, during the same trading hours, on the futures market in Osaka or Singapore. Where frictionless and continuous information sharing across markets exist, trades can take place seamlessly on a single market with simultaneous changes in the stock, index, and derivative prices. If markets are not frictionless, one market may be more attractive than another because of differences in transaction costs, regulations or liquidity, resulting in differences in price discovery across the various markets.

This paper investigates the location of price discovery for the Nikkei 225 index on three informationally linked markets—the domestic spot market of the Tokyo Stock Exchange (TSE), and two futures markets, the Osaka Securities Exchange (OSE) and the Singapore Exchange (SGX), which represents the satellite market. The proportion of price discovery attributed to each market is estimated using both the Gonzalo and Granger (1995) common factor components method and the Hasbrouck (1995) information shares method on overlapping trading hours in an intraday setting.

Herbst, McCormack, and West (1987); Kawaller, Koch, and Koch (1987); Stoll and Whaley (1990); Chan (1992); Dwyer, Locke, and Yu (1996); Fleming, Ostdiek, and Whaley (1996); and Martens, Kofman, and Vorst (1998) report that S&P 500 Index futures price changes lead those on the spot market by five to 45 minutes. In contrast, there is weak evidence that spot index price changes lead futures price changes. Lihara, Kato, and Tokunaga (1996) find that the futures market leads the spot market by up to 20 minutes in Japan but that the spot market leads the futures market by up to five minutes. This lead-lag relationship between futures and spot index markets is usually explained by low overall transaction costs, no short sales restrictions, and high leverage on the futures market. Though infrequent trading in the index component stocks causes spurious lead-lag effects, Chan (1992) and De Jong and Nijman (1997) show that it cannot completely explain the lead-lag relation. Moreover, Tse (1999) provides evidence from the Dow Jones Industrial Average (DJIA) spot and futures that most of the price discovery takes place on the futures market. In contrast, Booth, So, and Tse (1999) find that the price discovery role is shared about equally by the spot and futures markets, with no role for the options market.

The price behavior of dually listed securities has also been investigated. Grammig, Melvin, and Schlag (2001) look at the price discovery in internationally traded stocks and find that, for German stocks cross-listed in the United Staes, at least 80% of price discovery takes place at home. Ding et al. (1999) examine the relative price discovery contributed by the stock of a large company traded in Malaysia (home market) and in Singapore. They show that, while 70% of price discovery occurs on the home market, the 30% of price discovery attributable to the foreign market is statistically significant and exceeds Singapore's share of the trading volume. Using minute-by-minute transaction prices for a two-week period, Shyy and Lee (1995) investigate the price transmission of the Bund futures between the London International Financial Futures Exchange (LIFFE) and the Deutsche Terminborse (DTB). They find a unidirectional lead of two minutes from the DTB to the LIFFE. Using both the Hasbrouck and Gonzalo-Granger methodologies, as in our study, Roope and Zurbruegg (2002) find that price discovery primarily originates in the Singapore Exchange for the Taiwan Index Futures, which trades in both Singapore and Taiwan.

The information transmission among three futures markets, i.e., the Osaka Securities Exchange, the Singapore Exchange, and the Chicago Mercantile Exchange, has been explored by Booth, Lee, and Tse (1996). Using daily closing prices of the Nikkei 225 Index futures contract from 1990 to 1994, they find that none of the three markets can be considered the main source of information flow. Our study is different from that of Booth et al. in several ways. Their study dealt mainly with the lead-lag relations among the three markets, whereas our paper focuses on price discovery using a different research methodology. We quantify the contribution of each market (information shares) using two distinct methodologies and provide evidence of the price discovery process for the SGX during the non-overlapping trading periods. In addition to the inclusion of spot market data, we utilize tick data instead of daily data. Our conclusions are also different. We report that the satellite market (SGX) contributes disproportionately higher to price discovery in terms of its share of market trading volume. Furthermore, a key difference is that all three markets trade in the same time zone, whereas the CME data used by Booth et al. (1996) occur in a different time zone. As such, we are able to more accurately reflect the markets' relative information shares.

This paper presents a novel approach to assessing the intraday price discovery process for the Nikkei 225 spot index traded on the TSE, and the futures contracts traded simultaneously on the OSE and SGX. It examines the relative contribution of the futures market to price discovery compared to the spot market, and the role of the competing foreign futures market (the SGX in this case) in the price formation process. The extant literature already described provides evidence that the futures market leads the spot market. Thus, the futures market is expected to have a larger contribution to price discovery than the spot market.

In the futures markets, the source of information flow is often uncertain. There are several reasons for expecting a significant information share by the futures market in Osaka. First, the OSE is located in the home country of the cash instrument. Empirical evidence from international cross listings suggests that price discovery takes place mainly on the home market (e.g., Grammig, Melvin, and Schlag, 2001). Second, the OSE is also a more liquid market than the SGX as it captures about 75% of the total annual trading volume of Nikkei 225 Index futures traded on both markets.[1] Third, financial centers have scale economies that attract trades which increase liquidity and depth, leading to an even more attractive market.

In contrast, there are several attractive institutional characteristics of the SGX that contribute to a larger information share on the SGX compared to the OSE such as lower transaction costs and longer trading hours. Moreover, the SGX has fewer trading restrictions than the OSE, including greater accessibility to foreigners. The *trading cost hypothesis* proposed by Fleming, Ostdiek, and Whaley (1996) suggests that the market with the lowest overall trading cost will react the fastest to new information. However, the two exchanges have different trading systems. The OSE uses a computer auction trading system, whereas the SGX trades through open outcry.[2] Shyy and Shen (1997) find no conclusive evidence that either the SGX open outcry or the OSE computer auction trading system dominates the price discovery process in

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[1] In 2000, the annual trading volume of the Nikkei 225 futures in OSE and SGX were about 7.4 million contracts and 2.2 million contracts, respectively.

[2] The SGX Nikkei 225 futures contracts also trade on the Electronic Trading System (ETS) from 4:00 pm to 8:00 pm, Tokyo time. Electronic trading on the SGX accounts for less than 10% of total volume.

Japanese Government Bond and Nikkei 225 index futures. However, Frino, McInish, and Toner (1998), Martens (1998), and Tse and Zabotina (2001) find that a market with an open outcry mechanism has a higher market quality and pricing efficiency than one with a computer auction trading system, especially during volatile periods. This finding explains the appeal of the SGX to some investors. Thus, there appears to be reasons to expect a significant contribution of both the Osaka and Singapore markets to the price discovery process on the futures markets.

The contribution of each market to the price discovery is assessed using the Gonzalo and Granger (1995) common factor component approach as well as the Hasbrouck (1995) information share method. The results show that the proportion of information attributable to the Nikkei 225 spot market averages 23%, to the OSE futures market, 44%, and to the SGX futures market, 33%. Furthermore, the futures market, with a 77% information share, dominates the spot market's share of 23%. The findings on the contribution to price discovery are remarkable in that the SGX accounts for 42% of the total information share due to futures trading, which far exceeds its share of trading volume of 24%. This result suggests that the SGX appeals not only to liquidity traders, but also to informed traders who execute a significant amount of their deals through the smaller satellite market. The paper provides a detailed discussion of the institutional differences between the two exchanges that explains the appeal of the SGX to a segment of informed traders. The evidence suggests that a small satellite market can co-exist with a larger home market and play a key role in price discovery through a careful design of the trading mechanism and contract specifications.

The remainder of the paper is structured as follows. The next section presents the sample data and institutional details of the various markets. The subsequent section discusses the cointegration tests followed by a section that explores the price discovery process. The fifth section reports the results of the multivariate Granger causality tests. The final section summarizes and concludes.

DATA AND INSTITUTIONAL DIFFERENCES

The Nikkei 225 index comprises 225 Japanese companies listed on the First Section of the Tokyo Stock Exchange (TSE). The SGX introduced trading of Nikkei 225 futures in September 1986, followed by the OSE in September 1988. Since then, the OSE has captured much of the

TABLE I
Annual Trading Volume for Nikkei 225 Futures Contract on OSE and SGX

	OSE		SGX	
Year	*Number of contracts*	*Percentage share*	*Number of contracts*	*Percentage share*
1992	11,927,329	88.86%	1,494,622	11.14%
1993	8,461,458	78.95%	2,255,519	21.05%
1994	6,208,754	68.16%	2,900,549	31.84%
1995	7,220,900	69.10%	3,228,492	30.90%
1996	7,043,977	74.24%	2,443,662	25.76%
1997	7,484,182	75.55%	2,422,248	24.45%
1998	8,191,130	74.74%	2,768,779	25.26%
1999	9,067,883	76.96%	2,714,922	23.04%
2000	7,426,478	76.81%	2,242,489	23.19%
Mean	8,114,677	75.93%	2,496,809	24.07%

Note. This table summarizes the annual trading volume in terms of the number of contracts for the Nikkei 225 futures contracts traded on the OSE and SGX. Since the contract size of each SGX contract (¥500 × index value) is half that of the OSE contract (¥1,000 × index value), the number of SGX contracts is divided by two to allow easy comparisons to the OSE.

trading volume (see Table I).[3] As the size of the contracts traded on the SGX is half those on the OSE, the SGX volume is halved for comparison with the OSE. In 2000, the OSE traded 7.4 million contracts and about 2.2 million (adjusted to OSE contract size) contracts were traded on the SGX, culminating in a market share for Osaka of more than three times that of Singapore.

In Japan, the TSE trades from 9:00 am to 3:00 pm (Tokyo time), and the OSE, from 9:00 am to 3:10 pm (Tokyo time). Both exchanges have a lunch break from 11:00 am to 12:30 pm. In contrast, the SGX is open from 8:55 am to 3:25 pm (Tokyo time) with a lunch break from 11:15 am to 12:15 pm. Thus, the Nikkei 225 is traded simultaneously on the OSE, the SGX, and the TSE, except for a window of between five to 15 minutes around the opening, lunch break, and closing time. The additional 50 minutes of trading on the SGX enveloping the entire trading hours of

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[3] The SGX share of the total trading volume has fluctuated over time. Before 1992, the OSE dominated the market. However, from January 1990 to August 1993, the OSE increased margins on four occasions, while the SGX decreased margins five times and increased margins twice. In December of 1993, margin requirements in the SGX were 15% of a contract's face value, versus 30% in Japan. Furthermore, the OSE also shortened its trading hours in 1992 to prevent market disorders at the closing. This was relaxed in 1997. As shown in Table I, the SGX captured more than 30% of the market share in 1994 and 1995. Its subsequent loss of market share is likely due to the fallout from the collapse of Baring Futures in Singapore in 1995 and the gradual reduction of margins by the OSE to 15% of contract's face value by 1995. Margins in the OSE were further reduced in 1997 by a major change in its method of computation.

the OSE allows for information flow from the OSE to the SGX where traders can continue to trade when the OSE is closed. This extra time may be important to liquidity traders, and this issue is explored in the last section of the paper. We compare the daily average number of trades on the SGX during the time when the OSE is closed against that over a comparable period when both exchanges are open. The daily average number of trades on the SGX over four sets of comparable time periods are: 8:55–9:00 am (47 trades) and 9:00–9:05 am (50 trades); 11:00–11:15 am (34 trades) and 10:45–11:00 am (92 trades); 12:15–12:30 pm (34 trades) and 12:30–12:45 pm (92 trades); and 3:10–3:25 pm (66 trades) and 2:55–3:10 pm (107 trades). The average trading activity on the SGX is lower by about 42% on average when the OSE is closed. It is observed that, during the time period 8:55–9:00 am and 9:00–9:05 am, the number of trades on the SGX is smaller by only 6%.[4] Nonetheless, trading on the SGX remains active even when the OSE is closed.

Although the Nikkei 225 futures on both the OSE and SGX use an identical underlying index, there are some key contract design and regulatory differences on the two exchanges. Table II provides a summary of these key differences. First, the OSE and the SGX use different trading mechanisms. The OSE employs a computer auction trading system without a designated market maker, whereas the SGX uses the traditional open outcry auction trading system with a large number of brokers/dealers during the trading hours of the OSE. Second, the OSE contract size of 1,000 yen times the underlying index is double that of the SGX. Even though a larger contract size on the OSE may appeal to institutional investors with large orders, a smaller contract size on the SGX means that traders are required to have a smaller capital base to trade.

Third, the minimum price fluctuation on the OSE is 10 index points compared to the SGX's five points, which is associated with a smaller bid-ask spread and lower transaction costs on the SGX. The average percentage bid-ask spread on the OSE of 0.069% is statistically different, at the 1% level, from the SGX's 0.040%.[5] The key institutional differences between the SGX and the OSE that might explain the observed differences in the percentage bid-ask spread are related to the size of the trading volume, the trading mechanism, and the minimum tick size.

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[4] This observation is in line with the evidence in the current literature that observes a higher trading volume when both exchanges in which a security is dual listed are open (see Chan, 2002; Chan, Chan, & Cheng, 2001).

[5] The percentage bid-ask spread (BAS) is computed by taking the difference between the quoted bid and ask prices and dividing it by the mid-quote of the bid and ask.

TABLE II
Nikkei 225 Futures: OSE and SGX

	OSE	*SGX*
Contract size	¥1000 times Nikkei Index	¥500 times Nikkei Index
Minimum fluctuation	10 index points	5 index points
Contract months	March, June, September, December (five nearest quarter months)	March, June, September, December (five nearest quarter months and three nearest serial months)
Daily price limit	Trading is restricted within a discrete price band of around 5% from the previous day's settlement price, depending on the futures index level: • Less than 20,000: 1,000 • 20,000–less than 30,000: 1,500 • 30,000–less than 40,000: 2,000 • 40,000 or more: 2,500	Whenever the price moves by 7.5%, in either direction from the previous day's settlement price, trading within the price limit of 7.5% is allowed for the next 15 minutes. Thereafter, an expanded price limit of 12.5% (above or below the previous day's settlement price) shall apply for the rest of the day.
Circuit breaker	Trading is halted if prices move by a certain amount from the previous day's settlement price, depending on the futures index level: • Less than 20,000: 700 • 20,000–less than 30,000: 1,000 • 30,000–less than 40,000: 1,300 • 40,000 or more: 1,600 Duration of halt is 15 minutes.	No trading halts
Commission costs (trading value)	0.04%	0.03%
Trading system	Computer automated trading	Open outcry
Trading hours (Tokyo time)		
Morning session	9:00 am–11:00 am	8:55 am–11:15 am
Afternoon session	12:30 pm–3:10 pm	12:15 pm–3:25 pm
		4:00 pm–8:00 pm (Computer automated trading)

Note. This table summarizes the differences in contract specifications and market structure of the Nikkei 225 futures contracts traded on the OSE and SGX.

The data reveals that the OSE has the largest share of trading volume and the widest bid-ask spread. While these observations are inconsistent with previous findings on other markets (e.g., McInish & Wood (1992) and Laux & Senchack (1992) that the spread is inversely related to trading volume, and Tse & Zabotina (2001) and Pirrong (1996) that the nominal trading cost is lower in a computerized trading system as on the OSE), they are not unexpected given the larger tick size on the OSE. Hence, the lower spreads in Singapore is attributable to the smaller minimum tick size.

Fourth, commission costs in Singapore are lower than in Osaka. The average commission cost is about 0.03% of the transaction value on the SGX and 0.04% on the OSE. Last, the SGX does not have a daily price limit that halts trading but has a more lenient circuit breaker that allows trading to continue within a restricted price band. This potentially leads to a more efficient dissemination of new information into the futures prices.

The data used in this paper contains the time-stamped market bid and ask quotes for the Nikkei 225 futures contracts traded in Osaka and Singapore, as well as the minute-by-minute underlying spot index, for the period March 13, 2000 to June 13, 2000.[6] Bid and asked quotes are used in order to avoid a potential bid-ask bounce that is well documented in the microstructure literature (e.g., Roll 1984). The study uses the contemporaneous trading hours of the three markets—TSE, OSE, and SGX—from 9:00 am to 11:00 am and 12:30 pm to 15:00 pm, Tokyo time. The futures price series is a logarithm of the average of the bid and ask quotes. From this, a series of prices at one-minute intervals is constructed, resulting in 16,505 observations per series. The one-minute frequency is chosen because it provides the highest frequency for the spot data. However, considering that the Nikkei contract is active in both Osaka and Singapore (an average of 13 trades per minute for Osaka and seven for Singapore), the non-synchronous effect is expected to be negligible. A further consideration is made for the contract expiration dates. During the sample period, only "nearby" contracts (excluding the expiration month) are used as they are the most actively traded.[7]

Table III provides summary statistics for the three return series. The results indicate that the price series are non-stationary and, based on the Augmented Dickey-Fuller tests, the return series are stationary. The return series have similar means and standard deviations, and have large kurtosis. Further, both the spot and the OSE series have a symmetric distribution

[6] The data was downloaded from the Bloomberg database. Bloomberg does not archive their high frequency data but keeps them for only 50 days.

[7] This decision is taken after visually inspecting the daily trade activities.

TABLE III
Descriptive Statistics of Returns

	Spot	*OSE*	*SGX*
Augmented Dickey-Fuller (log levels)	−0.72 (>0.05)	−0.65 (>0.05)	−0.66 (>0.05)
Augmented Dickey-Fuller (returns)	−44.32 (<0.001)	−55.84 (<0.001)	−54.89 (<0.001)
Mean ($\times 10^{-6}$)	−9.33	−9.5	−9.51
Standard Deviation	0.0008	0.001	0.00094
Skewness	−1.32	−1.14	−5.1
Excess kurtosis	46.9	74.36	50.7
Autocorrelation lag 1	0.081 (<0.001)	−0.117 (<0.001)	0.053 (<0.001)
Autocorrelation lag 12	−0.0014 (<0.001)	0.006 (<0.001)	−0.003 (<0.001)

Note. This table provides summary statistics for the one-minute return series from the three Nikkei 225 markets—Tokyo Stock Exchange spot index, Osaka Securities Exchange futures, and Singapore Exchange futures—for the period March 13, 2000 through June 13, 2000. The moments and autocorrelations correspond to the return series are also provided. The Augmented Dickey-Fuller tests are for the price level and return series. The futures price series is the natural logarithm of the average of the bid and ask quotes. *P* values are given in parentheses.

compared to the SGX series, which is negatively skewed. All the series show a strong autocorrelation at the first lag that declines significantly by the twelfth lag. Overall, the findings are typical for samples at one-minute intervals and are similar in magnitude with those in other studies.

TESTS FOR COINTEGRATION

Before estimating each market's contribution to price discovery, a test for cointegration among the three price series is carried out. We first determine the order of integration and optimal lag length for the system of equations formed by the series in the levels. Having confirmed the presence of non-stationarity in the price series in the previous section, the Schwarz (1978) Information Criterion (SIC) on the undifferenced VAR is used to identify the optimal lag length for use in the cointegration tests. Reimers (1991) finds that the SIC does well in selecting the optimal lag length. The longer lags are tested against the shorter lags and it is found that the SIC is minimized at six lags.

Next, we determine whether the series are cointegrated and establish the number of cointegrating vectors. This is done following the methodology proposed by Johansen (1988 and 1991) that requires the testing of the null hypotheses of at most zero, one or two cointegrating vectors using the trace and maximal eigenvalue statistics. The tests are conducted using a lag length of six, and estimations using four to eight lags show that the cointegration results are robust with respect to the number of lags. Table IV shows the Johansen cointegration test results for the three price series. Panel A of the table contains the results from a test for

TABLE IV

Cointegration Tests

H_0	*Trace test*	*Maximal eigenvalue test*
Panel A: Test for number of cointegrating relationships		
$r = 0$	448.74 (<0.0001)	396.78 (<0.0001)
$r \leq 1$	51.96 (<0.0001)	49.05 (<0.0001)
$r \leq 2$	2.91 (>0.0500)	2.9 (<0.0500)

Beta 1 (Spot)	*Beta 2 (OSE)*	*Beta 3 (SGX)*	*Sum of Betas*
Panel B: Number of cointegrating vectors: 2			
−25.10	−200.12	226.06	0.84
662.79	−651.02	−10.49	1.28

Note. This table presents the results from the Johansen (1991) cointegration tests on the Tokyo Stock Exchange Nikkei 225 spot index, the Osaka Securities Exchange futures, and the Singapore Exchange futures price series. Minute-by-minute prices of the three markets over the period from March 13, 2000 to June 13, 2000 are used. A lag length of six is used even though the cointegration results are robust with respect to the number of lags. Panel A contains the results of a test for the number of unique cointegrating relationships where *r* represents the number of cointegrating vectors. The Johansen procedure requires the testing of the hypotheses of at most zero, one or two cointegrating vectors using the trace or maximal eigenvalue tests. The results indicate two cointegrating vectors. Panel B contains the values for the estimated cointegrating vectors (the betas) and the sum of the betas. Note that, when the system is in equilibrium, the sum of betas should be close to zero. *P* values are in parentheses.

the number of unique cointegrating relationships. The null hypotheses of $r = 0$ and $r \leq 1$ cointegrating vectors are successfully rejected by both the trace and maximal eigenvalue tests, implying that the system has two cointegrated vectors and one common stochastic trend. Panel B of Table IV contains the values for the estimated cointegrating vectors (betas) and the sum of betas. Both cointegrating vectors have a sum of betas that is not different from zero, implying that none of the price series has deviated very far from the other and that the system is in equilibrium. According to the cost-of-carry relationship, spot and futures prices are cointegrated. Since the OSE and the SGX futures contracts have an identical underlying asset, their prices should move together, and arbitrage activity is expected to prevent them from drifting away from each other. Overall, the cost-of-carry relationship between the spot and futures prices and arbitrage activity explain the cointegration of these three series.

THE PRICE DISCOVERY PROCESS

Common Factor Components Method

This section investigates the contribution of each market to the price discovery process of the Nikkei 225 Index by using the common factor components approach of Gonzalo and Granger (1995) extended to financial markets by Harris, McInish, and Wood (2002) and Booth, So, and

Tse (1999). All three methods are based on a vector error correction (VEC) model, which separates the information based permanent common factor component of the prices from the transitory component due to microstructure noise. The ultimate goal is to calculate the proportion of the common factor innovation and the common factor weights (price discovery shares) attributable to each market.

If the three price vectors $P_{i,t}(i = 1 \text{ to } 3)$ are cointegrated, a fully specified VECM for the ith price of the three markets j is:

$$\Delta P_{i,t} = \sum_{j=1}^{3} \gamma_{i,j} \sum_{s=1}^{S} w_{t-s} + \sum_{j=1}^{3} \sum_{s=1}^{S} \gamma_{i,j,t-s}\, \Delta\varepsilon_{j,\,t-s} + \sum_{j\neq i}^{2} \alpha_{i,j}\, (\varepsilon_{i,\,t-1} - \varepsilon_{j,\,t-1}) + u_{i,t} \tag{1}$$

where the γ_j's are common factor weights for each market, Σw_{t-s} is the common stochastic trend, S is the optimal lag length, ε_j's are the idiosyncratic transitory disturbances, $\alpha_{i,\,j}$'s are the parameters corresponding to the error correction processes $(\varepsilon_{i,t-1} - \varepsilon_{j,t-1})$, and $u_{i,t}$ is the error term that may be serially correlated across markets. Equation (1) establishes that the price adjustment $\Delta P_{i,\,t}$ is a linear combination of permanent (the first term) and transitory (the latter three terms) components. Intuitively, since the vector of common factor weights is orthogonal to the coefficient vector α, the lower the $\alpha_{i,j}$ for market i, the higher the common factor weight $\alpha_{\perp j} \equiv \gamma_j$, and the larger the contribution of the jth market to the revelation of the innovations underlying the implicit efficient price in that ith price.

The factor weights are estimated by employing the following VECM:

$$\Delta P_{i,t} = c_i + \alpha_{i,1}(P_{\mathrm{OSE},t-1} - P_{\mathrm{SGX},t-1}) + \alpha_{i,2}(P_{\mathrm{OSE},t-1} - P_{\mathrm{SPOT},t-1}) + \sum_{i=1}^{3} \sum_{q=1}^{p} \gamma_{i,t-q} \Delta P_{i,t-q} + u_{i,t} \tag{2}$$

where 1, 2, and 3 correspond to the three Nikkei markets, spot, OSE and, SGX. By virtue of the permanent-transitory decomposition outlined above, the vector of common factor weights is calculated using the orthogonality condition $\alpha_\perp' \alpha = 0$ and α_{ij} estimates from Equation (2). The normalized vector of factor weights $\alpha_\perp$ provides the contribution of each market to the price discovery process.

As shown in panel A of Table V, about 46% of the price discovery occurs on the domestic futures market in Osaka, followed by the Singapore futures market with 33%. The remaining 21% of price discovery

TABLE V
Price Discovery Weights

	Spot	*OSE*	*SGX*
Panel A: Overall common long-memory weights and information share			
Common factor weights (%)	20.71	46.14	33.15
Mean information share (%)	26.76	39.15	34.09
Standard error	3.34	4.65	4.21
Lower bound	10.2	9.97	12.22
Upper bound	66.89	86.66	86.86
Panel B: Common long-memory weights and information share for first 10 minutes of trading			
Common factor weights (%)	18.24	39.94	41.82
Mean information share (%)	22.31	36.72	40.97
Standard error	3.16	4.27	4.08
Lower bound	8.74	12.43	16.31
Upper bound	59.65	82.49	89.1
Panel C: Common long-memory weights and information share for first 10 minutes of trading after the lunch break			
Common factor weights (%)	22.58	43.37	34.05
Mean information share (%)	25.04	38.63	36.33
Standard error	3.65	4.77	4.32
Lower bound	7.32	11.45	11.41
Upper bound	61.07	85.96	76.27

Note. Panel A presents the common long-memory weights estimated using the common factor component methodologies (Gonzalo & Granger, 1995; Harris, McInish & Wood, 2002) for each of the three markets—TSE spot, OSE futures, and SGX futures. The weights are interpreted as the contribution of each market to price discovery. The estimates are in percentage terms and are calculated from a vector error-correction model containing only one common factor and estimated using the minute-by-minute prices of the three markets over the period from March 13, 2000 to June 13, 2000. The mean, standard errors, and upper and lower bounds of the information share corresponding to each market following the methodology outlined by Hasbrouck (1995) are also provided. Panel B and C provide similar information during the first 10 minutes of trading at the beginning of the day and after the lunch break, respectively.

occurs on the domestic spot market in Tokyo. Over the sample period, the information share attributable to the futures market (both the OSE and the SGX) is 79%, whereas the spot market's share is 21%. These results indicate that the futures market plays the primary role in the price discovery process of the Nikkei 225 index, and are consistent with the lead-lag effects literature. The results support Tse's (1999) finding that the DJIA futures market contributes 90% of the price discovery but contradict Booth, So, and Tse (1999), who report an equal share for the spot and futures market in the German DAX equity index. However, Roope and Zurbruegg (2002) find that, using the Gonzalo-Granger methodology, the Singapore Exchange contributes four times more to price discovery for the Taiwan Index Futures than the Taiwan Futures Exchange.

More than one-third of the price discovery attributed to the futures market (33%/79% = 42%) in this study comes from Singapore. The importance of the SGX in the price formation process is somewhat surprising. Since Osaka is the home market of the cash instrument and the OSE trading volume is about three times that of the SGX, one would expect it to have a much larger proportion of the information share. However, the results indicate that there is a significant amount of informed trading originating in Singapore, albeit a small satellite market.

To add robustness to these findings, we investigate the contribution of the SGX to price discovery during the first 10 minutes of trading only. We note in panel B of Table V that, during the first 10 minutes of trading, the SGX contributed an even larger share of 42% to price discovery. What is noteworthy is that the SGX's contribution is greater than that of the OSE. Between the two exchanges, the SGX contributed 51% of the total price discovery attributed to the futures market, whereas the contribution of the cash market (TSE) is 18%.

There are several institutional differences between the SGX and the OSE that can explain the importance of the Singapore market to the price discovery process. First, the total trading costs on the SGX where the average bid-ask spread is 0.040% are lower than the 0.069% on the OSE. The lower spread on the SGX is likely due to the imposition of a smaller minimum tick size. The finding is consistent with Ito and Lin's (2001) evidence that the OSE has a higher total transaction cost, including margin requirements, than the SGX, contributing to the OSE's loss of market share to the SGX. It also supports the trading cost hypothesis of Fleming, Ostdiek, and Whaley (1996) that the market with the lowest overall trading cost will react most quickly to new information. The results are in congruence with the suggestion of Booth, Lee, and Tse (1996) that the market with a higher transaction cost would have a lower informational efficiency.

Second, the SGX employs an open outcry auction trading system during the overlapping trading period with the OSE, which uses an electronic auction trading system. Studies exploring the impact of trading mechanisms on information transmission markets (Shyy & Shen, 1997; Fremault-Vila & Sandmann, 1995) do not find support on the superiority of any one trading system. However, recent studies by Frino, McInish, and Toner (1998), Martens (1998), and Tse and Zabotina (2001) find that a market with an open outcry mechanism has a higher market quality than the electronic market during volatile periods. One possible explanation is that traders are unwilling to submit orders to an electronic system during volatile periods for fear of not being able to change them fast enough to cope with the pace of information arrival as old quotes have to be withdrawn before new ones can be entered. In contrast, traders on the floor are most active during volatile periods.[8]

Third, the SGX has no circuit breakers and imposes a more lenient daily price limit than the OSE. Berkman and Steenbeek (1998) show that the more lenient daily price limits on the SGX resulted in trades migrating to the SGX when the likelihood of hitting the price limit on the OSE increases. Thus, both the actual and potential order flow's migration to a less restrictive trading environment seem to have helped the SGX capture a higher information share. The success of the SGX in attracting order flow, both informed and liquidity driven, suggests that a small satellite market can coexist with a larger home market and still play a key role in the price discovery process through a careful design of the trading mechanisms and contract specifications.

Information Shares Approach

Additional evidence on the price discovery process using the Hasbrouck (1995) information shares approach is provided. Both the Gonzalo and Granger (1995) approach (described in the previous section), and the information shares approach are based on the assumption of a common stochastic trend. They both interpret the common stochastic trend as an implicit efficient price (Harris, McInish, and Wood, 2002). However, the Gonzalo and Granger model focuses on the components of the common factor and the error correction process, whereas the Hasbrouck model considers the contributions of innovations in each market to the total variance (Baillie et al., 2002). Baillie et al. and De Jong (2002) compare the two models and show that they provide different results if the residuals between the markets are correlated. Therefore, for robustness, Hasbrouck's method is also employed.

Since prices on the three markets have a common stochastic trend, price changes can therefore be expressed in a vector moving average form:

$$\Delta P_t = \Psi(L)\varepsilon_t \tag{3}$$

where ε_t is a zero mean vector of serially uncorrelated disturbances with covariance matrix Ω and Ψ is a polynomial in the lag operator.

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[8] To ensure that the results are not biased by the volatility during our sample period, we compare the annualized volatility of Nikkei 225 spot index during our three-month sample period (i.e., 26.5%) with the average annualized volatilities of the Nikkei 225 index over 24 successive quarters from February 1997 to April 2003 (i.e., 24.15%). The maximum and minimum annualized volatility over the 24 three-month periods are 36.68% and 16%. As the volatility during our sample period is close to the average volatility, it is unlikely for our results to be biased by the sample period selected.

Cointegration of the price series with cointegrating vector β' implies that $\beta'\Psi(1) = 0$, where $\Psi(1)$ is the sum of the moving average coefficients. ψ is denoted as the common row vector in $\Psi(1)$, and it can be shown that the elements of ψ sum to unity. As shown in Hasbrouck (1995), the system may be written in error correction form as

$$\Delta P_t = \alpha(\beta' P_{t-1} - E\beta' P_t) + \Gamma_1 \Delta P_{t-1} + \Gamma_2 \Delta P_{t-2} + \cdots + \Gamma_{K-1} \Delta P_{t-K+1} + U_t \tag{4}$$

when there is a non-stationary autoregressive representation of order K for the market prices. The term $E\beta' P_t$ captures systematic differences in the market prices. In order to estimate this model, the mean value over the sample is calculated so that $(\beta' Y_{t-1} - E\beta' Y_t)$ is a "demeaned" quote vector. Once this vector is created, the model can then be estimated by the linear least-squares method.

If the error covariance matrix Ω is diagonal, then it is possible to directly compute the contribution of the innovations on one market, say Nikkei 225 futures traded on the OSE, to the total variance. This may be thought of as the "information share" of the futures market on the OSE. However, the presence of public information leads to the innovations being contemporaneously correlated across markets. In this case, Ω is not diagonal. Hasbrouck recommends a procedure to bind the information shares of each market using the Cholesky factorization of Ω. This is accomplished by recognizing that, for any real positive semi-definite matrix Ω, there exists a lower triangular matrix $\mathbf{F}$ such that $\Omega = \mathbf{FF}'$. Then the proportion of the new information attributable to each market can be determined using:

$$S_j = \frac{([\psi F]_j)^2}{\psi \Omega \psi'} \tag{5}$$

where $[\psi\mathbf{F}]_j$ is the jth element of the row matrix $\psi\mathbf{F}$. By permuting ψ and Ω, an upper (lower) bound on the information share of each market can be obtained. The magnitude of the difference between the upper and lower bound reflects the importance of contemporaneous correlation among the market returns.

Table V, panel A, contains the estimated bounds together with the mean information shares corresponding to each of the three markets. The standard errors for the information shares are computed via a bootstrap on the estimates. The Li and Maddala (1997) method is employed where the residuals are bootstrapped from the VEC model rather than from the actual data.[9] The estimated residuals are resampled by drawing observations randomly with replacement and then building a new vector of observations by recursively inserting the bootstrapped residuals into the estimated ECM. The parameters and information share bounds are re-estimated using the new set of observations and the bootstrapping process is repeated 1,000 times to generate the empirical distributions for the information shares.

The information share attributed to the OSE and the SGX are 39.15% and 34.09%, respectively, with almost half of the futures market's share coming from the SGX (34.09%/73.24% = 47%), whereas the information share attributed to the cash market (TSE) is 26.76%.[10] There are large bounds for the information share, with the spot market's share of 10.2% at the lower bound and 66.89% at the upper bound, while the OSE (SGX) information share is 9.97% (12.22%) at the lower bound and 86.66% (86.86%) at the upper bound. The wide difference between the higher and lower bounds is an indication of cross-markets residual autocorrelation and the need for an alternative to the Gonzalo and Granger method. However, the Hasbrouck results are not qualitatively different from the Gonzalo and Granger method, suggesting that the futures market plays a primary role in the price discovery process. Our results are consistent with those using the Gonzalo and Granger method and highlight the importance of the Singapore market to the price discovery process.

In Table V, panel B, the results for the information share during the first 10 minutes of trading reveal that the SGX's share is 41% compared to the OSE's 37%. This represents almost 53% of the futures market's contribution, compared to the spot market's contribution of 22%. The finding using the *information shares approach* shows that the SGX commands a larger information share than the OSE during the first 10 minutes of trading compared to its share during the full trading day and is consistent with the results from the *common factor components method*. The results during the first 10 minutes of trading after the lunch break are slightly different. In panel C of Table V, we report that the information share attributed to the SGX is 36%, compared to the OSE's 39%. Nonetheless, the SGX still accounts for 48% of the overall contribution by the futures market compared to the 25% contribution

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[9] See Sapp (2002) and Grammig, Melvin, and Schlag (2001) for a similar bootstrap application to high-frequency data.

[10] In contrast, using the Hasbrouck method, Roope and Zurbruegg (2002) find that price discovery for the Taiwan Index Futures occurs twice as often on the Singapore Exchange than the Taiwan Futures Exchange.

by the cash market. These results support those from the common factor weights.

MULTIVARIATE GRANGER CAUSALITY TESTS

Apart from examining the long-run price co-movements from the three trading venues and their corresponding contribution to the common implicit efficient price, we explore the short-run dynamics in the prices by performing Granger causality tests for cointegrating systems using the methodology suggested by Dolado and Lutkepohl (1996). Dolado and Lutkepohl point out that, if the variables considered are cointegrated, Wald tests for Granger-causality may have non-standard asymptotic properties that depend on the cointegration properties of the system.[11] They propose a method that leads to Wald tests with standard asymptotic χ^2 distributions and avoids possible biases found in the previous tests. Their method may be performed directly on the least squares estimators of the coefficients of the VAR process specified in the levels of the variables. The procedure is based on the argument that the non-standard asymptotic properties of the Wald test on the coefficients of a cointegrated VAR system are due to the singularity of the asymptotic distribution of the least squares estimators. The idea is to avoid this singularity by fitting a VAR process whose order exceeds the true order. The method involves the following steps. The first step requires the estimation of the appropriate lag length of the VAR system by testing a VAR(k) against a VAR($k + 1$) using the standard Wald test. The VAR system is specified in the levels of the variables and the Wald statistic has an asymptotic χ^2 distribution. In the second step, if the true data generating process is a VAR(k), a VAR($k + 1$) is fitted and the standard Wald tests applied to the first k VAR coefficient matrix provide the correct statistics for the causality tests.

Panel A of Table VI reports the Wald statistics for the null hypothesis that past prices on one market do not affect the current prices on another market. There is a two-way Granger causality for every pair of prices that is significant at less than the 0.01% level. In line with its dominant role in price discovery, the OSE has the strongest influence on the other markets, followed by the spot market and the SGX, in that order. Although the Singapore market plays the smallest role among the three markets, its relative contribution is still statistically significant at smaller than the 0.01% level.

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[11] It should be pointed out that the usual procedure involving the estimation of unit roots, cointegration rank, and cointegrating vectors in an ECM framework results in a lower powered test that leaves open the possibility of severe distortions in the inference procedure.

TABLE VI
Causality Tests

Null hypothesis	*Wald test*	*P value*
Panel A: Wald tests		
OSE Futures does not cause Nikkei 225 Spot	741.3	(<0.0001)
SGX Futures does not cause Nikkei 225 Spot	55.4	(<0.0001)
Nikkei 225 Spot does not cause OSE Futures	347.4	(<0.0001)
SGX Futures does not cause OSE Futures	88.9	(<0.0001)
Nikkei 225 Spot does not cause SGX Futures	587.5	(<0.0001)
OSE Futures does not cause SGX Futures	951.9	(<0.0001)

	Dependent variable		
Coefficient	*Spot*	*OSE*	*SGX*
Panel B: Speed of adjustment coefficients			
α_1	−0.00254	−0.00461	0.008
	(0.0524)	(0.0005)	(<0.0001)
α_2	0.04890	−0.14070	−0.011
	(<0.0001)	(0.0042)	(0.0006)

Note. Panel A reports the results of the Wald test for the null hypothesis that past prices from one market do not cause the current price from another market. The tests are performed following the methodology proposed by Dolado and Lutkepohl (1996). The Wald statistics have an asymptotic distribution of $\chi^2(6)$. All the estimations are conducted using the minute-by-minute prices of the three markets over the period from March 13, 2000 to June 13, 2000. Panel B presents the speed of adjustment coefficients from the vector error-correction model:

$$\Delta P_{i,t} = c_i + \alpha_{i,1}(P_{\mathrm{OSE},\,t-1} - P_{\mathrm{SGX},\,t-1}) + \alpha_{i,2}(P_{\mathrm{OSE},\,t-1} - P_{\mathrm{SPOT},\,t-1}) + \sum_{i=1}^{3}\sum_{q=1}^{p}\gamma_{i,\,t-q}\,\Delta P_{i,\,t-q} + u_{i,\,t}$$

where 1, 2, and 3 correspond to the three markets: spot, OSE, and SGX. *P* values are in parentheses.

The short-term cross-market effects can also be assessed by looking at the speed of adjustment coefficients from the Error Correction Model. Panel B of Table VI presents the coefficients of the two error correction terms corresponding to Equation (2). The results yield a number of important observations. First, all the speed of adjustment coefficients have the expected sign and are significant at well below the 1% level, except for α_1 of the *spot* regression at just above the 5% level. This implies that price adjustments take place on all three markets in maintaining price equality. Second, the magnitude of the coefficients shows that reactions on all three markets to the price differentials between the OSE and the spot market are larger than the ones corresponding to the price differentials between the OSE and the SGX, i.e., the economic significance of α_2 is larger than that of α_1. This suggests that prices adjust faster to changes on the spot market than on the SGX. These results are consistent with those of the Wald test, and demonstrate that the strongest short-run causality comes from the OSE, followed by the spot market, and then the SGX.

CONTRIBUTION OF LONGER TRADING HOURS ON THE SGX TO PRICE DISCOVERY

We assess the contribution of the longer trading hours of the SGX to the daily price changes by applying the tests advanced by Barclay and Warner (1993) and extended by Cao, Ghysels, and Hatheway (2000). The significant price contribution during the periods when the SGX is open for trade but the OSE remains closed indicates that the longer trading hours of the SGX play an important role in the price discovery process and provides a motivation for the success of SGX.

The non-overlapping period consists of four sub-periods. The first sub-period constitutes the pre-opening period, from 8:55 am to 9:00 am (Tokyo time). The other three sub-periods are around the lunch period and after the close in Tokyo, 11:00 am to 11:15 am, 12:15 pm to 12:30 pm, and 15:10 pm to 15:25 pm. The overlapping trading period consists of two sub-periods, the pre-lunch period from 9:00 am to 11:00 am, and afternoon period from 12:30 pm to 15:10 pm. For each given non-overlapping sub-period i ($i = 1$ to 4), we first compute the *weighted price contribution* of period i to daily price change (WPC), determined as:

$$\mathrm{WPC}_i = \sum_{t=1}^{T} \left(\frac{|\Delta P_t|}{\sum_{t=1}^{T} |\Delta P_t|} \right) \times \left(\frac{\Delta P_{it}}{\Delta P_t} \right) \tag{6}$$

where $(\Delta P_{it}/\Delta P_t)$ is the relative contribution of the price change for period i on day t to the price change on day t and $(|\Delta P_t|/\sum_{t=1}^{T}|\Delta P_t|)$ weights each day's contribution of period i based on that day's contribution to the cumulative absolute price change over the entire sample period.

We further account for the fact that the first sub-period (8:55 am to 9:00 am) is much shorter than the other three sub-periods (five minutes versus 15 minutes). We take the time length of each period into account by rescaling the weighted contribution of the first sub-period by five minutes and that of the other three sub-periods by 15 minutes to get the contribution per minute. We calculate the relative time-weighted price contribution (RTWPC) for each period i as the ratio of the contribution of period i toward the daily price change per minute over the time-weighted price change during the entire trading period as:

$$\mathrm{RTWPC}_i = \frac{\dfrac{\mathrm{WPC}_i}{\sum_{t=1}^{T} \mathrm{Time}_{i,t}}}{\dfrac{\mathrm{WPC}_{\mathrm{trading}}}{\sum_{t=1}^{T} \mathrm{Time}_{\mathrm{trading},t}}} \tag{7}$$

TABLE VII
Relative Time-Weighted Price Contribution of SGX

	Non-overlapping trading periods				*Overlapping trading periods*
	8:55 am–9:00 am	*11:00 am–11:15 am*	*12:15 pm–12:30 pm*	*15:10 pm–15:25 pm*	*9:00 am–11:00 am/ 12:30 pm–15:10 pm*
RTWPC	0.43	0.09	0.46	0.88	1.00

Note. This table reports the statistics of the time-weighted daily stock price change attributable to the four non-overlapping periods when the SGX is open but the OSE remains closed: 8:55 am–9:00 am; 11:00 am–11:15 am; 12:15 pm–12:30 pm; and 15:10 pm–15:25 pm. The two overlapping trading periods are merged together into one period: 9:00 am–11:00 am and 12:30 pm–15:10 pm. The sample period extends from March 13, 2003 through June 13, 2000. For each sub-period, the table shows its relative time-weighted price contribution (RTWPC) toward the daily price change per unit of time (i.e., one minute) relative to that of the trading period.

With the rescaling refinement, the new results show the contribution of each period toward the daily price change per unit of time (i.e., one minute) relative to that of the trading period. Table VII presents the results for each sub-period and for the overlapping trading period. The results show that the price contribution per minute during the morning pre-opening period (8:55 am to 9:00 am) is less than half than that during the overlapping trading period, with a ratio of 0.43. Interestingly, during the pre-opening periods of both the morning (8:55 am to 9:00 am) and afternoon (12:15 pm to 12:30 pm) sessions have similar price contributions of 0.43 and 0.46, respectively. The late morning sub-period (11:00 am to 11:15 am) has the lowest contribution of 0.09, raising questions about the practical value of that period to the trading activity. Among the four non-overlapping sub-periods that the SGX remains open, three have substantial contributions to price discovery on a per minute basis. In comparison to the contribution of the entire overlapping trading periods, the contribution of the end-of-trading day sub-period (15:10 pm to 15:25 pm) is only slightly smaller at a factor of 0.88 suggesting that this period has the largest contribution to price changes, thus providing a valuable avenue for Nikkei trading when Japanese markets are closed.

SUMMARY AND CONCLUSION

This paper examines the price discovery process of the Nikkei 225 index traded on three competing and informationally linked markets—the domestic spot market (TSE), the domestic futures market (OSE), and the foreign futures market (SGX)—using intraday data. The Gonzalo and Granger (1995) common factor components method and the Hasbrouck (1995) information share method provide evidence of the dominant role of the futures markets (about 79% of the information share) in the price discovery process. We find that the SGX contributes a share of around 33% despite it being a foreign futures market with a much smaller trading volume. A lower transaction cost, a more lenient daily price limit, the absence of a circuit breaker that leads to possible trading halts, longer trading hours, fewer trade restrictions, and a different trading system and contract design appear to attract informed traders to execute some of their transactions through Singapore. The findings shed light on the reasons why a small satellite market can co-exist with a large home market and yet still play a significant price discovery role by being a niche player through careful design of contract details and trading mechanisms. The paper also provides support for the extended trading hours on the SGX for three of the four non-overlapping trading sub-periods.

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