Price Discovery in the German Equity Index Derivatives Markets

G. GEOFFREY BOOTH*
RAYMOND W. SO
YIUMAN TSE

This article examines the intraday price discovery process among stock index, index futures, and index options in Germany using DAX index securities and intraday transactions data. The three index securities contribute to a common factor, but the spot index and index futures have substantially larger information shares than index options. Moreover, the returns of the three index securities exhibit feedback effects, with futures being dominant. Because the trading costs of the futures appear to be the lowest of the three and those of the options to be the highest, the results are consistent with the transaction cost hypothesis. © 1999 John Wiley & Sons, Inc. Jrl Fut Mark 19: 619–643, 1999

We are grateful to Otto Loistl and the Deutsche Terminbörse for providing the German data, and to the Hong Kong Monetary Authority for supplying data on Euromark LIBOR fixing. We thank Gregory Koutmos, Otto Loistl, Hartmut Schmidt, Mark Powers, Robert Webb, and two anonymous referees of this journal for their helpful comments during different stages of this project.
*Correspondence author, Department of Finance, Eli Broad Graduate School of Management, Michigan State University, East Lansing, MI 48824-1121.

- *G. Geoffrey Booth is the A.J. Pasant Chair of Finance at the Eli Broad Graduate School of Management at Michigan State University in East Lansing, Michigan.*
- *Raymond W. So is an Assistant Professor in the Department of International Business at the Chinese University of Hong Kong in Hong Kong.*
- *Yiuman Tse is an Assistant Professor in the School of Management at Binghamton University (SUNY) in Binghamton, New York.*

The Journal of Futures Markets, Vol. 19, No. 6, 619–643 (1999)

CCC 0270-7314/99/060619-25

INTRODUCTION

In an informationally efficient market, financial asset prices reflect information available to market participants. Price discovery is the process by which markets incorporate this information to arrive at equilibrium asset prices. If a single financial asset or multiple highly related financial assets are traded on more than one market, each market may be involved in the price discovery process—but the one that provides a combination of the greatest liquidity, lowest execution costs and greatest leverage opportunities should dominate. Price discovery is typically documented by noting the speed at which prices react to new information. This is a direct outcome of the assertion that price discovery (informed trading) occurs in the market in which the smallest overall transaction costs are incurred.

A prominent example of highly related financial assets trading in different markets is a stock index (typically the component stocks are the securities actually traded) and its derivatives—these financial assets henceforth being referred to as index securities. An overwhelming number of studies have examined the price discovery process involving stock indexes and their futures contracts. The list is too long to provide a census here, but notable examples using United States data include studies by Herbst, McCormack, and West (1987); Kawaller, Koch, and Koch (1987); Stoll and Whaley (1990); and Chan (1992). Together, these and similar studies generally support the notion that index futures react to information up to 30 minutes faster than the spot index, although there is some evidence of a feedback relationship as evinced by the spot index reacting to news one to two minutes before the futures price.

International evidence documenting the primacy of futures in the price discovery process is not as strong. For instance, Iihara, Kato, and Tokunaga (1996) report that the Japanese Nikkei Stock Average (NSA) lags the price of its futures contract, a finding generally echoed by Grübichler, Longstaff, and Swartz (1994) for the Deutscher Aktienindex (DAX) and its futures contract. Shyy, Vijayraghavan, and Scott-Quinn (1996), however, report the opposite for the French CAC spot and futures prices. Moreover, Abhyankar (1995) detects a contemporaneous relationship between FTSE-100 spot and futures prices but indicates that in periods of high volatility futures prices lead spot prices.

With but two exceptions, studies of the above genre involve only stock indexes and index futures, thereby ignoring the potential informational role of index options, if these options exist. The first exception is Fleming, Ostdiek, and Whaley (1996), who study the intraday price discovery process among the S&P 500 stock index, S&P 500 index futures, S&P 100 stock index and S&P 100 index options. Using bivariate analysis, they find that index futures lead index options and index options lead the spot index and contend that this sequence supports the notion that trading costs and response time are positively correlated. The second exception is De Jong and Donders (1998), who investigate the relationships among the index securities traded on the Amsterdam European Options Exchange using lead–lag regressions and cross-correlations adjusted for irregular trading intervals. They find that AEX futures lead the stock index and index options, but that the lead–lag relationships between the latter two index securities are symmetrical. They also attribute (at least partially) these lead–lag patterns to transaction costs.

The purpose of this article is to examine the robustness of Fleming, Ostdiek, and Whaley's (1996) and De Jong and Donders's (1998) findings that index options contribute to the price discovery process involving index securities. This is accomplished by investigating the pricing relationships among the German DAX and its futures and options contracts using a multivariate Vector Error Correction Model (VECM). This econometric scheme, which presupposes cointegration, permits exploration of both short- and long-run price discovery relationships. It also permits the results to be interpreted in terms of a price common to the DAX index securities and their idiosyncratic components. This breakdown makes it possible to determine the information share—that is, a measure of the contribution to the price discovery process—of each index security. It also makes it possible to view the pricing relationships among the index securities without these relationships being confounded by the common price. Because DAX index securities are used, this article extends Grübichler, Longstaff, and Schwartz (1994), who restrict their price discovery investigation to the DAX and DAX futures. It also complements Bühler and Kempf's (1995) investigation into the presence and exploitation of arbitrage opportunities between the DAX and its futures contracts.

The results show that the DAX index securities have a common factor with the DAX index and DAX futures having the largest shares of information, whereas that of the DAX option has the smallest share. Moreover, test results indicate that returns of the three index securities exhibit feedback effects, the DAX futures being dominant. Taken together, these findings suggest that, although the individual index securities do not exhibit the same degree of information sharing, they all contribute to the price discovery process. Because the trading costs of DAX futures appear to be the lowest and the DAX options to be the highest, the empirical results are supportive of the transaction cost hypothesis.

THE GERMAN STOCK AND DERIVATIVES MARKETS

Since the early 1990s, the German stock and derivatives markets have evolved in response to the Frankfurt financial community's desire for Frankfurt to be Europe's undisputed financial capital. The sample period for which intermarket price discovery is analyzed begins on the first trading day in 1992 and ends on the last trading day in March 1994. The institutional details, therefore, primarily pertain to the sample period, with important institutional changes being noted where appropriate.

The German stock market is one of the largest developed equity markets in the world, with a market capitalization of US $470,519 million at the end of 1994 (International Finance Corporation, 1995). In terms of market capitalization, the German market ranks only behind the U.S., Japan, and the U.K. The DAX is a capital-weighted index of the share prices of 30 of Germany's largest companies, including firms such as Deutsche Bank, Siemens, and Volkswagen. In contrast to other well-known stock indices like the S&P 500, the DAX reflects stock distributions (for example, subscription rights, dividends, stock splits, and so forth) in its calculation, thereby making the DAX a "total (pre-tax) performance" index. The DAX is reported once a minute and at the same second for every minute throughout the same day. The second is determined daily by the time of the first trade of a component stock within the minute. For example, if the first trade on a given day occurs at 10:33:24 AM, then the DAX is reported at the 24th second of each minute throughout the same trading day.

Trading of common stocks in Germany may be executed either through floor or electronic trading. Floor trading is done on eight stock exchanges located in Berlin, Bremen, Dusseldorf, Frankfurt, Hamburg, Hanover, Munich, and Stuttgart. The Frankfurt Stock Exchange (FSE), however, is the dominant stock exchange, accounting for 90% of the total volume of DAX stocks traded on the eight exchanges. The FSE is open for trading from 10:30 AM to 1:30 PM German time. Trading is typically conducted using limit orders, and bid and ask quotes are not available. Alternatively, investors can trade using the Integriertes Börsenhandels—und Informations—System (IBIS), an electronic trading system designed so that its screens display the bid and ask prices provided by its participants. Currently the IBIS accounts for about 30% of the trading volume of the DAX stocks, with trading hours being from 8:30 AM to 5:00 PM. Formal reporting of the DAX is done by the FSE, although market participants can calculate its value from stock prices displayed on IBIS screens. A substantial portion (around 30%) of FSE and IBIS trades involving DAX stocks are made in conjunction with derivative positions.[1]

Contrary to equities, DAX stock index futures (FDAX) and DAX stock index options (ODAX) are traded electronically on the Deutsche Terminbörse (DTB), which is headquartered in Frankfurt.[2] DTB screens are located throughout Germany and in major European financial centers. These screens display bid and ask prices. Market participants are anonymous and no trading statistics relating to individuals are reported. Participants only receive monthly reports on their own transactions and their rankings in transaction volume. The reported time from the DTB is also the actual transaction time, because there are no delays in reporting trades. Prior to April 1997, DTB trading hours were from 9:30 AM to 4:00 PM German time, but at that time they were changed to match those of the IBIS.

The FDAX contract size is DM100 per index point. Quotations are in index points and are reported up to one decimal place, with the minimum price movement being 0.5 of an index point. Contract months are the three nearest months of the cycle March, June, September, and December. The last trading day of each contract is the trading day prior to the respective final settlement day. The ODAX is a European option with contract size of DM10 per DAX index point. Similar to the FDAX, quotations of the ODAX are also in index points, which are also reported to one decimal place. The minimum price movement is 0.1 of an index point. Expiration months are the nearest month as well as the next two quarterly expiration months (March, June, September, and December). Additional details of contract specifications of the FDAX and the ODAX are given in Table I.[3]

FDAX and ODAX brokerage fees are DM4 and DM3, respectively, per contract roundtrip. The corresponding fee (Courtage) for a DAX stock trade is 0.12% of its Deutsche mark value. There is also a settlement fee

[1]Prior to 1998, the bulk of FSE floor trading for established firms was conducted by the *kursmakler*, who facilitated the trade between counterparties. His tasks included holding and executing limit orders, maintaining a stock's book, opening and closing a stock, and quoting prices on request from the trading crowd. The *kursmakler* could also buy for his own account but was not required to "make a market." The trading of each stock was the responsibility of one *kursmakler*, but one *kursmakler* could be responsible for more than one stock. In November 1997, Xetra was introduced, and one year later became fully functional and succeeded IBIS. At the time of this writing, all DAX stocks are traded on the Xetra system and the FSE floor. For additional details on the microstructure of the FSE, see Booth et al. (1999). See also Emmons and Schmid (1998) for a useful discussion of the German stock market as an external control system.

[2]In September 1998 the DTB merged with SOFFEX, the Swiss Options and Futures Exchange, to create Eurex, a cross-border exchange.

[3]There are certain changes to the FDAX and ODAX contract specifications after the sample period. See Table I for details.

TABLE I

Specifications of the FDAX and ODAX Contracts

Panel A: FDAX Contract Specifications	
Contract Size:	DM100 per DAX index point.
Quotation:	Points, with one decimal place.
Minimum Price Movements:	0.5 point.
Settlement Months:	The three nearest months of the cycle March, June, September, December.
Last Trading Day:	The exchange trading day prior to the respective final settlement day.
Final Settlement Day:	The third Friday of the respective settlement month if that is an exchange trading day, otherwise the exchange trading day immediately preceding this Friday.
Settlement:	Cash settlement based on the final settlement price, due the second exchange trading day following the last trading day.
Final Settlement Price:	The value of the DAX index calculated on the basis of the opening prices fixed by the Frankfurt Stock Exchange for the DAX-listed shares on the final settlement day.
Trading Hours:	9:30 a.m.–4:00 p.m. German time. (*8:30 a.m.–5:00 p.m.*)
Panel B: ODAX Contract Specifications	
Contract Size:	DM10 per DAX index point.
Quotation:	Points, with one decimal place.
Minimum Price Movements:	0.1 point.
Expiration Months:	Options are available for the nearest months as well as the next two quarterly expiration months: March, June, September, December. *(In addition, options are now available for the two following months out of the cycle June and December, i.e., there are options for 1, 2, 3, 6, 12, 18 and 24 months.)*
Expiration Day:	The expiration day of an option series is the exchange trading day following its last trading day.
Last Trading Day:	The third Friday of the expiration month if that is an exchange trading day, otherwise the exchange trading day immediately preceding this Friday. Trading in the expiring series closes at 1:30 p.m. Frankfurt time on the last trading day.
Exercise:	European-style.
Settlement:	Cash settlement on the first exchange trading day after the last trading day.
Final Settlement Price:	The average value of the DAX calculations performed at the Frankfurt Stock Exchange from 1:21 p.m. to 1:30 p.m. Frankfurt time on the last trading day of the option series.
Exercise Prices:	Exercise price intervals are in increments of 25 index points, e.g., 2125, 2150, 2175. Five exercise prices are introduced for each contract month.
Option Premium:	The DM-equivalent of the premium in points is payable in full on the exchange trading day following the day the option was purchased.
Trading Hours:	9:30 a.m.–4:00 p.m. German time. *(8:30 a.m.–5:00 p.m.)*

Notes: There are certain changes to contract specifications after the sample period. Trading hours of the DTB change on April, 1997 and specifications of the ODAX change on March 18, 1997. These changes are denoted in parentheses and in italics.

of DM 0.7, or DM 21 for trading the 30 DAX stocks as a unit. Because the FDAX contract size is DM 100 per index point, whereas that of the ODAX is DM10, the direct transactions costs of the ODAX are 7.5 times greater than those of the FDAX. Assuming a plausible value for the DAX (say, DM 2,000), the direct transactions costs for a similar Deutsche mark position in the 30 DAX stocks amount to 8.7 times greater than the ODAX costs.

Those taking positions in the DAX component stocks and the DAX derivatives are typically investment professionals who are prepared to make substantial financial commitments. Institutional investors own major blocks of DAX stock shares.[4] Their ownership is not constrained by round lot (50 shares), transactions often being in greater than DM 25,000. Resources committed to derivative positions are equally large, with FDAX and ODAX contracts individually valued in excess of DM 200,000 and DM 20,000, respectively.

DATA DESCRIPTION

Minute-by-minute data of the DAX are from the FSE. These observations represent the most recent transaction data of its 30 component stocks. Transaction data for the FDAX and the ODAX are obtained from the DTB, and for analysis purposes are censored so that only data occurring during the trading hours of the FSE are considered. These data are then converted to matched returns. Several steps are required to accomplish this task.

First, although the DAX "price" can be used directly, FDAX and ODAX prices cannot be. This is because each type of derivative is characterized by more than one contract with each contract having a different expiration date. This problem is solved in the conventional manner by constructing pseudo-price series. In the case of the FDAX, this series is developed by splicing together the prices of sequential nearby futures contracts. The well-known rationale behind this approach is that, the more actively traded an instrument is, the more information contained in its price. As documented in Table II, panel A, nearby FDAX contracts always exhibit more trading volume than those contracts of other maturities. A contract becomes "nearby" at the beginning of the previous contract's expiration month, thereby avoiding the often-noted expiration ef-

[4]By way of illustration, Deutsche Bank, a DAX stock, at one point owned nearly 30% of Daimler-Benz, another DAX stock. Moreover, Deutsche Bank's equity holdings are so extensive that investment wags often say that holding the bank's stock is an alternative to owning shares in a mutual fund specializing in German stocks.

TABLE II

Average Number of DAX, FDAX and ODAX Trades per Minute During FSE: Opening Hours

Contract	*All Contracts*	*Nearby Contracts*	*Non-Nearby Contracts*
DAX	5.85		
FDAX	6.07	5.66	0.41
ODAX			
Call	2.21	1.12	1.09
Put	2.13	1.00	1.13

Notes: To compute the average number of trades for the DAX, each transaction involving one of the 30 component stocks is considered a trade.

fects. According to Schlag (1996), these effects are exhibited by German stock index derivatives.[5]

The ODAX pseudo-price series is created by implying the DAX value from the ODAX price using the Black and Scholes (1973) European option pricing model.[6] Henceforth, ODAX is used interchangeably to refer to the index option price and the implied DAX price, with the intended reference made clear by the context of its usage. Because the DAX is constructed to be similar to a nondividend paying instrument, the implied DAX price can be calculated using only estimates of the risk-free rate and the DAX's volatility. Typically, the yield on short-term government securities is used to proxy the risk-free rate. In this case, this is not possible because German securities of this type do not exist. Instead, the three-month Euromark LIBOR (London Interbank Offer Rate) fixing rate is used.[7]

Historical data are used to measure DAX volatility.[8] Specifically, each trading day is broken down into 15-minute intervals. For each heavily

[5]As an alternative to the FDAX transaction price, it is theoretically possible to imply the value of the DAX from the FDAX using the widely accepted cost-of-carry futures pricing model. This is not done because, as reported by Bühler and Kempf (1995), this model does not accurately portray the relationship between the two German index securities during the sample period. Using the FDAX itself does not cloud the VECM relationships for two reasons. First, as Koutmos and Tucker (1996) point out, the cointegrating coefficients relating the futures price and the implied futures price to the cash index are both unity. This one-to-one relationship does not hold in the case of the ODAX. Second, any cost-of-carry pricing discrepancies are modeled as FDAX idiosyncratic components.

[6]The implied DAX must be within ± 20 index points of the current DAX. This filter aims to correct for reporting errors in the original data base. Less than 0.01% of the observations are considered as errors.

[7]LIBOR fixing is done daily at 11:00 AM London time (that is, noon German time) by averaging the offer rates of leading London banks for Eurocurrency deposits. The three-month rate is used because this is the bellwether rate that the Bundesbank uses to gauge its monetary policy actions. Results, however, are qualitatively the same if the one-month Euromark LIBOR fixing rate is used.

[8]There is a volatility index (VDAX) for the ODAX. Its calculation is based on the implied volatiles of

traded ODAX contract within each interval, the DAX implied volatility is calculated using the Black and Scholes (1973) model with the day's LIBOR rate and the DAX value associated with the minute the ODAX trade occurred. Only those at-the-money ODAX contracts with a maturity of more than nine days and less than or equal to two months are used.[9] The former restriction is invoked because, as noted by Fleming, Ostdiek, and Whaley (1996), there is a sizeable increase in the implied volatilities when options approach expiration. The mean of the implied volatilities within a given 15-minute interval is used to proxy the volatility occurring in the next 15-minute interval, with separate means being computed for call and put options.[10]

Second, to investigate the relationship among two or more price series, ideally the observations should start at the same time and occur at regular intervals. In the case of transactions data, this rarely (if ever) occurs. Thus some sort of sensible algorithm is required to mitigate the problem of nonsynchroncity. This article employs both the REPLACE ALL and MINSPAN approaches put forward by Harris et al. (1995). REPLACE ALL may be summarized as follows. Beginning at the start of each FSE trading day, as soon as an observation is obtained for each DAX securities, the most recent trade for the other two is acquired to form the first matched trade. This matched trade is then saved and a new matched trade is formed in the same manner so that each observation contains new trades in all three markets. MINSPAN, however, minimizes the time span among the matched trades of the three index securities. Details of these two dataset construction procedures are given in the Appendix.

As reported in Table III, the average time spans of both approaches using both ODAX puts and calls is approximately 25 to 30 seconds. These small time spans indicate that the trades are practically simultaneous, suggesting that the nonsynchronous trading problem within a matched

DAX option contracts and follows Whaley's (1993) method. The series is not used here because it is a daily series from 5 December 1994 until 11 July 1997 only. Since 14 July 1997, the VDAX, as well as its subindexes, have been calculated and distributed every minute.

[9]Trades involving at-the-money options with time to expiration of less than two months accounts for 44% of the total ODAX trading volume. Moneyness is defined as 100 * (S/X − 1) for calls and 100 * (1 − S/X) for puts, where S is the current stock index, and X is the exercise price. At-the-money options are defined as those options that are priced within $\pm 2.5\%$ of the exercise price. Unlike the nearby FDAX contracts, the nearby ODAX contracts are not necessarily the most actively traded, as is documented in Table II. This is because the DTB introduces new nearby option contracts with maturities of less than one month at the beginning of each month.

[10]Fleming, Ostdiek, and Whaley (1996) use the implied volatility at day $t - 1$ to proxy for σ^2 at day t. Fleming (1998) also shows that the best proxy for implied volatility at day t is the implied volatility at day $t - 1$. Thus, to ascertain that empirical results are not sensitive to different estimates of implied volatilities, implied volatilities of past hour and previous day are used. Empirical results are qualitatively the same.

TABLE III

Data Collection Procedures and Time Span within Each Matched Trade

Data Collection Procedure	*ODAX Contract Type*	*No. of Obs.*	*Avg. Time Span (seconds)*	*% of Time Earliest Observation*		
				DAX	*FDAX*	*ODAX*
MINSPAN	Call	45,070	25.59	36.96	26.66	36.42
	Put	45,099	25.49	37.02	26.63	36.39
REPLACE	Call	46,632	30.08	38.38	26.36	36.27
ALL	Put	46,884	30.06	38.63	26.37	35.02

Notes: The data collection procedures, MINSPAN and REPLACE ALL, are from Harris et al. (1995).

trade is not serious. Moreover, the proportion of the time that each index security is the earliest observation in the matched trade is also not influenced by whether a put or call option is used to imply the DAX from the ODAX. In both cases, the DAX and the ODAX appear first about the same number of times, with the FDAX appearing first slightly fewer times. Because of the similarity of the MINSPAN and REPLACE ALL outcomes using either the ODAX put or call option, the remainder of this article presents only the statistical analysis based on REPLACE ALL and the ODAX call option.

Third, the index security return contained in a matched trade is defined as $R_{j,t} = P_{j,t} - P_{j,t-1}$, where $P_{j,t}$ is the logarithmic price (log-price) of the jth index security such that DAX = 1, FDAX = 2, and ODAX = 3. Close-to-open returns as dictated by the trading hours of the FSE are excluded to eliminate any possible confounding effects from information arriving when the FSE is closed. The resulting matched trade dataset contains 46,632 observations. Interpreting statistical tests applied to a sample this large from the classical perspective is likely to indicate statistical significance for values that are economically insignificant. This is often referred to as Lindley's (1957) Paradox. One way to respond to this problem is to decrease the significance level as the sample size increases. For example, Chan (1992) uses a critical value of 0.1% for a sample of approximately 15,000 instead of the customary 5% or 1%. Because there is no precise or generally accepted approach to balance these two significance concepts, where appropriate, p-values are provided to assist in judging the economic-statistical relationship.

Several statistics describing the three index security returns series are provided in Table IV. All three price series after being transformed to logarithms are I(1) variables, making the first differences of their log-

TABLE IV

Descriptive Statistics of Returns of the Index Securities

	DAX	*FDAX*	*ODAX*
Phillips-Perron Unit Root Test with Trend Level (Log Price)	−1.845	−1.845	−1.846
	(>0.05)	(>0.05)	(>0.05)
First Difference (Return)	−576.5	−577.4	−592.86
	(<0.0001)	(<0.0001)	(<0.0001)
Moments			
Mean (10^{-7})	2.659	−40.74	−80.490
	(<0.0001)	(<0.0001)	(<0.0001)
Variance (10^{-7})	1.478	3.277	40.147
Skewness Coefficient	−0.266	−0.213	−0.012
	(<0.0001)	(<0.0001)	(0.2802)
Excess Kurtosis Coefficient	24.37	7.199	7.005
	(<0.0001)	(<0.0001)	(<0.0001)
Autocorrelation			
Lag 1	0.276	−0.054	−0.423
	(<0.0001)	(<0.0001)	(<0.0001)
Lag 2	0.154	0.010	−0.015
	(<0.0001)	(0.0456)	(0.0028)
Lag 12	−0.004	−0.009	0.001
	(0.3898)	(0.0524)	(0.8330)

Notes: P-values are in parentheses. The Phillips-Perron test adjusts for autocorrelation and is robust to heteroskedasticity.

price (continuous returns) stationary. Apart from this similarity, the DAX and the ODAX appear to be dramatically different, with the FDAX's descriptive statistics falling somewhere in between those of the other two. For instance, the mean DAX return is positive, whereas the mean ODAX return is negative. The DAX volatility is noticeably smaller than that of the ODAX. The DAX is negatively skewed but the ODAX is symmetric. Although both return series are thick tailed, the DAX tails are noticeably thicker than the ODAX tails. Moreover, the DAX contains strong positive autocorrelation for its first two lags, but the ODAX exhibits even stronger negative correlation for its first lag only. It is possible that these observed autocorrelations are due to the nature of the data. In the case of the DAX, the positive autocorrelation may be the result of its component stocks trading on average less often than the DAX is calculated. In contrast, the negative autocorrelation in the ODAX returns may reflect some sort of bid-ask bounce. The empirical implications of these possibilities are explored in more detail in the next section.[11]

[11]This source of positive autocorrelation in a stock index has been noted by others, with a recent example being Miller, Muthuswamy, and Whaley (1994). The negative autocorrelation in the ODAX is an example of the price behavior motivating Roll's (1984) autocovariance bid–ask spread estimator.

Despite the moment and autocorrelation differences, the presence of arbitrage opportunities among these index securities suggests that their prices should not drift too far apart in the long run. To examine this possibility, the Johansen (1988, 1991) λ_{trace} and λ_{max} tests are employed to test for cointegration among the index securities, the Johansen tests being robust to non-normal innovations and GARCH effects (Cheung & Lai, 1993; and Lee & Tse, 1996). Critical values of the Johansen tests are obtained from Johansen and Juselius (1990) and Osterwald-Lenum (1992). As shown in Table V, the null hypothesis of no cointegration is rejected. In addition, the test results show that the three securities are cointegrated with two cointegrating vectors. In other words, the three index securities share a long-run price equilibrium and are affected by one common stochastic factor.

THE MODEL

It is now well accepted to use a VECM to describe the relationships exhibited by cointegrated asset prices. This is also the approach used to model the interactions among the DAX, FDAX and ODAX. In particular,

$$\begin{aligned}
R_{1,t} &= \alpha_1 + \sum_{k=1}^{3}\sum_{i=1}^{5} \beta_{1k,i}R_{k,t-i} + d_{12}(P_{1,t-1} - P_{2,t-1}) \\
&\quad + d_{13}(P_{1,t-1} - P_{3,t-1}) + \xi_{1,t}, \\
R_{2,t} &= \alpha_2 + \sum_{k=1}^{3}\sum_{i=1}^{5} \beta_{2k,i}R_{k,t-i} + d_{21}(P_{2,t-1} - P_{1,t-1}) \\
&\quad + d_{23}(P_{2,t-1} - P_{3,t-1}) + \xi_{2,t}, \\
R_{3,t} &= \alpha_3 + \sum_{k=1}^{3}\sum_{i=1}^{5} \beta_{3k,i}R_{k,t-i} + d_{31}(P_{3,t-1} - P_{1,t-1}) \\
&\quad + d_{32}(P_{3,t-1} - P_{2,t-1}) + \xi_{3,t},
\end{aligned} \tag{1}$$

where $R_{1,t}$, $R_{2,t}$, and $R_{3,t}$ are the respective returns of the DAX, FDAX and ODAX at time t; α_1, α_2 and α_3 are intercepts; $P_{j,t}$ continue to represent the log-prices of the index securities so that $P_{j,t} - P_{k,t}$, $j \neq k$, the differences between any two price pairs, serve as the error correction terms.[12]

[12]A more complex definition of the error terms is possible. For example, $e_{12,t}$ could be defined as the innovation resulting from regressing $P_{1,t}$ on $P_{2,t}$ and a time trend. According to a log-likelihood test

TABLE V

Johansen Cointegration Test Results

H_0	λ_{max}	λ_{trace}	Eigenvalue
$r \leq 0$	1731.55 (<0.0001)	1788.04 (<0.0001)	0.0365
$r \leq 1$	56.22 (<0.0001)	56.49 (<0.0001)	0.0012
$r \leq 2$	00.27 (>0.0500)	00.27 (>0.0500)	0.0000

P-values are in parentheses. λ_{max} is the Johansen maximum lambda test statistic, and λ_{trace} is the Johansen *trace* test statistic. H_0 is the null hypotheses that the system contains at most r cointegrating vectors. The number of lags (23) used in the Johansen cointegration test is determined by the SIC. The finding of cointegration, however, is robust with respect to the number of lags. The null hypothesis that the price differentials are the cointegrating vectors may be tested by

$$Q_H = T\sum_{i=1}^{r} ln[(1 - \lambda_i^*)/(1 - \lambda_i)],$$

where λ_i^* and λ_i are the eigenvalues associated with the null and alternative specifications and T is the number of observations. Q_H is χ^2 distributed with the degrees of freedom being the number of cointegrating vectors, in this case two. The Q_H p-value is 0.0316, indicating that, because of the magnitude of T, the null should not be rejected.

Typically, β_{jk} and d_{jk} are used to measure the effects of the arrival of news. The β_{jk} measure the short-run effects as captured by lagged returns, and the d_{jk} show how the prices (via returns) arrive at a new equilibrium after being perturbed. The return to an equilibrium is the direct result of the prices being cointegrated. In this instance, however, their interpretation is more complicated. This is because, unlike economically dissimilar assets, the three index securities share an institutional common factor—that is, the combined influences of the 30 stocks that comprise the DAX. Thus, to facilitate interpretation, a theoretical framework that explicitly recognizes this commonality is necessary. Such a framework is provided by Stock and Watson (1988).

Using their framework to model the relationships among the three index securities results in

$$P_{j,t} = f_t + g_{j,t},\ j = 1, 2, 3, \tag{2}$$

where f_t is the common factor scalar and $g_{j,t}$ the j th index security's idiosyncratic component. In this scheme, the P_j contain a common factor, and this factor responds to new information. In other words, f_t represents the implicit common efficient price of the DAX, FDAX, and ODAX. The $g_{j,t}$ reflect the presence of phenomena such as infrequent trading, liquid-

statistic derived from Johansen (1991) and Johansen and Juselius (1990), however, the null hypothesis that the price differentials are the cointegrating vectors cannot be rejected (p-value = 0.0316). Thus the simpler price differential definition is adopted because it permits an intuitive description of the relationship between each of the index security's idiosyncratic factors. The statistical conclusions for either approach are qualitatively the same.

ity, price discreteness, potential mispricing, and the bid–ask spread. Underpinning this approach is the notion that the prices of the three index securities are linked together by arbitrage, and it is the presence of idiosyncratic factors that cause their prices to diverge.

Following Gonzalo and Granger (1995), f_t can be expressed as a linear combination of the prices. Thus

$$f_t = \phi_1 P_{1,t} + \phi_2 P_{2,t} + \phi_3 P_{3,t}, \tag{3}$$

such that the vector of ϕ_j is orthogonal to the vector of d_{jk}. The ϕ_j can be normalized so that their sum equals one, making ϕ_j the proportion of the common factor attributable to the j^{th} security. Thus ϕ_j can be referred to as the j^{th} security's information share. Substituting eqs. (2) and (3) into (1) clarifies the interpretation of β_{jk} and d_{jk}. Using the DAX VECM as an example,

$$R_{1,t} = \alpha_1 + \sum_{k=1}^{3} \sum_{i=1}^{5} \beta_{1k,i} \Delta g_{k,t-i} + \sum_{k=1}^{3} \sum_{i=1}^{3} \beta_{1k} R_{f,t-i} + d_{12}(g_{1,t-1} - g_{2,t-1}) + d_{13}(g_{1,t-1} - g_{3,t-1}) + \xi_t, \tag{4}$$

where $R_{f,t} = \Delta f_t$ is the return to the common factor, that is, the weighted average of the $R_{j,t}$ using ϕ_j as the weights. According to eq. (4), the $\Sigma\beta_{1k}$ measures the short-run response of index security returns to lagged returns of the common factor and the individual β_{1k} to lagged changes of the idiosyncratic components of the individual index securities. The same substitution shows that if the error correction term for a index security pair is represented by their price difference, then the d_{1k} measure the way in which returns adjust to differences in their idiosyncratic components.[13]

The usefulness of the common factor framework interpretation of β_{1k} and d_{1k}, as opposed to the traditional one, is that it explicitly considers the different effects associated with the prices of the index securities. For

[13]In some studies (for example, Grünbichler, Longstaff, & Schwartz, 1994, and Fleming, Ostdiek, & Whaley, 1996), a two step procedure is used to eliminate or at least mitigate the impact of these frictions prior to a VECM analysis. In particular, the returns in equation set (1) are innovations from an autoregressive-moving average model. The intended purpose of this filter is to remove dependencies caused by possible price staleness and the bid–ask bounce. Other studies (for example, Shyy, Vijayraghavan, & Scott-Quinn, 1996) have addressed the latter issue by using the midpoint of the bid and ask prices. Using the midpoint price may also serve to lessen the former phenomenon if the quotes are not stale. The common factor approach is a third alternative in which market frictions are explicitly modeled as idiosyncratic phenomena. Its comparative advantage is that it permits the focus of the analysis to be on the way in which the index securities react to news being impounded in their common price.

TABLE VI

Gonzalo-Granger Information Sharing Test Results

	DAX (j = 1)	FDAX (j = 2)	ODAX (j = 3)
ϕ_j (Common Factor Weight)	0.5027	0.4771	.0202
H_0: Index security j is not in the common factor ($\phi_j = 0$)	2208.7 (<0.0001)	2308.7 (<0.0001)	6.937 (0.0084)

P-values are in parentheses. The larger the index security's ϕ, the larger its contribution to the common factor. The sum of the weights equals one. For a system characterized by one stochastic for the null hypothesis that the j^{th} index security is not contained in the common factor, i.e., $\phi_j = 0$ is given by

$$Q_{GG} = -T \ln [(1 - \lambda^*)/(1 - \lambda)],$$

where λ^* and λ, respectively, are the largest eigenvalues from the model under the null and the unrestricted model and T is the number of observations. Q_{GG} is $\chi^2(1)$ distributed. Rejecting the null implies that the index security is contained in the common factor.

instance, it shows that the effect associated with the error correction term is not due to fundamental price differences but instead results from idiosyncratic component differences in the index securities. More importantly, however, is that the common factor framework provides the opportunity to examine the degree to which each index security is involved with the price discovery process, this being measured by its contribution to the common factor.

THE STATISTICAL RESULTS

The information share results of the Gonzalo and Granger (1995) model are given in Table VI. As shown in the table, the values of ϕ_j indicate that 50% of the common factor is contributed by the DAX and 48% by the FDAX, leaving but 2% being provided by the ODAX. The null hypotheses that the FDAX and DAX individually do not contribute to the common factor is rejected at p-value <0.0001, implying that both make a statistically significant contribution to the common price. Whether the ODAX contributes to the common price depends upon whether a p-value = 0.0084 is considered to be significant in view of there being over 46,000 observations. Regardless of its statistical significance, however, its economic significance is small. In sum, the price discovery role is shared about equally by the DAX and FDAX.

Table VII provides the VECM results. Before examining these in detail, however, several points merit special mention. First to account for heteroskedasticity and autocorrelation in the disturbance terms, $\upsilon_{j,t}$, the VECM is estimated using the Newey and West (1987, 1993) model. Sec-

TABLE VII

VECM Estimation Results

	Dependent Variables		
Parameters/Tests	*DAX (j = 1)*	*FDAX (j = 2)*	*ODAX (j = 3)*
Constant			
α_j (10^{-6})	12.303	−6.996	−19.720
	(<0.0001)	(0.1582)	(0.1647)
DAX Lags			
$\beta_{j1,1}$	0.0862	0.1659	−0.1697
	(<0.0001)	(<0.0001)	(<0.0001)
$\beta_{j1,2}$	−0.0134	−0.0159	−0.2457
	(0.0083)	(0.0776)	(<0.0001)
$\beta_{j1,3}$	−0.0256	−0.0308	−0.1563
	(<0.0001)	(0.0004)	(<0.0001)
$\beta_{j1,4}$	0.0036	−0.0168	−0.1105
	(0.4260)	(0.0370)	(<0.0001)
$\beta_{j1,5}$	0.0358	−0.0164	−0.0915
	(<0.0001)	(0.0012)	(<0.0001)
Robust Wald Stat.:	508.13	376.55	95.19
$\beta_{j1,i} = 0, \forall i$	(<0.0001)	(<0.0001)	(<0.0001)
FDAX Lags			
$\beta_{j2,1}$	−0.1619	−0.0909	0.4321
	(<0.0001)	(<0.0001)	(<0.0001)
$\beta_{j2,2}$	0.1641	−0.0235	0.4072
	(<0.0001)	(<0.0001)	(<0.0001)
$\beta_{j2,3}$	0.1178	−0.0267	0.3275
	(<0.0001)	(<0.0001)	(<0.0001)
$\beta_{j2,4}$	0.0736	−0.0161	0.2764
	(<0.0001)	(0.0036)	(<0.0001)
$\beta_{j2,5}$	0.0351	0.0078	0.1223
	(<0.0001)	(0.0523)	(<0.0001)
Robust Wald Stat.:	5952.24	333.69	1107.54
$\beta_{j2,i} = 0, \forall i$	(<0.0001)	(<0.0001)	(<0.0001)
ODAX Lags			
$\beta_{j3,1}$	−0.0094	0.0036	−0.2949
	(<0.0001)	(0.1295)	(<0.0001)
$\beta_{j3,2}$	−0.0072	0.0019	−0.1660
	(<0.0001)	(0.4227)	(<0.0001)
$\beta_{j3,3}$	−0.0033	0.0006	−0.0905
	(0.0084)	(0.7961)	(<0.0001)
$\beta_{j3,4}$	−0.0020	0.0007	−0.0427
	(0.0808)	(0.7216)	(<0.0001)
$\beta_{j3,5}$	−0.0020	0.0006	−0.0189
	(0.0305)	(0.6941)	(<0.0001)
Robust Wald Stat.:	139.63	6.80	24974.78
$\beta_{j3,i} = 0, \forall i$	(<0.0001)	(0.2362)	(<0.0001)

TABLE VII (Continued)

VECM Estimation Results

Parameters/Tests	*Dependent Variables* DAX (j = 1)	FDAX (j = 2)	ODAX (j = 3)
Error Correction Terms			
d_{j1}		0.0007 (0.7744)	−0.4688 (<0.0001)
d_{j2}	−0.0019 (<0.0001)		−0.0078 (<0.0001)
d_{j3}	−0.0125 (<0.0001)	−0.0005 (0.8413)	

Notes: The following VECM is used:

$$R_{1,t} = \alpha_1 + \sum_{k=1}^{3}\sum_{i=1}^{5} \beta_{1k,i} R_{k,t-i} + d_{12}(P_{1,t-1} - P_{2,t-1}) + d_{13}(P_{1,t-1} - P_{3,t-1}) + \xi_{1,t},$$
$$R_{2,t} = \alpha_2 + \sum_{k=1}^{3}\sum_{i=1}^{5} \beta_{2k,i} R_{k,t-i} + d_{21}(P_{2,t-1} - P_{1,t-1}) + d_{23}(P_{2,t-1} - P_{3,t-1}) + \xi_{2,t},$$
$$R_{3,t} = \alpha_3 + \sum_{k=1}^{3}\sum_{i=1}^{5} \beta_{3k,i} R_{k,t-i} + d_{31}(P_{3,t-1} - P_{1,t-1}) + d_{32}(P_{3,t-1} - P_{2,t-1}) + \xi_{3,t}, \qquad (1)$$

P-values are in parentheses. The robust Wald statistics are calculated using Newey and West's (1987, 1993) heteroskedasticity and autocorrelation consistent variance-covariance matrix. In each case, the test statics are $\chi^2(5)$ distributed.

ond, five lags are used, with each lag on average amounting to approximately 2.3 minutes. The results, however, are qualitatively the same for 1 and 10 lags. As pointed out by Sims (1980), however, the presence of strong autocorrelation in a vector autoregression often renders the interpretation of size, sign, and statistical significance of the individual lagged parameter estimates meaningless. As reported above, such autocorrelation is present for the DAX and the ODAX. Thus, although the individual parameters are reported for completeness, the approach adopted herein is to consider the impact of all the lags of a particular index security jointly. Third, only the lagged observations contained in the same day as observation t are considered, thereby avoiding any overnight influences. Finally, although not reported, the VECM is also estimated after incorporating dummy variables to take into account the ordering of the index securities in the matched trades. The coefficients of these variables are statistically insignificant at conventional levels.

Consider first the long-run parity relationships depicted by the error correction coefficients. According to Table VII, only the coefficients associated with the FDAX regression, d_{21} and d_{23}, are not statistically significant. The signs on the other four coefficients are negative, which is required for a long-run equilibrium to exist. In economic terms, this means that when the cointegrating relationship is perturbed by the arrival of news, the FDAX does not adjust to restore equilibrium. This is the task of the DAX and ODAX. These two index securities use the FDAX to represent the new equilibrium price, with the ODAX responding faster than the DAX ($|d_{32}| > |d_{12}|$). In arriving at this new price, the DAX and the ODAX adjust with respect to each other as well. The ODAX, however, reacts faster with respect to the DAX than the DAX does to the ODAX ($|d_{31}| > |_{13}|$

With respect to the relationships captured by the lagged returns, the robust Wald statistics reported in Table VII indicate that, taken as a whole, past own idiosyncratic components are significant explainers for each of the index securities. This may well be the result of one or more of the aforementioned market frictions. Moreover, these tests indicate that there is a bivariate feedback between the FDAX and the DAX as well as the DAX and the ODAX, but there is only a one-way explanation running from the FDAX to the ODAX. With the exception of the presence of a DAX to FDAX relationship, this pattern is the same as that present for the error correction terms. Although the p-values of the two relationships linking the FDAX and DAX are both less than 0.0001, the robust Wald statistic for $\beta_{12,i} = 0, \forall i$, is 16 times as great as that of $\beta_{21,i} = 0, \forall i$,. This seeming dominance of the FDAX over the DAX in this context is consistent with the findings reported by Grünbichler, Longstaff, and Schwartz (1994).

The analysis so far has focused on the relationship between market pairs. Although informative, the ODAX may not affect the FDAX directly, but it may affect it indirectly through the DAX. The possibility that these indirect effects may exist is examined by testing the null hypothesis that for a particular index security, apart from its own, there are no price effects emanating from the other two index securities. In other words, the ODAX and the DAX, for example, do not provide useful information for the pricing of the FDAX. Useful information is summarized by the lagged returns of the ODAX and the DAX—but also their error correction terms. According to the robust Wald statistics reported in Table VIII, in every case the null hypothesis is rejected, suggesting the possibility of indirect effects.

The trivariate relationships are further explored using the variance decomposition (VDC) and cumulative impulse response (CIR) analyses developed by King et al. (1991) and described in a financial market context by Tse (1998). As pointed out by Tse (1998), the more efficient that a market is, the more its price movement is explained by the common trend. With respect to the VDC, Table IX shows the fraction of the fore-

TABLE VIII

Robust Wald Test Results

Null Hypothesis (H_0)	*Robust Wald Statistics*	*P-value*
DAX returns are not affected by those of FDAX and ODAX	6374.87	<0.0001
FDAX returns are not affected by those of DAX and ODAX	385.81	<0.0001
ODAX returns are not affected by those of DAX and FDAX	7360.55	<0.0001

Notes: The robust Wald statistics are calculated using Newey and West's (1987, 1993) heteroskedascity and autocorrelation consistent variance-covariance matrix. The null model includes only own index security effects (i.e., own lags). The alternative model is equation (1). In this application the test statistics are $\chi^2(12)$ distributed.

TABLE IX

Accounting Innovations and Impulse Response Functions

Horizon (in periods)	*DAX*	*FDAX*	*ODAX*
1	0.927	0.857	0.269
2	0.926	0.855	0.193
3	0.992	0.855	0.193
4	0.921	0.855	0.193
5	0.921	0.855	0.193
20	0.920	0.855	0.192

Notes: Entries are fractions of the forecast error variance at horizon h that are attributable to common factor shocks.

cast error variance that is attributable to shocks in the common factor for horizons ranging from 1 to 20 periods. The point estimates of the VDC show that the portion accruing to the common factor stabilizes in 5 periods (on average 11.5 minutes) or less. Moreover, these estimates indicate that the forecast error variances for the DAX and FDAX are mainly due to common factor shocks, whereas the common factor's ability to explain the ODAX's forecast error variance is far less. For instance, for the initial forecast period, the common factor explains 92.7% and 85.7% of the DAX's and FDAX's fluctuations, respectively. The corresponding percentage for the ODAX is 26.9%.

The CIR results for various horizons are displayed in Table X. The statistics contained in this table are the cumulative impulse responses of $R_{j,t+h}$ to a common factor shock in period t, with the long-run common factor shock multiplier being one. This table indicates that the three index securities respond rapidly to a shock. In fact, the FDAX and the ODAX respond fully and instantaneously as evinced by their nearly 1.0 values for the period in which the shock occurred (h = 0). The DAX responds somewhat more slowly, but the shock's full effect materializes in three

TABLE X

Responses to Common Factor Innovations

Horizon (in periods)	*DAX*	*FDAX*	*ODAX*
0	0.828	1.032	0.982
1	0.921	1.029	0.980
2	0.970	1.027	0.986
3	0.997	1.025	0.989
4	1.009	1.017	0.999
5	1.015	1.016	1.005
20	0.998	1.010	0.994

Notes: Entries are the cumulative impulse responses of $R_{j,t+h}$ to a common factor shock in period t. The long-run multiplier of a common factor shock is unity.

periods. The spot index's somewhat slower reaction to the common factor shock may be due to the additional time required for trades to occur in all of its component stocks.

CONCLUDING REMARKS

In this article, the price discovery process among the DAX securities is examined. In terms of contributions to information, the FDAX and the DAX are found to be the main driving forces, whereas the ODAX contributes least.[14] Moreover, the results suggest that the FDAX and the DAX react to new information faster than the ODAX. The general importance of the FDAX in the price discovery process supports the transaction costs hypothesis. Its relationship to the DAX is consistent with the results Grünbichler, Longstaff, and Schwartz (1994) as well as those of Bühler and Kempf (1995).[15] In view of the findings of Fleming, Ostdiek, and Whaley (1996) and De Jong and Donders (1998), the most controversial finding appears to be the low informational role of the ODAX relative to the DAX.

This appearance, however, may be superficial. To understand why this may be the case, it is necessary to explore the nature of transactions

[14]The relative importance of the DAX is supportive of Shyy, Vijayraghavan, and Scott-Quinn (1996), who use the midpoint of the bid and ask prices instead of transactions prices (thereby avoiding the complications associated with bid–ask bounce) to show that French CAC spot prices lead CAC futures prices. This support may well be the result of splitting index security prices into a common and idiosyncratic components, the latter containing the bid–ask spread.

[15]Grünbichler, Longstaff, and Schwartz (1994) suggest that FDAX trading costs are lower than those of the DAX stocks because futures are electronically traded, whereas the individual stocks are floor traded. Although their conclusion is appears correct, this reason is suspect, however, because the 30 DAX stocks can also be electronically traded using IBIS.

costs in this context in more depth. The transactions costs reported in this article only include direct execution costs. The costs proxied by the bid–ask spread and market impacts are ignored. In measuring trading costs, however, Fleming, Ostdiek, and Whaley (1996) and Bühler and Kempf (1995) incorporate the bid–ask spread but quantitatively ignore market impact costs.[16] Including the bid–ask spread, however, only increases total costs; it does not change the relative cost rankings.[17] With respect to market impact costs Fleming, Ostdiek, and Whaley (1996) and Bühler and Kempf (1995) argue that their omission is justified because the index stocks and index derivatives being examined are highly liquid. Thus market impact costs are very small, if they exist at all.[18] This does not appear to be the case for ODAX. For instance, the average number of ODAX put or call contracts traded per minute is 19.8% of the number of FDAX contracts traded. This percentage drops slightly to 19.1% if the denominator is the number of DAX stock trades. Thus it is sensible to believe that, if market impact influences are incorporated into the calculation of transaction costs, the ODAX costs may well be the highest, followed by the DAX and then the FDAX. Such a belief would make the results of this study compatible with the transaction cost hypothesis. At this point, however, this plausible conclusion is only a conjecture.

In sum, regardless of the reasons, the statistical evidence suggests that the three markets are informationally linked, with arbitrage being the mechanism by which this linkage is obtained. The driving force appears to be stock index futures, but index options contribute to the price discovery process in a measurable way. The two derivatives may also contribute indirectly through the DAX stocks because a substantial portion

[16]Bühler and Kempf (1995) only consider the costs proxied by the FDAX bid–ask spread. Recall that this spread does not exist for the FSE. This, however, does not mean that these costs do not exist. Bühler and Kempf (1995) justify their not considering these costs by noting that Haller and Stoll (1989) report that Roll (1984) implied bid–ask spreads for heavily traded German stocks are virtually zero. In a more recent study, however, using IBIS quoted bid and ask prices, Booth et al. (1998) report small but significant bid–ask spreads for the 30 DAX stocks. Moreover, Loistl and Vetter (1998) calculate that FSE transaction costs (including market impact but excluding Courtage) are approximately 133% of IBIS transaction costs and 45% of those of the New York Stock Exchange.

[17]For instance, if only brokerage and settlement costs are considered, Fleming, Ostdiek, and Whaley (1996) find that transaction costs for an index portfolio is 3.1 times similar costs for index options and index options are 4.2 times as costly to transact as index futures. If the bid–ask spread is considered, these multipliers increase to 5.9 and 5.7, respectively. The increase is consistent with Subrahamanyan's (1991) observation that baskets of securities are the preferred trading vehicle for liquidity traders who trade portfolios because adverse selection costs are usually smaller in these markets than in markets for individual securities.

[18]Fleming, Ostdiek, and Whaley (1996) argue that Stephen and Whaley's (1990) finding that movements in the cash prices of individual stocks precede movements in their options prices is consistent with the transactions cost hypothesis. They base their argument on the notion that impact costs are not small for options on individual stocks.

of the trading in these stocks is derivative oriented. This may partially explain the observed importance of the DAX.[19] Thus all three markets should be considered as a system. Not to do so may mask important price discovery channels.

APPENDIX

REPLACE ALL and MINSPAN Procedures

The REPLACE ALL and the MINSPAN matching procedures are from Harris et al., (1995). To better understand these two approaches, consider the series of trades as follows:

Time	DAX	FDAX	ODAX
t = 0	DAX_1	$FDAX_1$	
t = 1	DAX_2		$ODAX_1$
t = 2	DAX_3	$FDAX_2$	
t = 3	DAX_4		$ODAX_2$
t = 4	DAX_5	$FDAX_3$	$ODAX_3$

For simplicity and illustrative purpose, the time interval between t-1 and t is fixed. In the actual dataset construction, the time intervals are not fixed. REPLACE ALL constructs the first matched pair as (DAX_2, $FDAX_1$, $ODAX_1$). The second matched pair is (DAX_4, $FDAX_2$, $ODAX_2$) and the third one is (DAX_5, $FDAX_3$, $ODAX_3$). MINSPAN has a natural stopping rule associated with the last security traded. The initial pair chosen is (DAX_2, $FDAX_1$, $ODAX_1$). Here the ODAX is the last security because the first trade of ODAX is the latest among the three securities. MINSPAN further checks if a further trade in the DAX and the FDAX can reduce the time span. If so, the pair is updated. Back to this example, the first pair is (DAX_2, $FDAX_1$, $ODAX_1$), because the span between (DAX_2, $FDAX_1$, $ODAX_1$) and (DAX_3, $FDAX_2$, $ODAX_1$) are the same. The second pair is (DAX_3, $FDAX_2$, $ODAX_2$) and the third pair is (DAX_5, $FDAX_3$, $ODAX_3$). One caveat, however, is that the numbers of matched trades using REPLACE ALL and MINSPAN are much smaller than that of simply using minute-by-minute returns.

[19]This additional volume may result in decreased trading costs for DAX stocks. Iversen (1994) points out that, for IBIS traded DAX stocks, volume is the primary explainer of the bid–ask spread. He also observes that the introduction of options on individual DAX stocks lowered the IBIS bid–ask spread of these stocks. Presumably, this reduction in cost would also be reflected in FSE transactions

BIBLIOGRAPHY

Abhyankar, A. H. (1995). Return and volatility dynamics in the FT-SE 100 stock index and stock index futures markets. The Journal of Futures Markets, 15, 457–458.

Black, F., & Scholes M. S. (1973). The pricing of options and corporate liabilities. Journal of Political Economy, 81, 637–659.

Booth, G. G., Iversen, P., Sarkar, S., Schmidt, H., & Young, A. (1999). Market structure and bid–ask spreads: IBIS vs. Nasdaq. European Journal of Finance, 5, 51–72.

Bühler, W., & Kempf, A. (1995). DAX index futures: Mispricing and arbitrage in the German markets. The Journal of Futures Markets, 15, 833–859.

Chan, K. (1992). A further analysis of the lead–lag relationship between the cash market and stock index futures market. Review of Financial Studies, 5, 123–152.

Cheung, Y.-W., & Lai, K. S. (1993). Finite sample sizes of Johansen's likelihood ratio tests for cointegration. Oxford Bulletin of Economics and Statistics, 55, 313–328.

De Jong, F., & Donders, M. W. M. (1998). Intraday lead–lag relationships between futures-options, and stock market. European Finance Review, 1, 337–359.

Emmons, W. R., & Schmid, F. A. (1998). Universal banking, control rights and corporate finance in Germany. Review, Federal Reserve Bank of St. Louis, July/August, 19–42.

Fleming, J. (1998). The quality of market volatility forecasts implied by S&P 100 index option prices. Journal of Empirical Finance, 5, 317–345.

Fleming, J., Ostdiek, B., & Whaley, R. E. (1996). Trading costs and the relative rates of price discovery in stock, futures, and option markets. The Journal of Futures Markets, 16, 353–387.

Grünbichler, A., Longstaff, F. A., & Schwartz, E. (1994). Electronic screen trading and the transmission of information: An empirical examination. Journal of Financial Intermediation, 3, 166–187.

Gonzalo, J., & Granger, C. W. J. (1995). Estimation of common long-memory components in cointegrated systems. Journal of Business & Economic Statistics, 13, 27–35.

Haller, A., & Stoll, H.R. (1989). Market structure and transactions costs: Implied spreads in the german stock market. Journal of Banking and Finance, 13, 697–708.

Harris, F. H. deB., McInish, T. H., Shoesmith, G. L., & Wood, R. A. (1995). Cointegration, error correction, and price discovery on informationally linked security markets. Journal of Financial and Quantitative Analysis, 30, 563–579.

Herbst, A. F., McCormack, J. P., & West, E. N. (1987). Investigation of a lead–lag relationship between spot stock indices and their future contracts. The Journal of Futures Markets, 7, 373–381.

Iihara, Y., Kato, K., & Tokunaga, T. (1996). Intraday return dynamics between the cash and futures markets in Japan. The Journal of Futures Markets, 16, 147–162.

International Finance Corporation. (1995). Emerging stock markets factbook 1995. Washington, DC: International Finance Corporation.
Iversen, P. (1994). Geld-brief-spannen deutscher standardwerte. Wiesbaden: Deutscher Universitatverlag.
Johansen, S.(1988). Statistical analysis of cointegrated vectors. Journal of Economic Dynamics and Control, 12, 231–254.
Johansen, S. (1991). Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. Econometrica, 59, 1551–1580.
Johansen, S., & Juselius, K. (1990). Maximum likelihood estimation and inference on cointegration—With applications to demand for money. Oxford Bulletin of Economics and Statistics, 52, 169–210.
Kawaller, I. G., Koch, P. D., & Koch, T. W. (1987). The temporal relationship between S&P 500 futures and the S&P 500 index. Journal of Finance, 42, 1309–1329.
King, R. G., Plosser, C. I., Stock, J. H., & Watson, M. W. (1991). Stochastic trends and fluctuations. American Economic Review, 81, 819–840.
Koutmos, G., & Tucker, M. (1996). Temporal relationships and dynamic interactions between spot and futures stock markets. The Journal of Futures Markets, 16, 55–69.
Lee, T.-H., & Tse, Y. (1996). Cointegration tests with conditional heteroskedasticity. Journal of Econometrics, 73, 401–410.
Lindley, D. V. (1957). A statistical paradox. Biometrika, 44, 187–192.
Loistl, O., & Vetter, O. (1988). Transaction costs for different stock exchange pricing systems. Wirtschaftuniversität Wien working paper.
Miller, M. H., Muthuswamy, J., & Whaley, R. E. (1994). Mean reversion of Standard and Poor's S&P 500 index basis changes: Arbitrage-induced or statistical illusion. Journal of Finance, 49, 477–513.
Newey, W., & West, K. (1987). A simple positive and semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica, 55, 703–708.
Newey, W., & West, K. (1993). Automatic lag selection in covariance matrix estimation. Review of Economic Studies, 61, 631–653.
Osterwald-Lenum, M. (1992). A note with fractiles of asymptotic distribution of the maximum likelihood cointegration rank test statistics: Four cases. Oxford Bulletin of Economics and Statistics, 54, 461–472.
Roll, R. (1984). A simple implicit measure of the effective bid–ask spread in an efficient market. Journal of Finance, 39, 159–163.
Schlag, C. (1996). Expiration day effects of stock index derivatives in Germany. European Financial Management, 1, 69–95.
Shyy, G., Vijayraghavan, V., & Scott-Quinn, B. (1996). A further investigation of the lead–lag relationship between the cash market and the stock index futures market with the use of bid/ask quotes: The case of France. The Journal of Futures Markets, 16, 405–420.
Sims, C. A. (1980). Macroeconomics and reality. Econometrica, 48, 1–48.
Stephan, J. A., & Whaley, R. E. (1990). Intraday price change and trading volume relations in the stock and stock option markets. Journal of Finance, 45, 191–220.

Stock, J. H., & Watson, M. W. (1988). Testing for common trends. Journal of the American Statistical Association, 83, 1097–1107.

Stoll, H. R., & Whaley, R. E. (1990). The dynamics of stock index and stock index futures returns. Journal of Financial and Quantitative Analysis, 25, 441–468.

Subrahmanyan, A. (1991). A theory of trading in stock index futures. Review of Financial Studies, 4, 17–51.

Tse, Y. (1998). International linkages in Euromark futures markets: Information transmission and market integration. The Journal of Futures Markets, 18, 128–149.

Whaley, R. E. (1993). Derivatives on market volatility: Hedging tools long overdue. Journal of Derivatives, fall, 71–85.