Volatility in the Foreign Currency Futures Market

Campbell R. Harvey
Duke University

Roger D. Huang
Vanderbilt University

We examine the volatility implications of around-the-clock foreign exchange trading with transaction data on futures contracts from the Chicago Mercantile Exchange and the London International Financial Futures Exchange. We find higher U.S.–European and U.S.–Japanese exchange-rate volatilities during U.S. trading hours and higher European cross-rate volatilities during European trading hours. While the disclosure of private information through trading may partly explain these volatility patterns, we conclude that the increased volatility is more likely driven by macroeconomic news announcements. An analysis of inter- and intraday data also reveals that volatility increases at times that coincide with the release of U.S. macroeconomic news.

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In this article, we examine volatility in the foreign currency futures market. The dollar trading volume in foreign exchange (FX) spot, forward, futures, and options markets is more than 100 times as large as the NYSE dollar volume, making it the largest in the world. The foreign currency market is characterized by high liquidity and low transaction costs, and it is open around the clock; this provides for a rich set of possible volatility patterns. Since arrival of new information induces volatility, we analyze the role of public news announcements in determining these patterns.

The literature on market microstructure mainly focuses on the market for common equity in the United States.[1] The work of Oldfield and Rogalski (1980), Wood, McInish, and Ord (1985), French and Roll (1986), Harris (1986), and others has uncovered empirical regularities in trading volume and security price behavior, which has in turn generated substantial interest among financial market theorists. A common feature of the empirical and theoretical research in this area is the central role of information in determining price volatility. Macroeconomic news, in particular, is a crucial factor affecting exchange-rate volatility.

This study of the futures transactions on the Chicago Mercantile Exchange's (CME) International Monetary Market (IMM) and the London International Financial Futures Exchange (LIFFE) reveals that the U.S.–European FX futures are, on average, twice as volatile during U.S. trading hours as during European trading hours. This suggests that the effect of U.S. macroeconomic news released during IMM trading hours dominates the effect of news released in the European markets in determining the volatility of U.S.–European rates.

Volatility can also be induced by trading that acts on private information. The dollar volatility may occur during the time the U.S. markets are open because most of the private information about the value of the dollar is revealed by U.S. investors at times when they face the least transactional impediments to trade. However, in the currency markets, U.S. investors have the ability to trade in many markets 24 hours a day. In addition, trading during U.S. business hours does not necessarily imply lower transactions costs. Indeed, the most liquid market for foreign exchange is not in the U.S.—the trading volume in London is twice the size of New York.[2] While it is not possible to test directly the relative importance of private information versus macroeconomic information-based trading on volatility, the ability to trade around the clock and the high liquidity in non-U.S. markets

[1] A recent notable exception is a study of the Japanese equity market by Barclay, Litzenberger, and Warner (1990).

[2] In spot and forward volume, London is the largest market, followed by Tokyo and then New York. See Krugman and Obstfeld (1988).

suggests that the concentration of volatility for the U.S. exchange rates during U.S. trading hours is probably driven by public- rather than private-information-based trading. In addition, the definition of private information and informed traders is not clear in the FX market.

Our examination of the exchange cross-rates reveals that the European currencies are generally more volatile during European trading hours. For example, the Swiss franc–Deutsche mark exchange rate is three times as volatile during European trading hours as it is when the European markets are closed. Surprisingly, some of the differences in exchange cross-rate volatilities between U.S. and European trading hours are small. For example, the British pound–Deutsche mark exchange rate is only 25 percent more volatile during European trading hours than it is during U.S. trading hours. The volatility of the British pound–Swiss franc exchange rate is similar during U.S. and European trading hours. In short, while most of the volatility of European exchange cross-rates is concentrated during European trading hours, U.S. macroeconomic news also appears to have an impact on some of the European currency cross-rates.

There is no exchange trading of currency futures in Japan during our sample period. However, a comparison of the IMM open-to-close return variances to weekday close-to-open variances for the dollar–yen futures suggests that the IMM trading time volatility is 2.2 times as large as the overnight volatility (when the Japanese market is the most active), which is again suggestive of the important role that U.S. macroeconomic information plays in global exchange-rate determination.

Transaction data on the IMM further enable us to explore the patterns of volatility across and within trading days. The concentration of U.S. macroeconomic announcements on Thursdays and Fridays appears to manifest itself in higher volatilities during the opening hours of the IMM on these days. The higher volatilities on Friday openings also coincide with the reopening of a primary market after the early Friday closings of major European markets. Studies of the U.S. equity markets, such as Wood, McInish, and Ord (1985), have also discovered that equity returns are more volatile during opening and closing hours. Kyle (1985), Admati and Pfleiderer (1988), and others have proposed models that may explain this empirical regularity and that may also account for the elevated Friday opening volatilities of the currency futures contracts.

The article is organized as follows. In the first section, an introduction to the institutional structure of the foreign currency markets is provided. In Section 2, the implications of public information trading for volatility patterns are explored across periods of exchange trading and nonexchange trading, both intraday and over the weekends. In the third section, the timing of U.S. macroeconomic news disclosures and the volatility patterns during trading intervals on the IMM are studied. Some concluding remarks are offered in the final section.

1. The Market for Foreign Exchange

The FX market is the largest financial market in the world. In a market survey conducted in April 1989, the Federal Reserve Bank of New York estimated that the average daily volume in the United States FX market was $128.9 billion. Since the U.S. share of the world FX market is about 25 percent, the total daily volume of FX transactions exceeds $500 billion per day.[3] Most of the FX trading is concentrated in the interbank spot and forward markets, which are over-the-counter markets whose major participants are banks and FX brokers.

Only a small portion of the total FX trading takes place in the futures market. However, the FX futures market is intimately linked to the spot and forward trades conducted in the interbank market. In the interbank market, simultaneous trades often occur at different prices, so that the single price posted by the futures exchange becomes an important source of information to the traders who are typically active in both markets. In principle, forward and future prices differ because of the daily resettlement of futures. However, empirical studies by Cornell and Reinganum (1981) and Hodrick and Srivastava (1987) confirm the close association between forward and future exchange rates.

The FX market is open 24 hours a day and is facilitated by electronic trading and a succession of overlapping business hours; when banks in one region of the world close for the day, banks in another part of the world open for business. Even when banks and brokers close for normal business hours, FX traders keep track of market movements via information relayed by Reuters and Telerate. London is the major market for FX transactions, followed by Tokyo, New York, Frankfurt, and Zurich. The market is most liquid during the period when the New York and European banks are open simultaneously.

Foreign currency futures. In this article, foreign currency futures traded on the IMM and the LIFFE are examined. On the IMM, the five most actively traded contracts are the Deutsche mark (DM), the Japanese yen (JY), the Swiss franc (SF), the British pound (BP), and

[3] The 25 percent estimate is based on surveys conducted simultaneously in March 1986 by the Federal Reserve Bank of New York, the Bank of England, and the Bank of Japan. See Krugman and Obstfeld (1988).

the Canadian dollar (CD). The exchange rates are quoted as U.S. dollars per unit of foreign currency. Trading occurs between approximately 7:30 A.M. Central Time (CT) and 1:30 P.M. CT.[4] The closing times of the contracts are staggered on the IMM. The SF closes at 1:16 P.M. and is followed by the DM at 1:20 P.M. The JY is the next to close at 1:22 P.M. The BP closes at 1:24 P.M., and the CD at 1:26 P.M. However, on the last trading day of the contract, which is the second business day before the third Wednesday of the delivery month, the currency futures close between 9:16 A.M. and 9:21 A.M.

The LIFFE trades currency futures for the BP, the DM, the JY, and the SF. The JY futures trade between 2:30 A.M. CT to 10:00 A.M. CT. The BP futures open at 2:32 A.M. and close at 10:02 A.M. The DM and SF futures follow 2 minutes apart. The CD contract is not traded on the LIFFE.

FX futures are also traded on other exchanges. For example, the same currency futures traded on the IMM are available on the Philadelphia Board of Trade. Although volume is smaller, the trading hours are longer. All contracts open at 7:00 A.M. CT and close at 1:30 P.M. CT. Recently, Philadelphia has changed its schedule to open at 3:30 A.M. CT and has added a second trading session between 6:00 P.M. CT and midnight. Additionally, the IMM has recently established a link to the Singapore International Monetary Exchange that will allow a second session between 10 P.M. CT and 4:00 A.M. CT. Finally, some currency futures are also available on South American exchanges.

2. Trading and Nontrading Volatility

Several studies, including Oldfield and Rogalski (1980), French and Roll (1986), and Stoll and Whaley (1990), document a dramatically higher volatility for equity returns during exchange trading hours than during nontrading hours. For example, French and Roll find that hourly variances during trading hours are more than 70 times as large as variances over the weekend.

French and Roll (1986) propose three possible explanations for the higher variances during trading hours. The first is that variances are higher during trading hours because *public information* is more likely to be released during normal business hours. The second hypothesis is that the volatility patterns are due to the revelation of *private information* through trading which can only take place when the exchanges are open. Their third hypothesis is that the patterns

[4] Central Europe's Daylight Time is in effect from the last Sunday in March to the last Sunday in September, while U.S. Daylight Savings Time begins the first Sunday in April and ends the last Sunday in October.

may be caused by *pricing errors* that are generated by the trading process. Based on their evidence, they conclude that the higher volatility during the exchange hours is primarily due to the revelation of private information through trading.

The IMM and the LIFFE provide a unique opportunity to study the differences in trading and nontrading volatilities, since, although the futures exchanges are open each day for only 6 and 7.5 hours, respectively, trading in other markets is possible around the clock on weekdays as well as weekends. The 24-hour nature of the FX market contrasts sharply with the market for U.S. equities in which there is virtually no trading overnight or during the weekend.

Following French and Roll (1986), we compute the hourly variance rates for exchange trading and nonexchange trading intervals and determine the ratios of these variance rates. The computation of the *variance rate ratio* is based on the assumption that returns are serially uncorrelated. We also report the *total variance ratio* of nonexchange to exchange trading variances.

In the equity market, French and Roll (1986) exploit the market closure to argue that trading based on private information leads to higher volatility when the market is open compared to when the market is closed. However, the FX market is not characterized by this special type of market closure. FX markets are liquid during European, U.S., and Japanese trading hours. Also, in contrast to the stock market, the impact of informed trading in the FX currency markets is limited as the determinants of FX rates are generally publicly available information.[5] These different market characteristics obscure the implications of the private information hypothesis on the relative variance rates of exchange trading time to nonexchange trading time, and make it difficult to apply the private information hypothesis of French and Roll.

The public information hypothesis suggests that even though trading outside exchange trading time is important, the exchange trading variance rate may exceed the nonexchange trading variance rate because individual exchange rates are also affected by public economy-wide information pertaining to the countries concerned and possibly to other countries as well. Public information released during trading hours in both countries will likely have an important influence on the volatility of their FX rate. In other words, we might observe volatility concentrated during the times when the most relevant macroeconomic news is released.

[5] Likewise, pricing errors may also occur around the clock and may partially account for the differences in volatilities. However, it is difficult in practice to distinguish between volatility induced by information and volatility due to noise trading.

The public information hypothesis implies that the CD should yield the highest ratio of the IMM exchange trading time to nonexchange trading time variance rates since Canadian macroeconomic news releases occur primarily during the IMM trading hours, and economic news in the nonexchange trading hours should be less relevant for the U.S.–Canadian exchange rate.[6] Moreover, given the tightly linked economies of Canada and the United States, macroeconomic news revealed during trading hours in *either* country should increase exchange-rate volatility. In contrast, the Japanese market is open when the IMM is closed and vice versa. In this case, the variance rate ratio will be low if news generated during Japanese trading hours contributes to exchange-rate volatility.

We also calculate the ratio of exchange trading time variance rate to nonexchange trading time variance rate for the LIFFE. In addition, we form ratios of variance rates during the IMM trading intervals and the LIFFE trading intervals. This allows us to investigate whether news released during U.S. trading hours is more important than news released during the LIFFE trading hours.

In summary, both private information and public information can induce volatility. While the private information hypothesis cannot be ruled out, given the ability to trade around the clock and the lack of differential transactional impediments in other markets, we expect the ratio of exchange trading time to nonexchange trading time variance rates to reflect primarily the timing of public information releases. Since the exchange rates are responsive to public economy-wide information pertaining to the countries concerned and possibly to other countries as well, the ratios for the foreign currency futures depend on the trading hours of the different countries and contain information on the relative importance of news released in different countries.

2.1 Data

Our data consist of foreign currency futures transactions on the IMM from the inception of trading to May 10, 1988. We elected to start the sample on July 21, 1980, when the opening was moved back from 8:20 A.M. CT to 7:20 A.M. CT. This ensures the same number of trading hours over the 8-year sample for our analysis of volatility patterns.[7]

We use the nearby futures contract on all days with one exception. On the last day of trading, we jump to the next-out futures contract to avoid the early closing time. Opening and closing prices are

[6] Scheduled Canadian macroeconomic news is released at 9:00 A.M. CT in the Statistics Canada publication called *The Daily*.

[7] Harvey (1988) provides an analysis of the heteroskedasticity in the daily returns using this same data set.

obtained by taking the first transaction price in the first 20 minutes of trading and the last transaction price in the last 20 minutes of trading.[8] The hourly returns are from Open–8:30 through 12:30–Close. They are computed as $(p_t/p_{t-1}) - 1$ by using the transaction price that is closest to the half hour, but within a 5-minute band on each side of the half hour.[9] Variances of the hourly returns are then computed to obtain the variance rate. When returns are measured over longer periods (i.e., open-to-close and close-to-open), a variance rate is calculated by deflating the measured total variance by the number of hours in the interval.

Our variance estimates derived from transaction data may be biased upward because of the bid–ask spread.[10] However, the bid–ask spread is narrow for currency futures traded on the IMM. It is about one tick (the amount of the minimum price fluctuation), which generally amounts to less than 0.05 percent of the bid or ask quotes. It is unlikely that the bias will systematically affect the variance ratios.

The LIFFE futures contracts are identical to the IMM contracts.[11] We have transaction data from 1986 through 1989. However, the currency futures contracts on the LIFFE never generated much interest and trading was finally suspended in 1990.[12] We confine our analysis to 1986 and 1987, when transactions are more frequent. Even for these years, there are insufficient observations to conduct a meaningful analysis of intraday variances. Therefore, we concentrate on variances computed from the daily opening and closing prices.

2.2 Empirical results

In Table 1, the volatility during IMM trading and nontrading intervals is compared. For the weekend, variances from Friday close to Monday open are compared with open-to-close variances during the week. The holiday and weekend definitions presented are the same as those used by French and Roll (1986).

The weekend variance rate ratio for all currencies traded on the

[8] Since all five contracts are actively traded, this eliminates very few observations.

[9] Since it is possible to enter a futures contract without any initial investment, the return is not defined. Nevertheless, the main focus in futures research is price changes, and we use *relative* price changes to facilitate cross-contract comparisons. The relative price change is an actual return if the full value of the contract is placed in a non-interest-bearing margin account.

[10] See Blume and Stambaugh (1983) and Smith (1989).

[11] In fact, the only significant difference is the trading hours. The LIFFE also offers two Deutsche mark contracts. The first matches the IMM and is expressed in terms of U.S. dollars per Deutsche mark. The other contract is the inverse: Deutsche marks per U.S. dollar. Our analysis focuses on the first contract.

[12] The low trading volume on the LIFFE is consistent with the predictions of Chowdhry and Nanda (1991) who consider a model where identical contracts are traded simultaneously on different exchanges. However, it is interesting to note that the volume of spot and forward trading in London is approximately double the New York volume. See Krugman and Obstfeld (1988).

Table 1
A comparison of (open-to-close) weekday return variances, σ_T^2, and (close-to-open) variances, σ_N^2, over holidays and weekends for the nearest to delivery futures contract on the IMM

Weekday holidays	Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/42)$	5.2	4.7	4.9	5.6	5.0	6.7
	Total variance ratio σ_N^2/σ_T^2	1.335	1.503	1.416	1.254	1.412	1.052
	Observations	80	16	16	16	16	16
Weekends	Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/66)$	6.5	6.7	7.1	6.6	4.9	13.9
	Total variance ratio σ_N^2/σ_T^2	1.685	1.648	1.550	1.676	2.234	0.793
	Observations	1796	359	360	360	360	357
Holiday weekends	Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/90)$	9.6	10.6	13.0	9.9	5.5	12.4
	Total variance ratio σ_N^2/σ_T^2	1.568	1.416	1.152	1.520	2.728	1.209
	Observations	199	40	40	40	40	39

The sample period is from July 21, 1980 to May 10, 1988. BP, British pound; SF, Swiss franc; DM, Deutsche mark; JY, Japanese yen; and CD, Canadian dollar. All quotations are in terms of U.S. dollar per currency unit. Variances are those of relative price changes, $(p_t/p_{t-1}) - 1$. The total variance ratio is the variance of returns from the close of the last trading day before a holiday (or weekend) to the open of the first trading day that follows, σ_N^2, divided by the variance of the daily open-to-close returns, σ_T^2. The variance rate ratio measures the relative volatility of the currencies during IMM trading hours compared to nontrading hours: the open-to-close variance per hour the exchange is open is divided by the close-to-open variance per hour the exchange is closed.

IMM is 6.5. This is sharply lower than the ratio of 71.8 reported by French and Roll (1986) for common equity.[13] The smaller ratio for currencies is consistent with the private information hypothesis, since trading in currencies takes place during the hours that the IMM is closed. However, the fact that the variance rate is higher during trading hours than during nontrading hours implies some concentration of private- or, more plausibly, public-information-induced volatility during trading hours. Since there are relatively few macroeconomic news announcements on weekends, a variance rate that is greater than unity may be attributed to trading based on public information.

The weekend variance rate ratio of 13.9 for the CD is higher than for the other contracts. Since trading on the Canadian FX markets substantially coincides with trading on the IMM, this result is also consistent with the public-information hypothesis.[14] In contrast, the Japanese markets are open during the nonexchange trading hours, and the JY variance rate ratio of 4.9 is the smallest of all the contracts. The same pattern is also observed in the analysis of 3-day holiday weekends: the CD ratio is 12.4 (highest) and the JY ratio is 5.5 (lowest). The CD ratio of 6.7 is also the highest for weekday holidays, but the results for the weekday holidays may be less reliable because of the small number of observations.

The weekend variance rate ratios of the three European currencies are between the JY and the CD contracts, which is what we would expect for currencies with overlapping trading hours. Specifically, the numerator of the IMM ratios contains 2.5 hours of trading when both the IMM and the LIFFE are operating and 3.5 hours of IMM trading alone.

Table 2 shows the variance rate ratios for daily (open-to-close) returns to overnight (close-to-open) returns for the IMM foreign currency futures. In Table 3, the same ratios are presented for the LIFFE foreign currency futures. The numerator variance only includes four overnights: Monday–Tuesday, Tuesday–Wednesday, Wednesday–Thursday, and Thursday–Friday.

The influence of non-IMM FX trading is apparent in Table 2. These ratios are sharply lower than the value of 16.2 for U.S. common equity found by Stoll and Whaley (1990). The U.S. dollar variance rate ratios for the IMM in Table 2 are higher than the ratios for the LIFFE reported in Table 3. Although the results are based on different samples (Table

[13] French and Roll (1986) compute the variance of returns from the close of the last trading day before a holiday (or weekend) to the close of the first trading day that follows. Since we use both opening and closing prices in the tables, we also compute the ratios in Table 1 using only closing prices to make our ratios comparable to those obtained by French and Roll. The weekend variance rate ratio for all currencies is 15.1. These results are available from the authors upon request.

[14] Private-information trading that is concentrated during exchange trading times may also contribute to the increased volatility.

Table 2
A comparison of overnight (close-to-open) variances, σ_N^2, and trading time (open-to-close) variances, σ_T^2, for the nearest to delivery currency futures contract traded on the IMM

	All currencies	US	BP	SF	DM	JY	CD
US$ per							
Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/18)$	3.4	—	3.6	3.9	3.6	2.2	3.9
Total variance ratio σ_N^2/σ_T^2	0.892	—	0.828	0.766	0.838	1.348	0.771
Observations	7660	—	1543	1543	1540	1533	1501
BP per							
Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/18)$	3.1	3.6	—	3.0	2.7	2.4	3.7
Total variance ratio σ_N^2/σ_T^2	0.965	0.825	—	0.988	1.101	1.225	0.817
Observations	7652	1543	—	1540	1538	1531	1500
SF per							
Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/18)$	3.6	3.9	3.0	—	4.0	3.0	4.0
Total variance ratio σ_N^2/σ_T^2	0.831	0.765	0.986	—	0.754	0.987	0.749
Observations	7653	1543	1540	—	1539	1533	1498
DM per							
Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/18)$	3.3	3.6	2.7	4.0	—	2.5	3.7
Total variance ratio σ_N^2/σ_T^2	0.919	0.837	1.106	0.755	—	1.198	0.804
Observations	7645	1540	1538	1539	—	1531	1497
JY per							
Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/18)$	2.5	2.2	2.5	3.0	2.5	—	2.3
Total variance ratio σ_N^2/σ_T^2	1.218	1.347	1.218	0.984	1.193	—	1.313
Observations	7620	1533	1531	1533	1531	—	1492
CD per							
Variance rate ratio $(\sigma_T^2/6)/(\sigma_N^2/18)$	3.4	3.9	3.7	4.0	3.7	2.3	—
Total variance ratio σ_N^2/σ_T^2	0.880	0.771	0.819	0.752	0.806	1.319	—
Observations	7488	1501	1500	1498	1497	1492	—

The sample period is from July 21, 1980 to May 10, 1988. The observations included in this table are only those days in which the close to the following observation's open is only one night. BP, British pound; SF, Swiss franc; DM, Deutsche mark; JY, Japanese yen; and CD, Canadian dollar. Variances are those of relative price changes, $(p_t/p_{t-1}) - 1$. The total variance ratio is the variance of returns measured from the close to the open (Monday–Tuesday, Tuesday–Wednesday, Wednesday–Thursday, and Thursday–Friday), σ_N^2, divided by the variance of the daily open-to-close returns, σ_T^2. The variance rate ratio measures the relative volatility of the currencies during IMM trading hours compared to nontrading hours: the open-to-close variance per hour the exchange is open (6 hours) is divided by the close-to-open variance per hour the exchange is closed (18 hours).

Table 3
A comparison of overnight (close-to-open) variances, σ_N^2, and trading time (open-to-close) variances, σ_T^2, for the nearest to delivery currency futures contract traded on the LIFFE

	All currencies	US	BP	SF	DM	JY
US$ per						
Variance rate ratio $(\sigma_T^2/7.5)/(\sigma_N^2/16.5)$	1.1	—	1.1	0.7	1.5	0.8
Total variance ratio σ_N^2/σ_T^2	2.058	—	2.012	3.398	1.471	2.814
Observations	868	—	308	90	274	196
BP per						
Variance rate ratio $(\sigma_T^2/7.5)/(\sigma_N^2/16.5)$	1.3	1.1	—	1.1	1.9	1.3
Total variance ratio σ_N^2/σ_T^2	1.652	2.013	—	2.003	1.196	1.714
Observations	800	308	—	81	237	174
SF per						
Variance rate ratio $(\sigma_T^2/7.5)/(\sigma_N^2/16.5)$	1.0	0.7	1.1	—	2.0	0.8
Total variance ratio σ_N^2/σ_T^2	2.297	3.390	2.004	—	1.091	2.880
Observations	321	90	81	—	84	66
DM per						
Variance rate ratio $(\sigma_T^2/7.5)/(\sigma_N^2/16.5)$	1.7	1.5	1.9	2.0	—	1.8
Total variance ratio σ_N^2/σ_T^2	1.304	1.462	1.189	1.105	—	1.225
Observations	753	274	237	84	—	158
JY per						
Variance rate ratio $(\sigma_T^2/7.5)/(\sigma_N^2/16.5)$	1.1	0.8	1.3	0.8	1.8	—
Total variance ratio σ_N^2/σ_T^2	1.967	2.802	1.726	2.877	1.230	—
Observations	594	196	174	66	158	—

The sample period is from January 2, 1986 to December 30, 1987. The observations included in this table are only those days in which the close to the following observation's open is only one night. BP, British pound; SF, Swiss franc; DM, Deutsche mark; and JY, Japanese yen. The Canadian dollar is not traded on the LIFFE. Variances are those of relative price changes, $(p_t/p_{t-1}) - 1$. The total variance ratio is the variance of returns measured from the close to the open (Monday–Tuesday, Tuesday–Wednesday, Wednesday–Thursday, and Thursday–Friday), σ_N^2, divided by the variance of the daily open-to-close returns, σ_T^2. The variance rate ratio measures the relative volatility of the currencies during LIFFE trading hours compared to nontrading hours: the open-to-close variance per hour the exchange is open (7.5 hours) is divided by the close-to-open variance per hour the exchange is closed (16.5 hours).

2 is 1980–1988 and Table 3 is 1986–1987), the comparison suggests that the U.S. exchange-rate volatility during U.S. trading hours is greater than the volatility during non-U.S. trading hours.

It is worth noting from Tables 2 and 3 that the IMM and the LIFFE ratios both exceed unity. In both of these ratios, the denominator contains a period of nonexchange (IMM or LIFFE) trading. If volatility during this nonexchange trading time is very low, then both variance ratios can be greater than unity.

The three U.S.–European currency rates are, on average, 3.7 times more volatile during IMM trading hours than during non-IMM trading hours; the corresponding figure for the same three contracts traded on the LIFFE is 1.1. The dollar-JY rate is only 2.2 times more volatile during the IMM trading hours. The lower Japanese ratio may be due to the fact that a full day of trading in Japan takes place when the

IMM is closed. The corresponding ratio for the LIFFE JY contract in Table 3 is only 0.8.

The highest ratios reported in Table 2 are for the dollar–CD and the dollar–SF, which are both equal to 3.9. It is puzzling that the SF ratio is so high, since one would expect the CD ratio to be the highest because the trading hours in Canada and the U.S. are identical, and the CD contract is not traded on the LIFFE.[15] However, it is reassuring to note from Table 1 that the greatest weekday–holiday and weekend variance rate ratios are found for the CD contract.

Table 2 also shows the volatility ratios for the exchange cross-rates. The volatility ratios for all the CD exchange rates are similar to those for the U.S. dollar, which is not surprising since the markets have overlapping trading hours and Canada is tightly linked to the U.S., so that any macroeconomic shock is likely to affect both countries in the same direction.

The variance rate ratios of the other cross-rates in Table 2 range between 2.4 and 4.0, and are uniformly higher than the corresponding ratios for the same contracts reported in Table 3. The close-to-open volatilities for the LIFFE cross-rates are affected by the reaction of the rates to U.S. news. Given the prominence of the U.S. in international trade and investment, it is not surprising to find that news from the U.S. has a strong impact on exchange cross-rates.

In Table 4, a direct comparison of volatility during trading hours on the LIFFE and the IMM is provided. The variances on both exchanges are measured over a common 1986–1987 period. The first panel shows that the U.S.–European exchange rates are, on average, twice as volatile during IMM trading hours.[16] The dollar–JY exchange rate is 1.8 times as volatile during the Chicago trading hours.[17] The volatility of the European exchange cross-rates is generally concentrated during European trading hours. For example, the BP–DM rate is 25 percent more volatile during LIFFE hours, and the BP–SF rate has roughly equal volatility during IMM and LIFFE trading hours. However, the SF–DM rate is more than three times as volatile during LIFFE hours. These higher exchange cross-rate variance ratios are consistent with the higher probability that relevant European mac-

[15] A similar result is reported over a different sample in Hertzel, Kendall, and Kretzmer (1989) for the dollar–CD ratio versus the U.S.–European ratios.

[16] This ratio is a conservative measure for detecting whether volatility is greater during U.S. trading hours because there is an overlap of trading time between the IMM and the LIFFE. U.S. macroeconomic news is released at the beginning of the day for the U.S. markets, which coincides with the end of trading for the European markets. LIFFE volatility will be higher if some of the U.S. news is reflected in late afternoon trading in the European markets.

[17] It would also be interesting to compare volatility during Chicago trading hours to volatility during Tokyo trading hours. Unfortunately, there is no exchange trading of the dollar–JY futures contract in Tokyo. However, Ito and Roley (1987) find that the volatility during New York business hours of the JY–dollar spot rate exceeds its volatility during Tokyo business hours.

Table 4
A comparison of trading time (open-to-close) variances on the IMM, σ^2_{IMM}, and the trading time (open-to-close) variances on the LIFFE, σ^2_{LIFFE}

	All currencies	US	BP	SF	DM	JY
US$ per						
IMM variance σ^2_{IMM}	2.231	—	2.508	3.343	2.610	2.224
LIFFE variance σ^2_{LIFFE}	1.878	—	1.649	1.654	2.480	1.505
Variance rate ratio $(\sigma^2_{IMM}/6)/(\sigma^2_{LIFFE}/7.5)$	1.5	—	1.9	2.5	1.3	1.8
BP per						
IMM variance σ^2_{IMM}	1.934	2.503	—	1.737	1.401	1.642
LIFFE variance σ^2_{LIFFE}	2.079	1.644	—	2.130	2.480	2.286
Variance rate ratio $(\sigma^2_{IMM}/6)/(\sigma^2_{LIFFE}/7.5)$	1.2	1.9	—	1.0	0.8	0.9
SF per						
IMM variance σ^2_{IMM}	2.000	3.330	1.735	—	0.368	1.155
LIFFE variance σ^2_{LIFFE}	1.619	1.649	2.124	—	1.476	1.151
Variance rate ratio $(\sigma^2_{IMM}/6)/(\sigma^2_{LIFFE}/7.5)$	1.5	2.5	1.0	—	0.3	1.2
DM per						
IMM variance σ^2_{IMM}	1.584	2.603	1.398	0.368	—	0.911
LIFFE variance σ^2_{LIFFE}	2.229	2.493	2.476	1.467	—	1.817
Variance rate ratio $(\sigma^2_{IMM}/6)/(\sigma^2_{LIFFE}/7.5)$	0.9	1.3	0.8	0.3	—	0.6
JY per						
IMM variance σ^2_{IMM}	1.641	2.207	1.638	1.154	0.910	—
LIFFE variance σ^2_{LIFFE}	1.781	1.503	2.277	1.149	1.816	—
Variance rate ratio $(\sigma^2_{IMM}/6)/(\sigma^2_{LIFFE}/7.5)$	1.2	1.8	0.9	1.2	0.6	—

The sample period is from January 2, 1986 to December 30, 1987. BP, British pound; SF, Swiss franc; DM, Deutsche mark; and JY, Japanese yen. The Canadian dollar is not traded on the LIFFE. Variances are those of relative price changes, $(p_t/p_{t-1}) - 1$. The variance rate ratio measures the relative volatility of the currencies during trading hours on the IMM compared to trading hours on the LIFFE: the open-to-close variance per hour the IMM is open (6 hours) is divided by the open-to-close variance per hour the LIFFE is open (7.5 hours).

roeconomic news is released during European trading hours. It is also possible that private-information traders concentrate their activities during European hours—when the market for these cross-rates is most liquid.

In summary, the results from Tables 1–4 suggest that U.S. dollar exchange rates are more volatile during U.S. trading hours. Given the highly liquid, around-the-clock market for the U.S. dollar, there is little reason to expect a concentration of private-information traders during U.S. business hours. Indeed, the highest FX (in spot and forward contracts) trading volume occurs in London. However, the concentration of volatility during U.S. trading hours is consistent with the importance of public information. It is intuitive that U.S. news is more important for the U.S. dollar contracts than news from other countries. Similar conclusions can be drawn from the analysis of exchange cross-rates. European news disclosures are at least as important as the U.S. news releases, and our results show higher European exchange cross-rate volatility during European trading hours. In the case of the European cross-rates, it is also plausible that there is a concentration of private-information trading during European trading hours when the cross-rate market is the most liquid. However, the identity of the informed traders is still unclear.

3. Variation in Volatility during Trading Intervals

In this section, we consider whether volatility during IMM trading hours is influenced by the release of public information through U.S. news announcements and whether the patterns of day of the week and intraday volatilities are consistent with the predictions of recent theoretical models.

Wood, McInish, and Ord (1985) find that the variability of equity returns over a trading day follows a U-shaped pattern. Admati and Pfleiderer (1988) illustrate the theoretical concentration of volatility in the presence of a particular type of adverse selection but not its timing. If there is an increase in nondiscretionary liquidity trading just before and after any period in which it is difficult to trade, then their model would predict prices to be more volatile and informative just after the open and just before the close.

The IMM opening coincides with the early afternoon trading [1:30 P.M. Greenwich Mean Time (GMT) in London and 2:30 P.M. GMT in Frankfurt and Zurich] in the European markets. From Monday to Thursday, the Continental banks close at 9:30 A.M. CT and the London banks close at 10:30 A.M. CT. On Friday, the European markets close at noon local time (5:00 A.M. to 6:00 A.M. CT). Therefore, on Fridays, the European banks have been closed for over an hour by the time the IMM opens. If nondiscretionary liquidity trading tends to increase before and after a period when it is relatively difficult to trade, then these would be the times that the Admati and Pfleiderer (1988) model would predict volatility concentrations. Given the presence of continuous and multiple markets for foreign exchange, it is unlikely that U-shaped intraday volatility patterns found in the analysis of the U.S. equity markets would be observed. However, given the early closure of the European markets on Fridays, volatility may be concentrated at the opening on Fridays.

Foster and Viswanathan (1990) have also developed a model of interday trading in which informed traders have more private information on Mondays after the stock market has closed for the weekend. Since informed traders have an incentive to trade before the information is publicly disseminated, their model predicts both higher trading costs and variability of price changes on Monday. The Foster and Viswanathan model would also suggest high opening Friday volatilities, because informed traders can replenish their stock of private

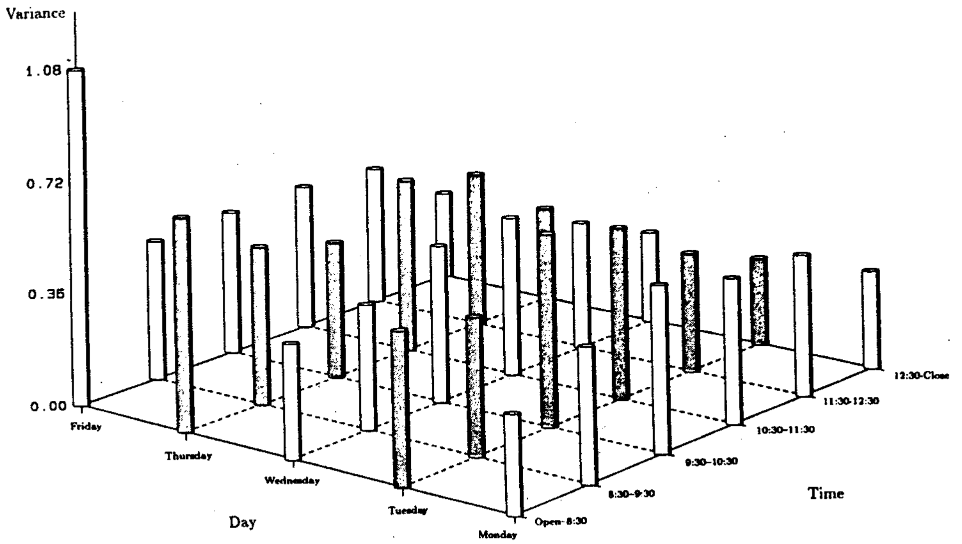

Figure 1
Inter- and intraday volatility: British pound futures
Variances for the nearest to delivery futures contract on the IMM are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The sample period is from July 21, 1980 to May 10, 1988.

information after important components of the European FX markets close early and before the IMM opens on Fridays.

Empirical results. Intraday variances by day of the week are reported in Table 5 and plotted in Figures 1–5. For Monday through Wednesday, there is an *inverse* U-shaped pattern in the volatilities. This pattern is most apparent for the U.S.–European exchange rates, less apparent for the dollar–JY rate, and absent in the dollar–CD currency futures.[18] During the first 3 days of the week, volatilities are low at the Open–8:30 period and the 8:30–9:30 period, higher during midday, and lower at the close. The higher midday volatilities coincide with the closing of the Continental markets at 9:30 A.M. CT and the London markets at 10:30 A.M. CT. In Table 5, a test of variance equality is presented which shows that, except for the SF, the intraday variances are significantly different from one another.[19] Since continuous trading is available in liquid markets, the concentration of midday volatilities is a puzzling phenomenon.

[18] Using intradaily spot market data for the BP, DM, SF, and JY from January 2, 1986 to July 15, 1986, Baillie and Bollerslev (1989) find a similar inverse U-shaped pattern over the hours in our sample. However, they do not partition the data by days of the week.

[19] In the Appendix, we develop a test of variance equality based on the generalized method of moments (GMM). The GMM test only requires weak distributional assumptions. The inference procedure also allows for general forms of conditional heteroskedasticity and for the returns to be contemporaneously correlated.

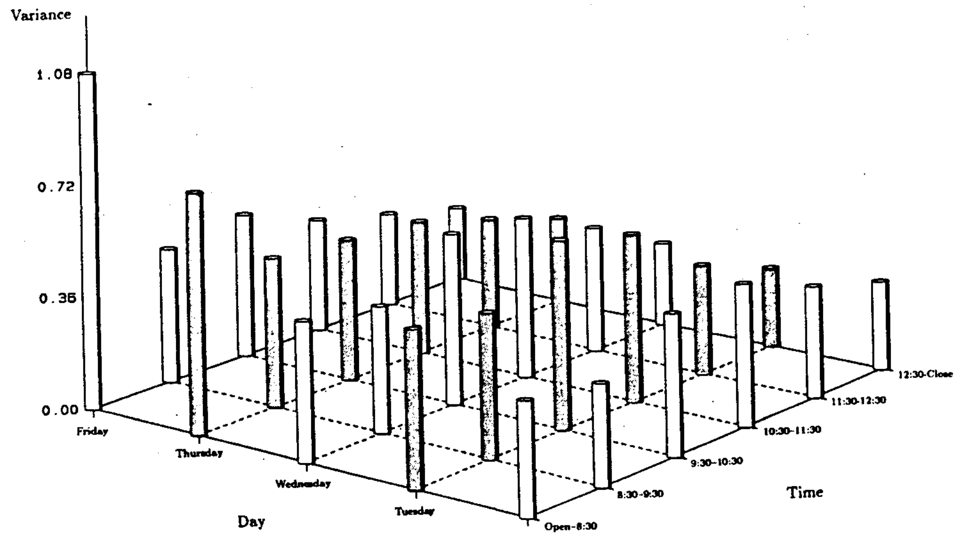

Figure 2
Inter- and intraday volatility: Deutsche mark futures
Variances for the nearest to delivery futures contract on the IMM are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The sample period is from July 21, 1980 to May 10, 1988.

The pattern on Fridays is quite different from that on the other weekdays. On Friday, high volatilities are observed in the first hour of exchange trading. The volatilities drop off sharply in the next hour, and remain moderately flat for the next 5 hours. Table 5 also shows

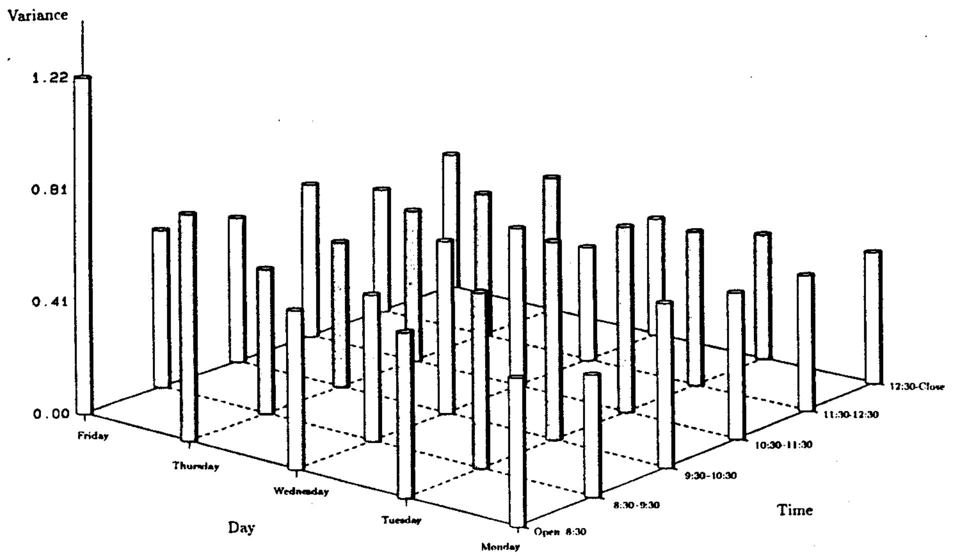

Figure 3
Inter- and intraday volatility: Swiss franc futures
Variances for the nearest to delivery futures contract on the IMM are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The sample period is from July 21, 1980 to May 10, 1988.

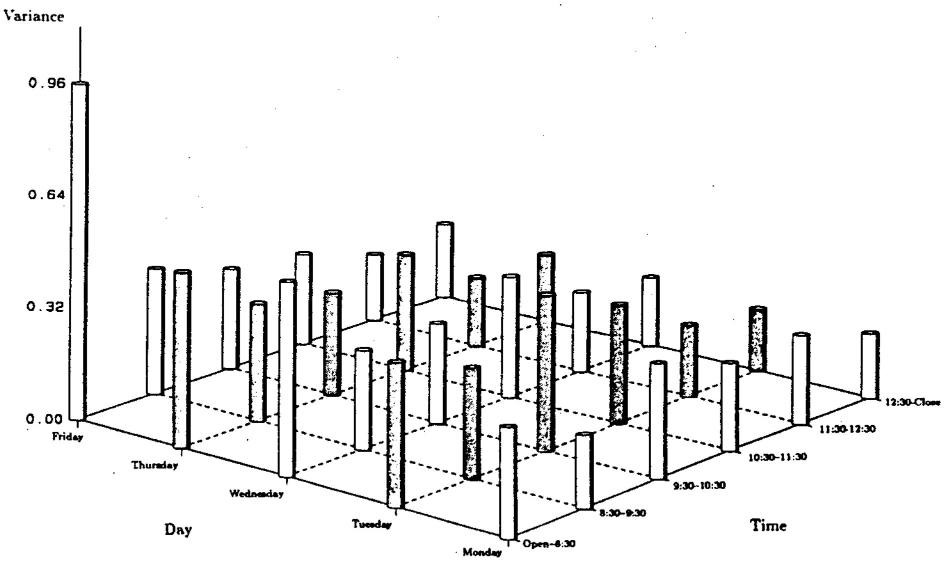

Figure 4
Inter- and intraday volatility: Japanese yen futures
Variances for the nearest to delivery futures contract on the IMM are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The sample period is from July 21, 1980 to May 10, 1988.

that the null hypothesis that the intraday Friday volatilities are equal can be rejected for all currencies except the SF. In fact, the strongest rejections occur on Fridays because of their elevated opening volatilities. It is important to note that the high Friday opening volatility

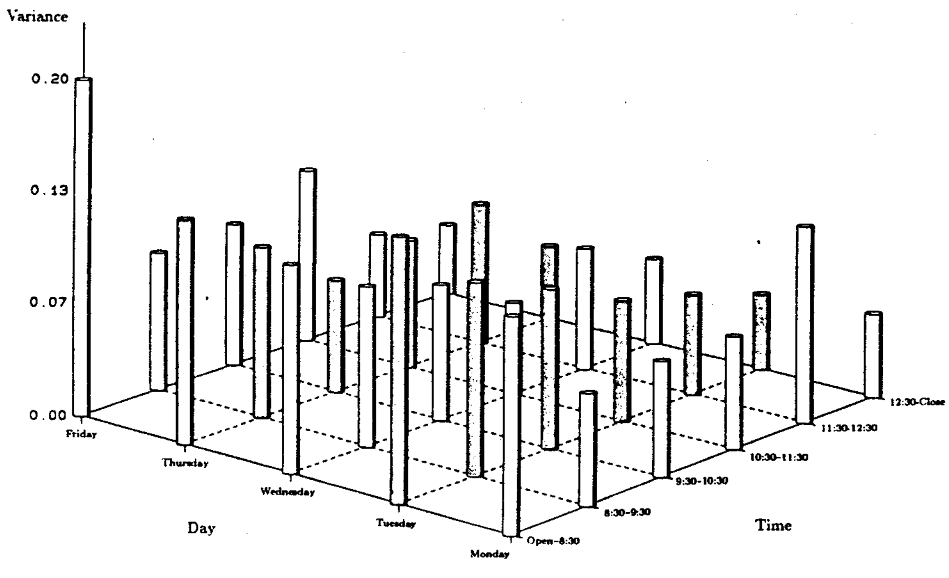

Figure 5
Inter- and intraday volatility: Canadian dollar futures
Variances for the nearest to delivery futures contract on the IMM are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The sample period is from July 21, 1980 to May 10, 1988.

Table 5
Intraday variance rates for the nearest to delivery futures contract on the IMM by day of the week and a test of whether the intraday variance rates are equal

	Day	Obs.	Open–8:30	8:30–9:30	9:30–10:30	10:30–11:30	11:30–12:30	12:30–Close	χ^2	p-value
British pound	Monday	337	0.32356	0.41820	0.54049	0.47493	0.46576	0.32735	17.193	.004
	Tuesday	360	0.50975	0.43078	0.61048	0.55461	0.37746	0.29452	20.557	.001
	Wednesday	359	0.37028	0.39013	0.51005	0.52334	0.42000	0.29049	17.752	.003
	Thursday	337	0.75865	0.52504	0.47252	0.60590	0.50565	0.[illegible]490	16.573	.005
	Friday	311	1.18719	0.46425	0.49760	0.48940	0.44797	0.29928	21.916	.001
	All days	1704	0.61807	0.44568	0.52882	0.53237	0.44420	0.30538	79.477	<.000
Swiss franc	Monday	372	0.45746	0.41080	0.57397	0.50994	0.49428	0.48604	7.770	.169
	Tuesday	396	0.56905	0.62267	0.71410	0.65784	0.56618	0.46757	8.759	.119
	Wednesday	387	0.55695	0.52996	0.62995	0.58702	0.42485	0.44378	11.664	.040
	Thursday	374	0.83779	0.52844	0.54286	0.56591	0.53962	0.51465	4.735	.449
	Friday	363	1.23321	0.56562	0.53178	0.57470	0.47249	0.52023	5.035	.412
	All days	1892	0.72785	0.53398	0.60188	0.58164	0.50086	0.48692	19.056	.002
Deutsche mark	Monday	362	0.31006	0.32973	0.45225	0.46138	0.36271	0.29001	14.629	.012
	Tuesday	387	0.49658	0.46706	0.61152	0.54600	0.35756	0.26332	26.963	<.001
	Wednesday	381	0.44680	0.40728	0.54756	0.50876	0.40772	0.26941	27.943	<.001
	Thursday	367	0.79335	0.49258	0.47615	0.44519	0.36552	0.29064	19.187	.002
	Friday	367	1.11897	0.43767	0.47112	0.36856	0.30091	0.24042	36.136	<.001
	All days	1864	0.63439	0.42843	0.51403	0.46809	0.35978	0.27133	98.961	<.000
Japanese yen	Monday	350	0.30281	0.19860	0.32607	0.24677	0.26382	0.19426	15.938	.007
	Tuesday	365	0.40035	0.31451	0.45651	0.33290	0.21170	0.18769	30.665	<.001
	Wednesday	356	0.56229	0.28027	0.28470	0.34765	0.23344	0.20554	21.531	.001
	Thursday	342	0.52814	0.33337	0.30363	0.35262	0.21115	0.21321	24.944	<.001
	Friday	334	1.02959	0.37064	0.30857	0.26694	0.19879	0.23041	17.484	.004
	All days	1747	0.56119	0.29942	0.33769	0.31124	0.22421	0.20632	68.218	<.000
Canadian dollar	Monday	214	0.14248	0.07243	0.07090	0.07172	0.08858	0.05894	25.346	<.001
	Tuesday	244	0.18526	0.13334	0.10246	0.07929	0.06086	0.05127	12.063	.034
	Wednesday	216	0.13648	0.10337	0.08077	0.06265	0.08447	0.05965	17.728	.003
	Thursday	214	0.17183	0.11337	0.07352	0.08198	0.08771	0.05328	39.454	<.001
	Friday	187	0.19626	0.08591	0.10140	0.11125	0.05619	0.05203	27.949	<.001
	All days	1075	0.16701	0.10337	0.08632	0.08087	0.07575	0.05502	48.904	<.000

The sample period is from July 21, 1980 to May 10, 1988. The variances are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. χ^2 is a heteroskedasticity-consistent test of whether the variances are equal across the hours of the day. The statistic has 5 degrees of freedom.

Table 6
The release days of major U.S. macroeconomic announcements

	Total	Monday	Tuesday	Wednesday	Thursday	Friday
GNP—preliminary (quarterly)	30 [100.0%]	3 [10.0%]	2 [13.3%]	11 [36.7%]	5 [16.7%]	7 [23.3%]
Civilian unemployment (monthly)	80 [100.0%]	0 [0.0%]	0 [0.0%]	0 [0.0%]	0 [0.0%]	80 [100.0%]
Producer price index (monthly)	80 [100.0%]	0 [0.0%]	0 [0.0%]	0 [0.0%]	0 [0.0%]	80 [100.0%]
Consumer price index (monthly)	99 [100.0%]	0 [0.0%]	34 [34.3%]	19 [19.2%]	11 [11.1%]	35 [35.4%]
Capacity utilization (quarterly until 1984)	9 [100.0%]	0 [0.0%]	0 [0.0%]	0 [0.0%]	0 [0.0%]	9 [100.0%]
Personal income (monthly)	89 [100.0%]	13 [14.6%]	16 [18.0%]	16 [18.0%]	28 [31.5%]	16 [18.0%]
Plant and equipment expenditures (quarterly)	29 [100.0%]	2 [6.9%]	6 [20.7%]	6 [20.7%]	14 [48.3%]	1 [3.4%]
Leading indicators (monthly)	88 [100%]	10 [11.4%]	25 [28.4%]	13 [14.8%]	18 [20.5%]	22 [25.0%]
Equally weighted average of frequency	[100.0%]	[5.4%]	[14.3%]	[13.7%]	[16.1%]	[50.6%]

Announcement dates supplied by the Department of Commerce's Bureau of Economic Analysis. These release dates include all years from 1980 through May 1988 except for 1983. The Department of Commerce did not have the history for the Consumer Price Index, and these data were obtained from a search through the *Wall Street Journal.*

is not caused by the expiration of the contract. The expiration takes place two business days before the third Wednesday of each month—which is almost always a Monday.

The large volatilities observed at the opening on Fridays may be attributed to U.S. public news announcements since a large number of U.S. macroeconomic announcements take place during the opening hour of trading on Fridays.[20] Some of these announcements are documented in Table 6. Three of the most important announcements, civilian unemployment, the producer price index, and capacity utilization, are always released on Fridays. A number of other announcements may also contribute to the opening Friday volatility. For example, beginning in February 1984, the Federal Reserve began releasing money supply aggregates on Thursdays at 3:30 P.M. CT (after the close of the IMM).

Table 6 also shows that many U.S. public announcements occur on Thursdays; in fact, Thursday is the second most frequent weekday for macroeconomic news releases. Perhaps it is no coincidence that the opening volatilities on Thursdays, reported in Table 5, are also elevated. Thursday appears to be a transition period with a mixture of

[20] For example, the Producer Price Index and the Civilian Unemployment Rate are released at the start of trading on the IMM (7:30 A.M. CT) on Fridays.

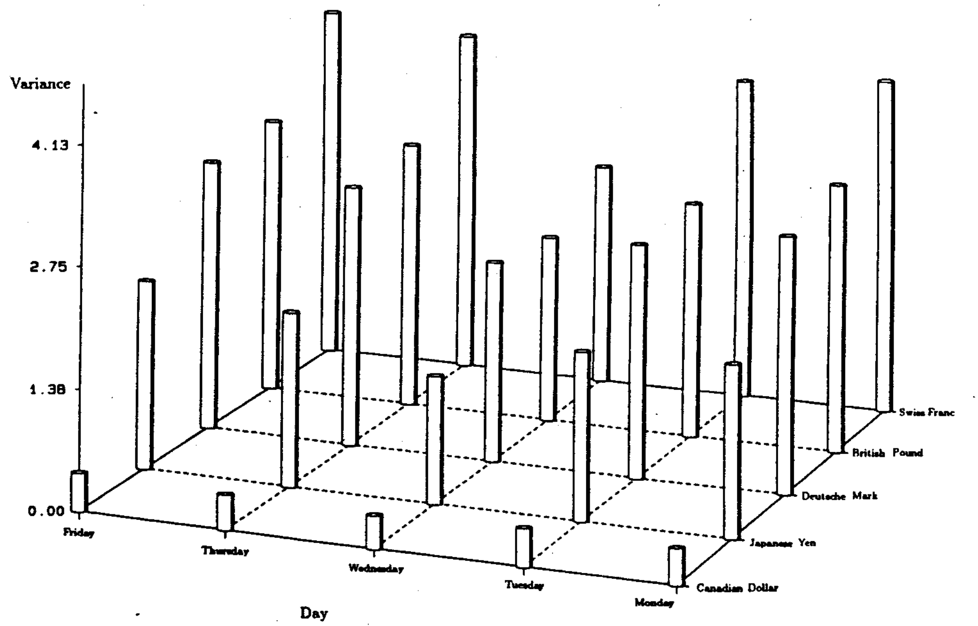

Figure 6
Interday volatility: All currency futures
Variances for the nearest to delivery futures contract on the IMM are those of the futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The sample period is from July 21, 1980 to May 10, 1988.

both Monday to Wednesday and Friday distributions. For example, we observe both a high opening volatility and an inverse U-shaped volatility pattern for all the European contracts. The Thursday opening volatilities are also not as high as the Friday openings.

The Friday opening variances are also consistent with the implication of the private-information models of both Admati and Pfleiderer (1988) and Foster and Viswanathan (1990). The high opening volatility coincides with the beginning of active trading in the New York interbank market and follows 1 to 2 hours of low market activity when the European banks are closed. Therefore, the elevated volatility may reflect the effects of major market closures earlier in the day. However, their model is unable to account for the higher variances observed on the Thursday opening.

In Table 7 and Figure 6, the currency volatilities by day of the week are reported and it is shown that a distinct U-shaped pattern characterizes the volatility during the week. Volatilities are high on Mondays and decrease on Tuesdays for all currencies except the CD. Wednesday volatilities are the lowest for all five currencies. From Wednesdays to Fridays, there is a monotonic increase in volatility for each currency. This U-shaped pattern does not support Foster and Viswanathan's (1990) prediction of monotonically decreasing volatility during the week. However, Monday's volatility is higher than

Table 7
Daily (open-to-close) total return variances for the nearest to delivery futures contract on the IMM by day of the week and a test of whether these variances are equal

	Monday	Tuesday	Wednesday	Thursday	Friday	χ^2 Mon = Tue	χ^2 All days
All currencies	2.47743 (1901)	2.31600 (2015)	1.78097 (2001)	2.50587 (1932)	2.61427 (1919)	3.152 [.076]	35.949 [<.001]
British pound	3.12293 (380)	2.73481 (405)	2.15908 (401)	3.08647 (389)	3.19604 (386)	1.605 [.205]	9.600 [.048]
Swiss franc	3.92981 (381)	3.76790 (405)	2.58316 (402)	4.00183 (389)	4.12999 (385)	0.490 [.484]	15.962 [.003]
Deutsche mark	2.95517 (381)	2.68918 (405)	2.30537 (402)	3.00956 (387)	3.12084 (385)	1.352 [.245]	4.890 [.299]
Japanese yen	1.96875 (381)	1.92686 (404)	1.46473 (399)	1.99665 (387)	2.16509 (384)	0.368 [.545]	9.628 [.047]
Canadian dollar	0.41814 (378)	0.43784 (396)	0.38228 (397)	0.40547 (380)	0.44237 (379)	0.251 [.616]	1.057 [.901]

Number of observations is in parentheses. The sample period is from July 21, 1980 to May 10, 1988. The variances are those of futures returns calculated as $(p_t/p_{t-1}) - 1$ and are multiplied by 100,000. The first χ^2 is a heteroskedasticity-consistent test of whether Monday's variance equals Tuesday's variance. The statistic has 1 degree of freedom. The second χ^2 tests whether the variances are equal across the days of the week. This statistic has 4 degrees of freedom. The p-values are in brackets.

Tuesday's volatility for all currencies except the CD, which is consistent with one version of their model. Nonetheless, a χ^2 test fails to reveal any evidence against the null hypothesis that the Monday volatility is equal to the Tuesday volatility.

For all currencies, the Friday volatilities are the highest, which is largely caused by the high variance at the opening, which is documented in Table 5 and is consistent with the effect of public news releases. Alternatively, an application of the Admati and Pfleiderer (1988) and Foster and Viswanathan (1990) private-information models to the FX market also predicts higher Friday volatility because the Friday opening follows 2 hours of low liquidity in Europe (as a result of the early closing of the European banks). However, these models are unable to explain the elevated variances at the opening on Thursdays. Therefore, the large number of macroeconomic news releases on both Thursdays and Fridays further suggests that volatility patterns in FX futures are induced by public-information announcements rather than by private-information trading.

4. Conclusions

The purpose of this article is to investigate volatility patterns in the market for foreign exchange. In contrast to equity markets, it is possible to trade FX around the clock, and there are no particular transactional impediments to trading in any market. The highest volume of FX trading takes place in London, followed by Tokyo and New York.

Volatility may be induced by the concentration of trading by investors with private information, or by public news announcements. Given that the private-information traders have access to liquid markets almost 24 hours a day, we argue that the volatility concentrations are more likely induced by the release of macroeconomic information. Using transaction data on foreign currency futures from the Chicago Mercantile Exchange's International Monetary Market and the London International Financial Futures Exchange, we present results that associate macroeconomic news with the variability of returns in nonexchange trading and exchange trading periods. We also examine the relation between the timing of U.S. macroeconomic news disclosures and the inter- and intraday volatility patterns on the IMM.

Our empirical evidence shows that intraday volatility on the IMM varies by day of the week. Fridays are much different from the other days of the week. The opening on Friday is characterized by sharply higher volatilities. A similar but less dramatic increase in volatility is also found on Thursdays. The high opening volatilities on Thursdays and Fridays may be explained by increased public-information announcements, since the most important day for U.S. macroeconomic announcements is Friday, and many key announcements also take place on Thursdays. The high opening volatilities on Fridays coincide with the reopening of the major market in foreign currency futures after a period of time during which the major European banks are officially closed and are also consistent with the private-information models of Admati and Pfleiderer (1988) and Foster and Viswanathan (1990). However, it is difficult to apply the private-information hypothesis to explain the high volatilities that are observed at the opening on Thursdays.

Our analysis of IMM trading, LIFFE trading, and nonexchange trading reveals that volatility is highest when the trading hours coincide with the business hours of the countries whose currencies are being traded. For example, the Swiss franc–Deutsche mark contract has higher volatility during London trading hours than during Chicago hours. This higher volatility could be due to an increased concentration of private-information trading during European business hours, when the market for exchange cross-rates is the most liquid. The volatility may also be a result of the timing of European macroeconomic news releases. For the U.S. dollar, the volatility is higher during Chicago trading hours even when the other currency is European. While it is possible that there is an increase in private-information trading during U.S. business hours, it is unlikely that this is the major determinant of the increased volatility. The market for the U.S. dollar is extremely liquid around the clock, with heavy trading during non-U.S. trading hours. We conclude that much of the volatility during U.S. trading hours is being driven by the release of U.S. macroeconomic news.

Appendix: Testing Variance Restrictions

In this appendix, we propose a test of variance equality based on the generalized method of moments (GMM). Rather than testing for differences in summary statistics (variances), we adopt a one-step testing procedure that uses all of the returns data. Let $\boldsymbol{\mu}$ be a five-element vector representing the unconditional means for a particular currency for each day of the week. The disturbance from the unconditional mean is

$$\boldsymbol{u}_t = \boldsymbol{r}_t - \boldsymbol{\mu}, \tag{A1}$$

where $\boldsymbol{r}_t$ is a five-element vector of daily returns for week t. Let $\boldsymbol{\sigma}^2$ be a five-element vector of daily unconditional variances. The disturbance from the unconditional variance is:

$$\boldsymbol{e}_t = (\boldsymbol{r}_t - \boldsymbol{\mu})^2 - \boldsymbol{\sigma}^2. \tag{A2}$$

Equations (A1) and (A2) can be combined into a system of equations:

$$\boldsymbol{\epsilon}_t = (\boldsymbol{e}_t \quad \boldsymbol{u}_t) = \begin{pmatrix} [\boldsymbol{r}_t - \boldsymbol{u}]' \\ [(\boldsymbol{r}_t - \boldsymbol{\mu})^2 - \boldsymbol{\sigma}^2]' \end{pmatrix}'. \tag{A3}$$

It is not necessary to include the equations for the means in (A3). However, it is computationally convenient to estimate the means and the variances simultaneously. Furthermore, the system (A3) could be used to test restrictions on the means as well as the variances.[21]

The definitions of unconditional mean and variances lead to the restriction

$$E[\boldsymbol{\epsilon}_t \mid \mathbf{Z}_{t-1}] = E[\boldsymbol{\epsilon}] = \mathbf{0}, \tag{A4}$$

where the conditioning information, $\boldsymbol{Z}$, is restricted to be the null information set—a vector of 1s. System (A3) has 10 parameters $(\boldsymbol{\mu}, \boldsymbol{\sigma}^2)$ and 10 orthogonality conditions. Hence, the model is exactly identified.

A natural way to estimate the parameters is with Hansen's (1982) GMM. The GMM technique forms a vector of the orthogonality conditions:

$$\boldsymbol{g} = \mathrm{vec}(\boldsymbol{\epsilon}'\boldsymbol{Z}), \tag{A5}$$

where $\boldsymbol{\epsilon}$ is the matrix of forecast errors $(\boldsymbol{e}, \boldsymbol{u})$ for T observations and 10 equations, and $\boldsymbol{Z}$ is the unit vector. Parameters $(\boldsymbol{\mu}, \boldsymbol{\sigma}^2)$ are chosen to make the orthogonality conditions as close to zero as possible by minimizing the quadratic form, $\boldsymbol{g}'\boldsymbol{w}\boldsymbol{g}$, where the $\boldsymbol{w}$ is a symmetric weighting matrix that defines the metric used to make $\boldsymbol{g}$ close to zero. Hansen outlines a form of the weighting matrix that guarantees that the estimates are consistent and asymptotically normal.

The minimized value of this quadratic form is distributed χ^2 under the null hypothesis with degrees of freedom equal to the number of orthogonality conditions minus the number of parameters to be estimated. This χ^2 statistic (which is a test of the *overidentifying* restrictions) provides a goodness-of-fit test for the model. In our case, the number of orthogonality conditions equals the number of parameters. As a result, there are no overidentifying restrictions and the χ^2 statistic is exactly zero. In addition, the means and variances are equal to the

[21] For example, (A3) can be used to test equality of the means during weekdays or the proportionality of the means to the variances.

classical estimates. However, since the parameters are consistent and asymptotically normal, it is straightforward to conduct inference on the variance parameters. Let $\boldsymbol{\beta}$ be a 10×1 vector of the mean and variance parameters. A test of whether the variances are equal across the days of the week can be conducted by forming the χ^2 statistic:

$$\chi_q^2 = (\mathbf{r} - \mathbf{R}\hat{\boldsymbol{\beta}})'[\mathbf{RVR}']^{-1}(\mathbf{r} - \mathbf{R}\hat{\boldsymbol{\beta}}), \tag{A6}$$

where $\mathbf{r}$ is a $q \times 1$ vector of zeros representing the number of restrictions (four in our case), $\mathbf{V}$ is the variance–covariance matrix of daily returns, and

$$\mathbf{R} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{pmatrix}$$

is a $q \times 10$ matrix.[22] We report the χ^2 statistics computed in (A6).

The proposed inference procedure is quite general. For example, (A5) could be augmented to include other parameters, such as skewness and kurtosis. Tests of the equality of these moments across the currencies can be conducted as in (A6).

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[22] There are other multivariate tests that are asymptotically equivalent. In one popular test, (A3) is estimated and the weighting matrix is saved. In a second run, the restrictions are imposed and the parameters are reestimated by the GMM using the saved weighting matrix. The χ^2 statistic is

$$\chi_q^2 = g_r' w_{ur} g_r - g_{ur}' w_{ur} g_{ur}, \tag{F1}$$

where r represents restricted, ur represents unrestricted, and q is the number of parameter restrictions (degrees of freedom). See Gallant and Jorgenson (1979), Newey and West (1987), Eichenbaum, Hansen, and Singleton (1988), Harvey (1989), and Eichenbaum and Hansen (1990) for discussions and implementations of this multivariate test.

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