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Trading Patterns and Prices in the Interbank Foreign Exchange Market

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ABSTRACT

The behavior of quote arrivals and bid-ask spreads is examined for continuously recorded deutsche mark-dollar exchange rate data over time, across locations, and by market participants. A pattern in the intraday spread and intensity of market activity over time is uncovered and related to theories of trading patterns. Models for the conditional mean and variance of returns and bid-ask spreads indicate volatility clustering at high frequencies. The proposition that trading intensity has an independent effect on returns volatility is rejected, but holds for spread volatility. Conditional returns volatility is increasing in the size of the spread.

THERE IS A GROWING body of theoretical studies on the pattern of trading activity in financial markets, with implications for the time series behavior of transactions prices and intensity of trading. The empirical literature addressing similar concerns using intraday market data appropriate for such tasks is sparse, particularly in the area of the trading of currencies. The purpose of this paper is to examine both international patterns of intraday trading activity and the time series properties of returns and bid-ask spreads for the deutsche mark-dollar exchange rate in the interbank foreign exchange market. The goal is to provide information useful in the further development of market microstructure models of trading and to compare empirical findings against theoretical results already in existence.

The foreign exchange market is in operation twenty-four hours a day, seven days a week, and is the closest analogue to the concept of a continuous time global marketplace. The deutsche mark-dollar rate is the most heavily traded, accounting for close to one-third of the overall volume.[1] For the continuously recorded bid and ask quotes analyzed in this paper, roughly 5,100 quotes are posted per trading day exclusive of weekends.

Although there has been a great deal of recent interest in the globalization of trading in general, very little evidence is available on the twenty-four

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[1] See Lyons (1991) and Tygier (1988) for further discussion.

hour trading activity in the foreign exchange market.[2] Our analysis of market activity across days of the week reveals remarkably similar and stable trading patterns for all but the weekend, at which time activity slows virtually to a halt. We also document the pattern of bid-ask spreads and the relationship between the intensity of quote arrivals and the magnitude of the spread with respect to the banks from which the bids and offers originate. A strong relationship between trading and spread activity is only evident for smaller banks, which operate mainly within regional markets with well-defined market openings and closings.

Previous studies of the intraday behavior of various foreign exchange series have used the bid or the ask quote exclusively as the "transactions price" for empirical analysis, even at low frequencies.[3] There are potential biases inherent in the intraday quotation data for the examination of pricing behavior. While it would be possible to post quotes in the hope of influencing market movements, and then subsequently refuse to deal at these prices, such behavior is effectively precluded by reputation effects. The screen quotes available for analysis are advertisements of prices at which the banks are willing to deal and may not be representative of true transactions prices. Also, a very busy market may preclude the updating of quotes, causing some staleness in the bid and offer series. The careful treatment of the lack of actual transactions prices and the potential staleness of quotations is an important feature of this paper.

In particular, we employ a model of quote cancellation as a function of market activity. We then construct price series based on theoretical models of optimal price determination and details of the institutional market structure. The basic time series behavior of returns differs somewhat across the various price constructs analyzed, but fundamental regularities also persist. The finding in the literature of negative serial correlation in returns is reversed, once an attempt is made to model prices in ways other than just the bid or the ask. Evidence on conditional movements in returns volatility is found to be remarkably similar across all the different price series, however.

Time series models incorporating various market activity measures are estimated for the mean and variance of the transactions returns, using the data recorded at five-minute intervals. In accordance with previous evidence on the behavior of other high-frequency returns data, pronounced volatility clustering is found to be present in the intraday exchange rate series examined here.[4] Our treatment of "news" effects differs from others, and depends

[2] One notable exception is the study by Goodhart and Demos (1990), who also study the deutsche mark-dollar rate. Wasserfallen (1989) and Baillie and Bollerslev (1991) examine returns and volatility over time of day, but provide no direct evidence on the intraday intensity of market activity.

[3] These studies include the work of Wasserfallen (1989), Goodhart (1990), Baillie and Bollerslev (1991), and Goodhart and Figliuoli (1991). Two related papers are those of Harvey and Huang (1991) and Laux and Ng (1991) on foreign currency futures for which transactions data are available. Activity is confined to one market location, however.

[4] A voluminous literature exists modeling the temporal dependencies of daily, weekly, and monthly foreign exchange rate data; see Bollerslev, Chou, and Kroner (1992) for a set of references. Little formal analysis is available on high-frequency intraday movements, however.

strongly on the use of intraday data. The particular news proxies that we employ include the intensity of the arrival rate of quotations, the size of the bid-ask spread, and the speed of transactions activity measured by the duration between trades. Interestingly, on estimating conditional volatility models that use these measures in addition to the effects of lagged variances and squared innovations, we find that the behavior of the bid-ask spread plays an important role in determining the conditional volatility of the returns process. This prompts an investigation of the time series properties of the bid-ask spread, including models of the conditional mean and conditional variance.

International patterns of trading activity are explored in Section I, with an emphasis on the relationship between intensity of quote arrivals and the bid-ask spread. Time series properties of the different transactions returns series are compared in Section II. Estimation of our model for the returns-generating process is the topic of Section III. Models of the bid-ask spread are proposed in Section IV. Some final comments conclude the paper. The means of deriving transactions price data from the raw quote series is outlined in the Appendix.

I. Trading Activity and Costs

The data analyzed consist of continuously recorded bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens.[5] Over that period, 305,604 quotes appeared on Reuters' screens from a total of 125 participating banks in the market. Our purpose in this section is to investigate trading activity across time, market centers, and market participants in terms of quote arrivals and bid-ask spreads.

Plots of the number of quote arrivals per minute over the day are given in Figure 1 for Monday and Friday. Trading activity picks up after midnight as the Tokyo and Sydney markets open with subsequent activity in Singapore and Hong Kong. The abrupt decline in arrivals at hour four signals lunchtime in these markets. Market intensity remains strong in the afternoon Far Eastern trading session, and continues as Hong Kong and Singapore close and London and Frankfurt open. Some decline thereafter is observed until the opening in New York. Activity bounces back during the overlap of the New York and European markets, declining monotonically after the New York close until the Far Eastern markets open again.

This pattern is reasonably well known. What is surprising is the regularity of activity over the course of the week. Quote volume is basically uniformly distributed over the five weekdays. With the exception of late Friday, which is already Saturday in the Australian and Asian markets, and Saturday and Sunday, there is no real discernable difference across all days of the week.

[5] These data have been kindly provided to us by Charles Goodhart, London School of Economics. A description of the method of data capture and screening of the data for outliers is contained in Goodhart and Figliouli (1991).

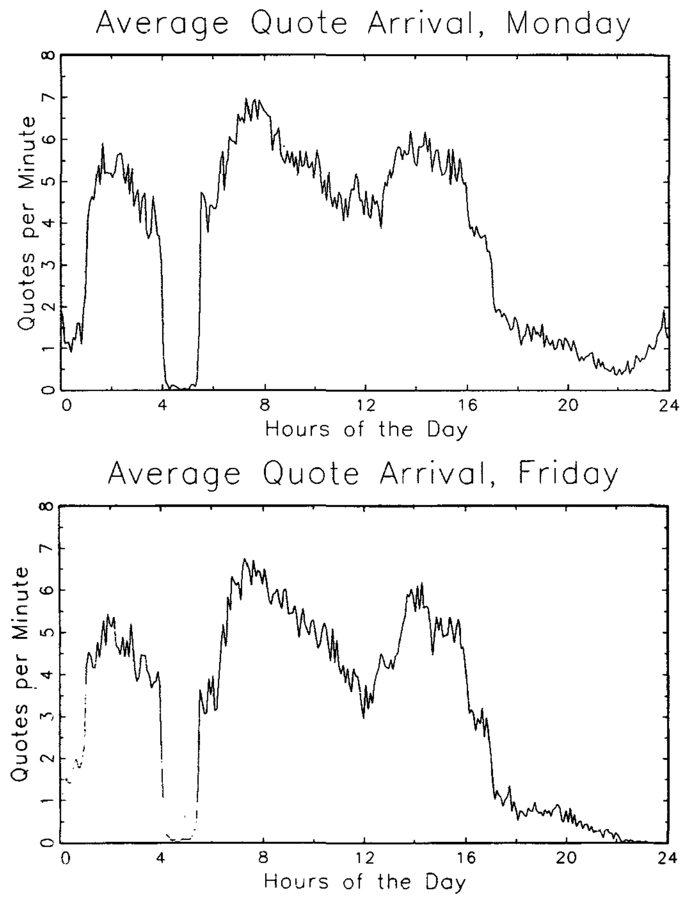

Figure 1. Intraday order arrival rates in the deutsche mark-dollar interbank foreign exchange market for Monday and Friday. Order arrivals per minute are based on continuously recorded pairs of bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. Over that period, 60,095 and 53,082 quotation pairs appeared on Mondays and Fridays, respectively. Hours of the day are standardized to London time.

Over the weekend, there simply is very little activity, except for late Sunday as the Monday morning eastern markets begin to open. The same pattern also shows only minor variations in the level of activity over each of the three months represented in our data.

Figure 2 contains pictures of quote arrival over the course of the day for three of the largest centers. There are three basic patterns of activity across geographical locations, and they are clustered in broader regional areas.[6]

[6] The five largest geographical areas are Hong Kong, London, Frankfurt, Singapore, and New York, in that order. These five market centers account for 58.1 percent of all quote activity. We note that our sample is taken from Reuters and does not constitute the market for deutsche mark-dollar trading in its entirety. It may be the case that centers with strong British connections, like Hong Kong and Singapore, are likely to have more Reuters subscribers.

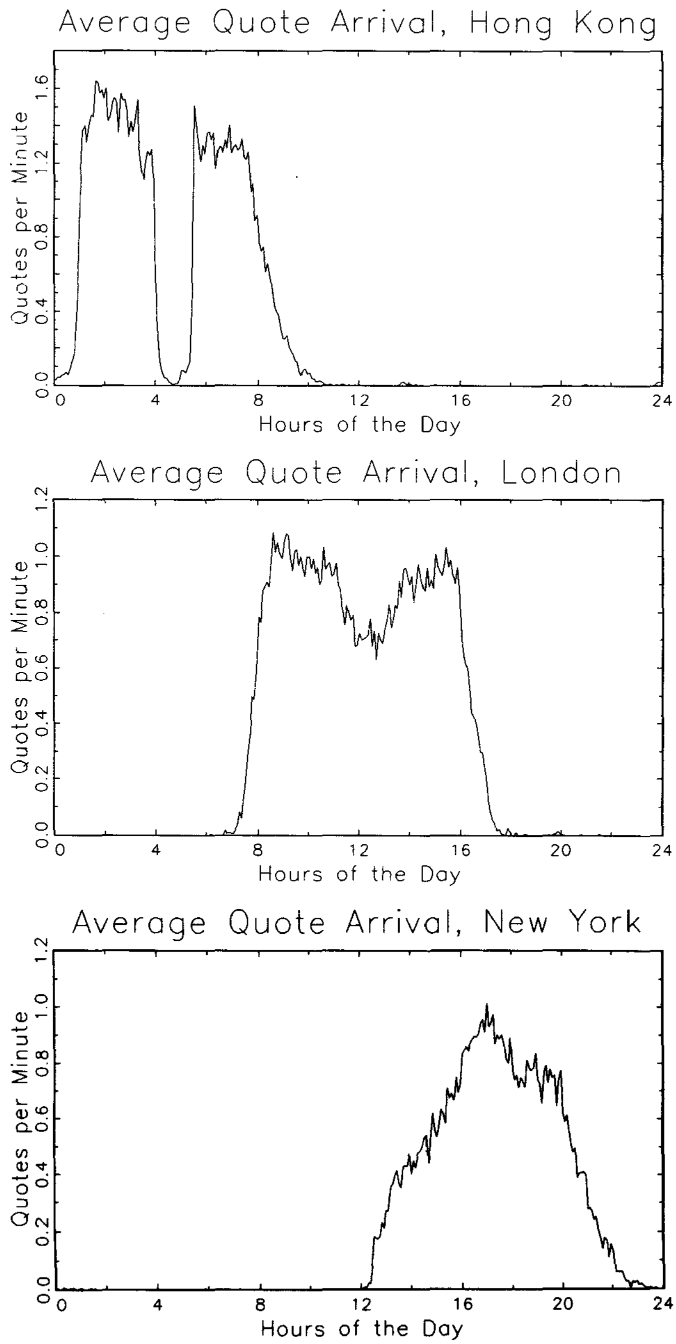

Figure 2. Intraday order arrival rates in the deutsche mark-dollar interbank foreign exchange market for Hong Kong, London, and New York. Order arrivals per minute are based on continuously recorded pairs of bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. Over that period, 41,228, 38,807, and 27,906 quotation pairs originated from Hong Kong, London, and New York, respectively. Hours of the day are standardized to London time.

Market activity in the Far East is bimodally distributed around the lunch hour, with no particular regularity to the pattern of activity before and after lunch. The decrease in lunchtime activity is marked in these centers.[7] European markets also show a bimodal distribution, but the declines in activity towards and directly after the lunch hour are much more gradual. In other words, there are clearly flurries of activity surrounding the open and the close of the market, with moderate trading in between. New York has a unimodal distribution of activity, peaking at the lunch hour. Lunch in New York coincides roughly with the high activity in London and Frankfurt at that hour, which in turn corresponds to the imminent closing of those markets.[8]

Existing theoretical models deliver different predictions of the relationship between the spread and trading activity, depending upon the exact specification of traders' preferences and information sets.[9] This motivates an empirical examination of the bid-ask spread over the course of the trading day. The distributions of the average spread and quote arrivals are graphed in Figure 3.[10] There is a sharp peak in the spread as the level of quote arrival goes virtually to zero during the Far Eastern lunch break. There is a dip in the spread during the middle of the day that corresponds to a lessening of aggregate market activity. Although the world market does not have a well-defined open or close, the increase in the spread at the endpoints does correspond to very low levels of trading activity around hour 24. Overall, the evidence of any systematic relationship between the spread and market activity is at best vague and at worst conflicting at the aggregate level, however.

Our data set allows an examination of the relationship between the spread and market activity disaggregated to a level at which variation in the characteristics of individual participants may be identified. In particular, small and large banks may differ in terms of attitudes towards risk, information due to differences in order flow, and operating hours. Thus, more

[7] The overall trading pattern in Tokyo, Singapore, and elsewhere in the Far East is virtually the same as that shown for Hong Kong. In fact, the FINEX 24-hour financial futures exchange closes between 10:00 P.M. and 11:30 P.M. New York time, coinciding with the Far Eastern lunch break.

[8] To the extent that traders can adjust positions around the clock, the pressures associated with nondiscretionary liquidity trading are weakened. In particular, the U-shaped pattern of activity arising in the model of Admati and Pfleiderer (1988, 1989) and Foster and Viswanathan (1990) is apparent only in the European markets.

[9] The theory of Admati and Pfleiderer (1988) predicts that spreads should be lowest when liquidity is high, suggesting lower spreads during periods of high market activity. Subrahmanyam's (1989) extension of the Admati and Pfleiderer model to include risk-averse behavior predicts that more trading by informed risk-averse participants brings about higher costs. This supports the hypothesis of larger spreads during periods of increased market activity. This is also consistent with the adverse selection model of Foster and Viswanathan (1990) and the U-shaped patterns of the spread documented for stocks in Brock and Kleidon (1992).

[10] The average bid-ask spread across all 305,604 quotes equals 0.000865 with a standard deviation of 0.000311.

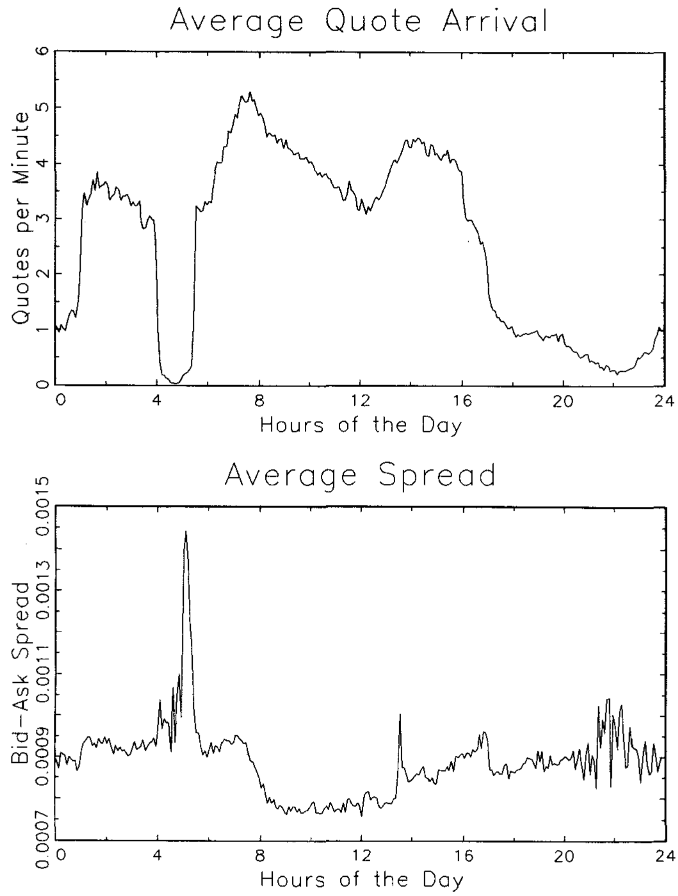

Figure 3. Intraday order arrival rate and bid-ask spread in the deutsche mark-dollar interbank foreign exchange market. Order arrivals per minute and the bid-ask spread are based on continuously recorded pairs of bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. Over that period, 305,604 quotation pairs originated from all participating banks. Hours of the day are standardized to London time.

information may be gleaned from the spread and quote activity of individual banks.

The average spread offered by the large international banks corresponds only sporadically to their pattern of market activity, illustrated here with Deutsche Bank in Figure 4.[11] In contrast, the activity pattern of the "smaller"

[11] The five largest banks in terms of quote activity are Deutsche Bank, Morgan, Société Générale, Citicorp, and Union Bank of Switzerland. Together, these banks account for 30.8 percent of all quotes submitted to the market. In the absence of any quotes during a particular five-minute interval, the average spread in the figure was set to zero. In interpreting the figures this should not be confused with a true spread of zero, however.

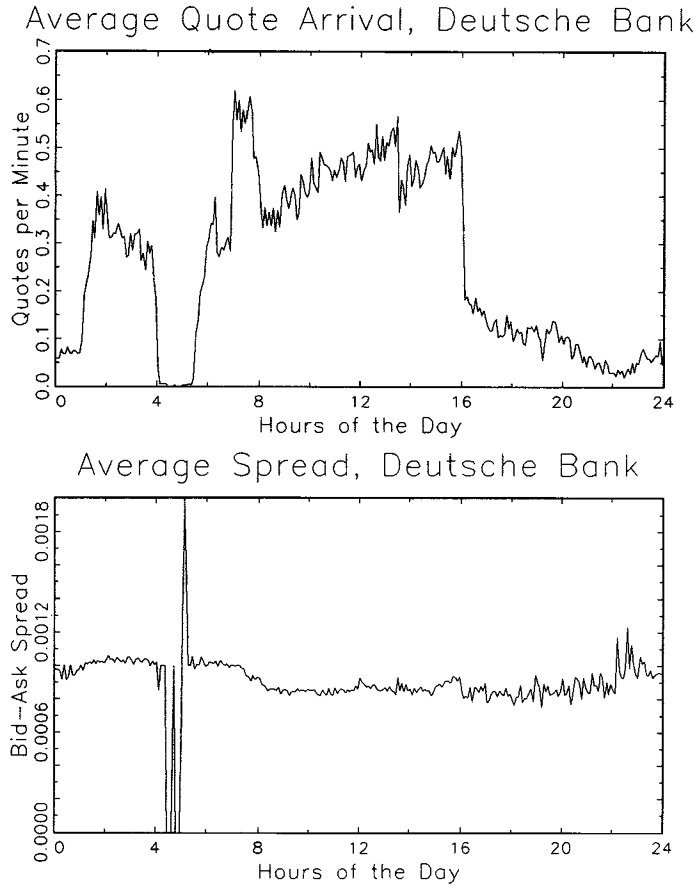

Figure 4. Intraday order arrival rate and bid-ask spread for deutsche mark-dollar quotes originating from Deutsche Bank. Order arrivals per minute and the bid-ask spread are based on continuously recorded pairs of bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. Over that period, 30,901 quotation pairs originated from Deutsche Bank. Hours of the day are standardized to London time.

banks typically shows a U-shape, as does the distribution of their own spreads over the course of the day. This is illustrated in Figure 5 for the smaller Danske Bank, which accounts for 1.0 percent of the total quotes in the market. The typical small banks only generate quotes during the regular business hours of their regional markets. Such banks are, therefore, potentially more sensitive with respect to their inventory positions at the close than larger banks, increasing both the quoted spread and market activity at the end of their regional trading day.[12] Smaller banks have less information based on retail order flow at the beginning of their regional trading day than

[12] This effect is formally modeled by Son (1991).

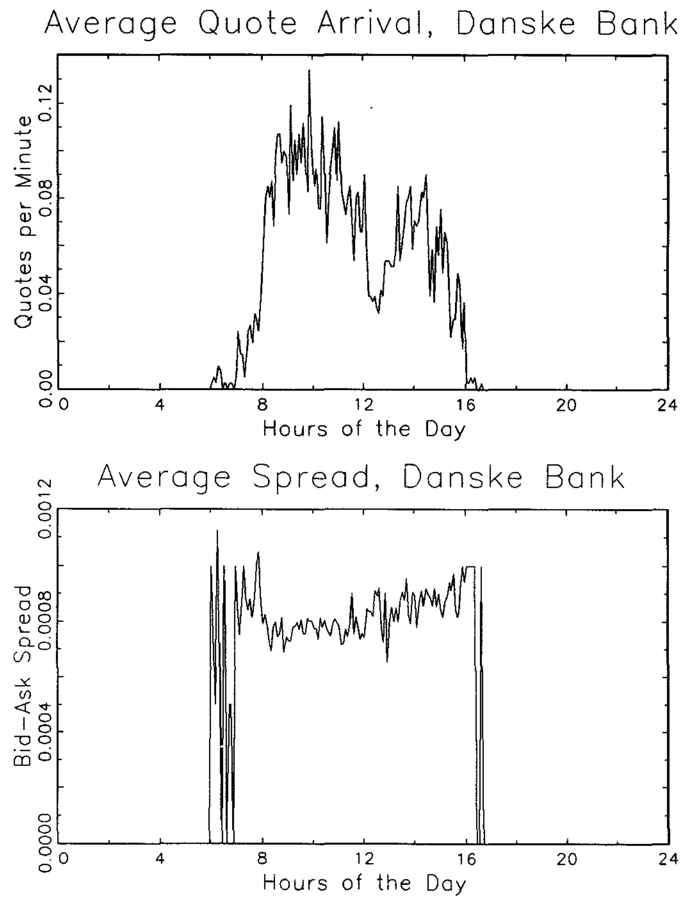

Figure 5. Intraday order arrival rate and bid-ask spread for deutsche mark-dollar quotes originating from Danske Bank. Order arrivals per minute and the bid-ask spread are based on continuously recorded pairs of bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. Over that period, 2,970 quotation pairs originated from Danske Bank. Hours of the day are standardized to London time.

larger banks that operate continuously.[13] Thus, the adverse selection component of the spread may be higher for small banks at their opening, widening quoted spreads during a period of increased market activity. In other words, these banks operate more like the risk-averse stock market traders modeled in much of the theoretical literature, with behavior influenced by openings and closings.

We can provide statistical evidence on the difference in spread/trading activity association between large and small banks by calculating the gain between the two series at frequency zero. Given the obvious but erratic delays

[13] Lyons (1991), in particular, identifies asymmetric information between dealers in the foreign exchange market with differences in retail order flow.

between movements of the spread and trading activity in the data, the gain is preferable to a calculation of the simple correlation between the series. The gain at frequency θ is defined as $|f_{ST}(\theta)|/f_T(\theta)$, where $f_{ST}(\theta)$ denotes the cross-spectrum between the spread and trading activity series and $f_T(\theta)$ refer to the spectrum of trading activity; see Engle (1976) for a more formal discussion. Intuitively, the gain at frequency zero can be interpreted as the correlation once the delays between the spread, S, and trading activity, T, have been eliminated.

A statistically insignificant value of the zero-frequency gain indicates that trading activity has little effect on the bid-ask spread. The heteroskedasticity-robust t-statistic for the estimated gain, obtained by regressing the spread against all leads and lags of the trading activity variable, equals 4.4 over all banks. On the other hand, the t-statistic for the active Deutsche Bank is only 1.0, while the gain for Danske Bank has a t-statistic of 24.0. Whereas the top ten geographical centers account for 80.2 percent of the quote arrivals, the ten most active banks only supply 46.6 percent of the quotes. Individual banks with less than 3.0 percent of the total quote volume constitute the majority of market participants. Most of these small banks are located in Europe, which may explain the aggregate relationship between market intensity and the spread observed during European trading hours, in particular.

II. Time Series Analysis of the Behavior of Returns

Previous analyses of intraday price behavior in the foreign exchange market have used either the quoted bid or ask price as the transactions variable, generally without any theoretical justification for the practice. We here examine five alternative means of approximating transactions prices based on theoretical models of optimal pricing behavior and details of institutional market structure. BID and ASK are the bid and ask quotation series, while IBA denotes the average of the incoming bids and offers. GBX is a series computed using an automated trade execution algorithm designed for the foreign exchange market. Finally, IMBA denotes a negotiation price obtained as the average of the standing bid or offer and the incoming offer or bid eligible for trade under the automated matching system. The details of the construction of all price series are given in the Appendix. In the empirical analysis below, we concentrate on data recorded at five-minute intervals.[14]

Standard testing procedures indicate the presence of a unit root in all of the logarithmic price series, motivating our focus on the percentage return

[14] Recording the transactions prices closest to the end of every five-minute interval produces a total of 9,662 price observations, By a one-hour truncation rule for the length of the return intervals, the sample is further reduced to 9,581 observations. Since we take the observation closest to the end of each five-minute interval, the return observations are not always exactly five minutes apart. The minimum duration between price changes leading to a recorded return is five minutes, but the average such "trade" duration is 8.2 minutes with a standard deviation of 5.7.

series throughout the rest of this study; i.e., $100\Delta \log P_t \equiv 100(\log P_t - \log P_{t-1})$. Summary statistics for the different five-minute return series are reported in Table I.

The unconditional variance of GBX returns is much lower than that for the series based simply on the incoming bid and ask quotes. This result is consistent with the findings in Bollerslev and Domowitz (1991), where the presence of an electronic order book was found to significantly reduce variability in returns relative to that observed in trading activity that depends only on current quotes. The IMBA price series is essentially a smoothed version of that obtained from the automated trade execution system, and not surprisingly exhibits the lowest unconditional volatility.

The BID and ASK series exhibit the low-order negative serial correlation observed in all previous studies of intraday foreign exchange rates. Since

Table I

Summary Statistics for Five-Minute Percentage Returns

The price series are constructed from continuously recorded bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. The results are based on 9,581 observations recorded at five-minute intervals. BID and ASK are the raw bid and ask quotation series, while IBA denotes the average of the incoming bids and offers. GBX is a series computed using an automated trade execution algorithm designed for the foreign exchange market. IMBA denotes a negotiation price obtained as the average of the standing bid or offer and the incoming offer or bid eligible for trade under the automated matching system. The details of the construction of all price series are given in the Appendix.

	BID	ASK	IBA	GBX	IMBA
μ[a]	0.030	0.026	0.028	0.034	0.033
ω[b]	44.68	45.39	44.26	29.20	28.98
$\rho(1)$[c]	−0.107	−0.118	−0.106	0.105	0.108
$\rho(2)$	−0.005	−0.011	−0.013	−0.021	−0.031
$\rho(3)$	0.011	0.013	0.012	0.015	0.016
$Q(20)$[d]	124.5	146.1	121.7	154.9	153.3
$\rho 2(1)$[e]	0.170	0.148	0.161	0.169	0.216
$\rho 2(2)$	0.137	0.122	0.133	0.119	0.154
$\rho 2(3)$	0.129	0.114	0.123	0.095	0.122
$Q2(20)$[f]	1162.8	918.0	1087.1	880.3	1395.8
S[g]	−0.252	−0.063	−0.172	−0.112	−0.278
K[h]	6.29	6.94	6.55	15.05	11.58

[a]The mean, μ, has been multiplied by 100.

[b]The variance, ω, has been multiplied by 10,000.

[c]$\rho(i)$ denotes the ith order autocorrelation.

[d]$Q(20)$ is the Ljung-Box portmanteau test for up to twenty order serial correlation in the returns.

[e]$\rho 2(i)$ denotes the ith order autocorrelation for the squared returns.

[f]$Q2(20)$ is the Ljung-Box portmanteau test for up to twenty order serial correlation in the squared returns.

[g]S is the sample skewness of the unconditional returns distribution.

[h]K is the sample kurtosis of the unconditional returns distribution.

these returns are calculated from bids and asks exclusively, such negative serial correlation is not induced from fluctuations across the bid-ask spread, but may be explained as a consequence of the end-of-interval nonsynchronous construction of the price series.[15]

This is in strong contrast to the behavior of the prices produced by the trade-matching algorithm or through the negotiation process. Both the GBX and IMBA returns show positive first-order serial correlation, followed by a substantially lower amount of negative correlation at the second lag. The existence of this positive correlation under trade matching suggests that some news is transmitted between the banks by trading activity. It may take some small period of time to fully absorb this news into transactions prices, as formally modeled by Cutler, Poterba, and Summers (1990). In this instance, we would expect to find less positive first-order serial correlation in returns measured at a slightly lower frequency. This is indeed the case, as we move from returns measured at five-minute intervals to those taken at the endpoints of ten-minute intervals. The first-order serial correlation in the GBX and IMBA series drops to 0.002 and 0.001, respectively, at the lower frequency. The degree of negative serial correlation for the nonsynchronous ten-minute BID, ASK, and IBA series is very similar to that of the five-minute returns, however, with first-order autocorrelations of -0.098, -0.104, and -0.096, respectively.

We find the magnitude of excess kurtosis in returns measured from the average of incoming quotes to be large and quite similar to that of the raw quotes themselves. Interestingly, the sample kurtosis for automated execution and negotiated returns is substantially higher. The combination of lower return variance and thicker tails of the returns distribution for order book trading relative to trading based only on current bids and offers also was documented in the trading simulations of Bollerslev and Domowitz (1991).

The excess kurtosis evident in all five-minute returns series from Table I is a feature of other previous work on intraday foreign exchange rate bid and ask returns. It is now well known that such excess kurtosis may be explained by serial correlation in the returns variance process. Indeed, all series exhibit very pronounced serially dependent conditional heteroskedasticity, as evidenced by the highly significant Ljung and Box (1978) Q-statistics and the slowly declining autocorrelation functions for the squared returns.

Interestingly, the observed differences in kurtosis across the five series do not translate into different estimates of the time series structure of the conditional variance process of returns. GARCH(1, 1) models do an excellent job of tracking the time series behavior in the second moments for all the series and produce virtually identical coefficient estimates. In order to further understand the determinants of the conditional variance process, we now turn to a more systematic analysis of the data.

[15] See, for example, Lo and MacKinlay (1990). Alternatively, the negative serial correlation in the raw quote series might be attributable to differences in information on the part of traders in different market centers, or that traders interpret the same news in different ways. Goodhart and Figliuoli (1991) find little support for this explanation, however.

III. News, Market Activity, and the Conditional Variance of Returns

The effect of news on the time series behavior of intraday exchange rate returns generally is inferred from the behavior of conditional volatility.[16] In this section, we examine the direct effect of market activity variables, including the intensity of quote arrivals, the bid-ask spread, and a measure of duration between trades, on the temporal dependencies in the returns process. Since preliminary data analysis suggests that none of these market activity variables have any economically or statistically significant impact on the mean returns process, we limit our investigation here to the conditional returns variance. Given the similarity of the results across the different definitions of returns, we only report the empirical results using the IMBA negotiated price series.

The particular model structure estimated for the five-minute returns is given by:

$$100\Delta \log P_t = \mu + \theta\epsilon_{t-1} + \epsilon_t \tag{1}$$

$$\sigma_t^2 = \omega + \alpha\epsilon_{t-1}^2 + \beta\sigma_{t-1}^2 + \delta(\text{Market Activity})_{t-1} \tag{2}$$

$$\epsilon_t|\Psi_{t-1} \sim N(0, \sigma_t^2) \qquad t = 1, 2, \ldots, T. \tag{3}$$

The MA(1) formulation for the conditional mean in equation (1) is designed to capture the first-order serial dependence discussed above. The GARCH(1, 1) structure in equation (2) is used to model autonomous movements in the conditional variance. We maintain the assumption on traders' information embodied in equation (3) by using lagged information on market activity to explain conditional volatility movements. This is necessary on statistical grounds, in order to avoid a potential endogeneity problem that would bias results obtained using contemporaneous market activity.[17]

All the model estimates reported below are obtained under the conditional normality assumption of equation (3). Although this assumption may not hold exactly in the data, quasi-maximum likelihood estimates of the parameters are generally consistent and asymptotically normally distributed, provided that the conditional mean and variance in equations (1) and (2) are correctly specified.[18] Estimated coefficients and some summary statistics are given in Table II, with robust standard errors appropriate to quasi-maximum likelihood estimation reported in parentheses.

[16] For example, Engle, Ito, and Lin (1990) examine whether news pertaining to the same currency is transmitted across different market locations as time passes, or is market specific, by the inspection of conditional second-moment properties. Baillie and Bollerslev (1991) find autocorrelation in the conditional second moments of currency returns series to be consistent with both such hypotheses.

[17] Within the class of inventory models of the spread, systematic changes in the variance of the underlying exchange rate cause movements in the contemporaneous spread. See Ho and Stoll (1983) and Brock and Kleidon (1992).

[18] See Domowitz and White (1982), Weiss (1986), and Bollerslev and Wooldridge (1992).

Table II

Quasi-Maximum Likelihood Estimates of the Determinants of Exchange Rate Volatility

The price, P_t, and Market Activity series are constructed from continuously recorded bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. The results are based on 9,581 observations recorded at five-minute intervals for the IMBA returns series. IMBA denotes a negotiation price obtained as the average of the standing bid or offer and the incoming offer or bid eligible for trade under the automated matching system; the details are given in the Appendix. The Market Activity variable denoted Arrivals gives the number of quote arrivals per minute over the most recent five-minute interval. Spread is the difference between the best offer and bid outstanding in the market at the end of the recording interval. Duration denotes the time, measured in minutes, between trades. Coefficients are obtained from quasi-maximum likelihood estimation of the model given by

$$100\Delta \log P_t = \mu + \theta\epsilon_{t-1} + \epsilon_t \tag{1}$$

$$\sigma_t^2 = \omega + \alpha\epsilon_{t-1}^2 + \beta\sigma_{t-1}^2 + \delta(\text{Market Activity})_{t-1} \tag{2}$$

$$\epsilon_t|\Psi_{t-1} \sim N(0, \sigma_t^2) \qquad t = 1, 2, \ldots, 9581 \tag{3}$$

	GARCH	Arrivals	Spread	Duration
μ^a	0.134	0.135	0.111	0.134
	(0.027)	(0.024)	(0.023)	(0.024)
θ	0.116	0.116	0.123	0.116
	(0.008)	(0.007)	(0.006)	(0.007)
ω^a	0.938	0.945	−5.952	0.939
	(0.173)	(0.252)	(0.450)	(0.150)
α	0.151	0.152	0.172	0.153
	(0.017)	(0.016)	(0.042)	(0.015)
β	0.828	0.827	0.700	0.826
	(0.019)	(0.018)	(0.014)	(0.017)
δ^b	—	−0.000	1.127	0.001
		(0.004)	(0.096)	(0.001)
$\text{Log}L^c$	15697.5	15697.5	15824.0	15698.0
$Q(20)^d$	21.597	21.599	19.509	21.472
$Q2(20)^e$	34.626	34.596	27.548	33.951
S^f	−0.305	−0.305	−0.254	−0.307
K^g	10.607	10.606	9.074	10.603

[a]The reported estimates and standard errors for μ and ω have been multiplied by 100 and 10,000, respectively.

[b]The estimates and standard errors for δ for the Arrivals and Duration variables have been multiplied by 10,000.

[c]$\text{Log}L$ denotes the value of the maximized gaussian quasi log likelihood function.

[d]$Q(20)$ refers to the Ljung-Box portmanteau tests for up to twenty order serial correlation in the standardized residuals, $\hat{\epsilon}_t\hat{\sigma}_t^{-1}$.

[e]$Q2(20)$ denotes the Ljung-Box portmanteau tests for up to twenty order serial correlation in the squared standardized residuals, $(\hat{\epsilon}_t\hat{\sigma}_t^{-1})^2$.

[f]S is the sample skewness of the standardized residuals, $\hat{\epsilon}_t\hat{\sigma}_t^{-1}$.

[g]K is the sample kurtosis of the standardized residuals, $\hat{\epsilon}_t\hat{\sigma}_t^{-1}$.

The positive and significant first-order moving average coefficient for the MA(1)-GARCH(1, 1) model with $\delta = 0$ reported in column one is consistent with the results of the last section on negotiated price returns. The portmanteau statistics for the standardized residuals, $\hat{\epsilon}_t \hat{\sigma}_t^{-1}$, indicate that the MA(1) model captures most of this serial dependence.[19]

The GARCH(1, 1) coefficients are highly statistically significant, with the estimate for $\alpha + \beta$ approximately equal to one, as in the Integrated GARCH, or IGARCH, model.[20] The decrease in the Ljung-Box statistics for additional serial correlation in the standardized squared residuals, $\hat{\epsilon}_t^2 \hat{\sigma}_t^{-2}$, relative to the raw series reported in Table I, is dramatic. The diagnostics provided by the sample kurtosis of the standardized residuals compared with the Ljung-Box statistic provide some additional interesting information. The degree of kurtosis is smaller, but declines little from that reported before the GARCH estimation of the variance, consistent with the literature on daily exchange rate changes. The presence of severe excess kurtosis despite the whitening of the squared innovations series indicates that attributing thick-tailed behavior to time-varying parameters in the underlying returns distributions is an oversimplification.[21]

The question of whether or not market activity affects volatility is of particular interest given the theoretical results of the mixtures-of-distributions hypothesis.[22] If news comes in clusters, the conditional variance of returns will be an increasing function of the actual number of information arrivals when measured in calendar time. Previous studies generally have used volume or number of transactions as a proxy for the information arrival process. Given the nature of our data, we use the number of incoming quotes as one of our proxies for the information variable. The interbank market structure precludes knowledge of the number of transactions and trading volume on the part of traders. The rate of quote arrival is, however, directly observable by the traders.

[19] There is also some evidence of positive deutsche mark appreciation. We do not draw any inference from this result with respect to market efficiency, however. Visual inspection of the average five-minutes IMBA returns indicates no systematic pattern in the depreciation during the course of the trading day. Similarly, we find no statistical evidence that the significant mean returns are due to a time-varying risk premium effect as approximated by a linear function of the own conditional variance.

[20] See Bollerslev, Chou, and Kroner (1992) for a description of the IGARCH class of models. Nelson (1990) has shown that if the true data generation process is a continuous time diffusion, a GARCH(1, 1) model with parameters $\omega_h = \omega h$, $\alpha_h = \alpha(h/2)^{1/2}$, and $\beta_h = (1 - \alpha(h/2)^{1/2} - \phi h)$, where $\alpha > 0$, $\omega \geq 0$, and ϕ are fixed, provides a consistent approximation to the true underlying continuous time variance as the sampling interval, h, goes to zero. The near integrated parameter estimates obtained might be related to this result.

[21] We also estimated the same model for ten- and sixty-minute returns with the same qualitative results. This is counter to the three-day analysis in Goodhart and Figliuoli (1991), who argue that heteroskedasticity and leptokurtosis are not a significant feature of high-frequency data, but become more important as the sampling interval lengthens to about ten minutes, declining again in importance for longer return intervals.

[22] See Clark (1973), Tauchen and Pitts (1983), Harris (1987), and Andersen (1992) among others.

From the results reported in column two of the table, the intensity of quote activity has a negative but economically and statistically negligible effect on conditional volatility. Other parameters in the GARCH(1, 1) formulation are unchanged. While no comparable model for exchange rates is available in the literature, the findings are similar to the study of daily National Association of Security Dealers Automated Quotation/National Market System security returns of Jones, Kaul, and Lipson (1991). These authors find that news arrival in the form of number of transactions has no effect on the conditional variance, using information available at time $t - 1$ and earlier.[23] Lamoureux and Lastrapes (1990) also discuss results based on an instrumental variables procedure, indicating that past volume, as a proxy for news arrival, has no ability to predict volatility.

Unobservable news also may be reflected in the bid-ask spread. News events which change traders' desired inventory positions result in order imbalances, with the potential of changing spreads. More generally, news can be thought of as simply changing the relative demand and supply for the currency, which might also effect the spread.[24] Estimates of our model, using the spread as an indicator of market activity, are given in column three of Table II.

Information in the form of the lagged spread provides a powerful positive and strongly statistically significant contribution to movements in the conditional variance. Hausman, Lo, and MacKinlay (1992) report a similar result using stock market data. Persistence in the form of the GARCH relationship remains strong, however, with the effect of the lagged variance declining somewhat relative to the results reported in column one.

We know of no theoretical model that provides a causal link between the magnitude of the spread and returns volatility. Bollerslev and Domowitz (1991) show, however, that screen-based market structure has the potential to transmit serial dependence in the spread to serial correlation in the returns variance. This possibility is further investigated in the next section. The results here imply an additional independent contribution to the conditional variance of returns over and above the serial dependence captured by the GARCH component of the model. Of course, to the extent that unobservable news is reflected in the spread, the results are consistent with the mixture of distributions hypothesis.

[23] They do find, however, that the contemporaneous number of transactions virtually eliminates all persistence in the conditional variance, using daily stock returns. A similar result is contained in Laux and Ng (1991) in their study of intraday currency futures returns, using the contemporaneous number of price changes in an observation interval. In the context of high-frequency intraday data, in particular, we believe that examination of contemporaneous activity is inappropriate, not being in the traders' information set at the time decisions are made. Regardless of our feelings about the relevant information set and simultaneity bias, we find that although the actual coefficient estimate is numerically larger, the negative effect from using contemporaneous arrivals remains statistically insignificant at any reasonable level for the five-minute exchange rate returns analyzed here.

[24] These effects are formally modeled by Amihud and Mendelson (1980) and Brock and Kleidon (1992).

Table II also contains the results of the estimation including the average duration between trades over the previous interval in the conditional variance as one further measure of market activity. This is similar in spirit to the Hausman, Lo, and MacKinlay (1992) probit analysis of stock market returns, in which a longer time between transactions was found to increase the variance of the returns process. There is a small, but statistically insignificant positive effect of lagged duration on returns volatility in the intraday foreign exchange data.[25]

IV. The Dynamics of the Bid-Ask Spread

The intraday relationship of the spread to trading activity and returns volatility documented in Sections I and III motivates an examination of the intertemporal dynamics of the bid-ask spread and the potential link between trading activity and such dynamics. This is an issue missing from the existing empirical literature on market microstructure concerned with intraday behavior. Theoretical predictions with respect to the time series properties of the spread are also scarce. The work of Madhavan (1992) does suggest, however, the existence of a unit root in the time series process of the spread, and further predicts that the spread declines with market activity. Serial correlation patterns in the spread also may arise from dynamics in the supply and demand for the security or from reasons related to market structure.[26]

Consistent with the above theoretical predictions, standard testing procedures reveal the presence of a unit root in the spread process. Estimates for three alternative time series models of the conditional mean and variance of the logarithmic first difference of the spread process are presented in Table III.[27]

Following the analysis in Section II, the first model specifies a moving average error process for the proportional change in the spread, augmented by a GARCH(1, 1) model for the conditional variance. Changes in the spread are highly negatively serially correlated, with an unconditional mean of zero. Pronounced volatility clustering is observed for the spread process. The GARCH parameters are highly statistically significant, and the model appears to track the volatility movements quite well, as indicated by the low value of the Ljung and Box (1978) statistic for serial correlation in the squared standardized residuals of the model.

The second formulation adds trading activity in the form of quote arrivals to the basic time series model in both conditional mean and variance. A likelihood ratio test indicates a strong rejection of the restriction that trading

[25] Interestingly, using the contemporaneous duration as in Hausman, Lo, and MacKinlay (1992) does not alter the finding of statistical insignificance regarding the time between trades as an explanatory variable for returns volatility.

[26] See Madhavan (1992), Brock and Kleidon (1992), and Bollerslev and Domowitz (1991).

[27] Whereas the quote-by-quote spread for individual banks is distinctly discrete, the logarithmic first difference of the market spread defined to be the difference between the best bid and ask at any given time may be meaningfully approximated as a continuous random variable.

Table III

Quasi-Maximum Likelihood Estimates of the Determinants of the Exchange Rate Bid-Ask Spread

The bid-ask Spread and Market Activity series are constructed from continuously recorded bid and ask quotations for the deutsche mark-dollar exchange rate from Sunday, April 9 to Friday, June 30, 1989, obtained from Reuters' network screens. The results are based on 9,581 observations recorded at five-minute intervals. Spread is the difference between the best offer and bid outstanding in the market at the end of recording interval. The Market Activity variable denoted Arrivals gives the number of quote arrivals per minute over the most recent five-minute interval. Duration denotes the time between trades. Coefficients are obtained from quasi-maximum likelihood estimation of the model given by

$$\Delta \log(\text{Spread})_t = \mu + \gamma(\text{Market Activity})_{t-1} + \theta\epsilon_{t-1} + \epsilon_t$$

$$\sigma_t^2 = \omega + \alpha\epsilon_{t-1}^2 + \beta\sigma_{t-1}^2 + \delta(\text{Market Activity})_{t-1}$$

$$\epsilon_t|\Psi_{t-1} \sim N(0, \sigma_t^2) \qquad t = 1, 2, \ldots, 9581$$

	GARCH	Arrivals	Duration
μ^a	−0.043	−0.077	0.086
	(0.030)	(0.061)	(0.029)
θ	−0.835	−0.836	−0.841
	(0.004)	(0.004)	(0.003)
γ^b	—	0.097	−1.210
		(0.193)	(0.144)
ω^a	0.567	0.320	0.434
	(0.106)	(0.075)	(0.082)
α	0.067	0.073	0.061
	(0.007)	(0.006)	(0.006)
β	0.880	0.843	0.894
	(0.013)	(0.015)	(0.010)
δ^b	—	1.842	0.421
		(0.235)	(0.062)
$\text{Log}\,L^c$	−2591.7	−2532.1	−2563.1
$Q(20)^d$	25.270	26.760	26.119
$Q2(20)^e$	14.406	15.766	12.979
S^f	−0.283	−0.278	−0.272
K^g	5.752	5.446	5.812

[a] The estimates and standard errors for μ and ω have been multiplied by 100.

[b] The estimates and standard errors for γ and δ have been multiplied by 10,000.

[c] Log L denotes the value of the maximized gaussian quasi log likelihood function.

[d] $Q(20)$ refers to the Ljung-Box portmanteau tests for up to twenty order serial correlation in the standardized residuals, $\hat{\epsilon}_t \hat{\sigma}_t^{-1}$.

[e] $Q2(20)$ denotes the Ljung-Box portmanteau tests for up to twenty order serial correlation in the squared standardized residuals, $(\hat{\epsilon}_t \hat{\sigma}_t^{-1})^2$.

[f] S is the sample skewness of the standardized residuals, $\hat{\epsilon}_t \hat{\sigma}_t^{-1}$.

[g] K is the sample kurtosis of the standardized residuals, $\hat{\epsilon}_t \hat{\sigma}_t^{-1}$.

activity does not affect the conditional mean and variance of the spread. The rejection is traceable to effects on the conditional variance. Variations in trading activity have a statistically negligible effect on the conditional mean. To the extent that quote arrivals are correlated with actual trades, time series analysis cannot support the hypothesis that increased activity lowers the spread. We note that this finding does not conflict with the statistically significant correlation between the spread and market activity at frequency zero reported in Section I. That relationship is based on an examination of both leads and lags of the two processes. The results in Table III rely on an information set consisting only of the past history of market activity. This is, indeed, the information available to traders.

Trading activity does, however, have a strong positive effect on the conditional variance of the spread process. The bid-ask spread is a major cost of trading for incoming retail order flow. This result implies that, as market activity increases, the retail transactions costs become more uncertain. It is interesting to note that the overall GARCH effect, measured by the sum of the GARCH coefficients, is little changed by the addition of trading activity to the model.

Consistent with the analysis in the previous section, the final column in Table III contains a model based on the alternative measure of trading activity provided by the duration between trades. Duration has a negative effect on the conditional mean of the spread process, as well as a statistically significant positive effect on conditional volatility. The negative coefficient on duration provides additional evidence with respect to the empirical findings of Biais, Hillion, and Spatt (1992), who suggest that executed orders are more frequent when the spread is relatively small. We do not want to place great emphasis on our findings with respect to this duration model, however. The fact that the kurtosis of the model residuals is larger than that of the time series model in column one is evidence of misspecification. The model including trade activity in the form of quote arrivals also produces a much higher value of the likelihood function.

VI. Concluding Remarks

The evidence presented in this paper is encouraging with respect to the ability to validate and discriminate between theoretical models of trading activity using intraday information of foreign exchange trading. In particular, only a weak relationship between the spread and market activity indexed by the intensity of quote arrivals is evident in the data aggregated across banks. Further examination at the level of individual banks, however, shows that this relationship is much stronger for participants who restrict their trading to regional markets with well-defined openings and closings. The daily patterns of the spread and market activity suggest risk-averse behavior on the part of these traders.

Our results also highlight the importance of the bid-ask spread and its behavior over the course of the trading day in explaining the movements of the conditional returns variance. This is a topic little explored in the theoretical literature. The models of bid-ask spread dynamics also provide evidence on serial correlation patterns in both the conditional mean and variance of the spread process. Although trading activity fails to influence the volatility of returns, it does affect the uncertainty of trading costs. The fact that the level of bid-ask spread changes is not statistically influenced by the level of quotation activity is consistent with the finding that, while spreads have a positive effect on returns volatility, quote activity does not.

The treatment of transactions prices in this paper stands in sharp contrast to that in previous work, and provides some important insights in assessing the existing empirical literature on intraday foreign exchange rate movements. The main difference between the different price constructs is found in the serial correlation pattern. The negative first-order correlation documented in previous work using bid and ask prices is also evident here, but such correlation is likely to be spurious due to the nonsynchronous recording of the data. Price series reflecting either an order-driven transaction at the bid or the ask or a smoothed version, as a result of price negotiation behavior, show a mild positive first-order correlation coefficient. On the other hand, the statistical characterization of the volatility of returns is fundamentally the same across all means of inferring unobservable transactions data from quotes.

We conclude by noting the potential importance of extending existing literature to replace volume by quote generation activity in order to explain the theoretical link between market activity and the bid-ask spread. Quote generation signals willingness to trade within certain parameters, and provides a direct indication of market liquidity. Derivation of a relationship between returns and such signals would better mimic the specific information structure of the interbank foreign exchange market, and help in understanding the empirical regularities documented in this study.

Appendix: The Construction of Prices

The theoretical models of Stoll (1978), Roll (1984), Copeland and Galai (1983), and Madhavan (1992) suggest approximating transactions prices by the bid, the ask, and the average of incoming bids and offers from banks participating in the market. These series are denoted BID, ASK, and IBA in the tables and text. Such models are necessarily stylized and do not fully reflect the institutional structure of the foreign exchange market. Trading is screen based. Bid and ask quotations are submitted by market participants to the Reuters network, which immediately displays the quotes on the screen. Although final transactions are subject to possible negotiation, the screen display gives a "book" of available bids and offers to all participants. Motivated by this distinctive feature of the market structure, we provide two alternative means of constructing price data from the observed bids and offers. The first is based on a trade-matching algorithm designed for the interbank market by Reuters, labeled Dealing 2000, while the second takes into account the possibility of negotiation.

The trade execution rules of the Dealing 2000 system will be the same as in the Chicago Mercantile Exchange/Reuters GLOBEX computerized futures and options system; see Domowitz (1990). Upon receipt of a new bid or offer, the automated trade execution system searches for one or more standing orders, defined as a bid or offer already in the electronic order book, that can be partially or completely matched with the incoming bid or offer. A match is possible if the incoming bid is equal to or greater than a standing offer, with the obvious analogue for incoming offers. The electronic book arranges bids and offers according to price and time priorities.

To generate "transactions prices" we submit the actual quotes from the banks participating in the market to this electronic book, and utilize the automated trade-matching algorithm to identify matches between the banks. All transactions prices will be either at the best market bid or ask quote. The probability of a transaction at either one is a function of the incoming flow of quotes, and therefore will change over time. We have no information on the bid and offer size. In line with institutional reality, we assume that any observed bid or offer is an invitation to trade a minimum predetermined quantity at such prices. This implies that there are no partial fills in the matching process. We denote this series by GBX in the tables and text.

We also consider a price construction based on the fact that the current telephone network allows negotiation between the two parties involved, who have signalled willingness to trade by posting quotes. The automated trade execution algorithm matches an incoming bid or offer with a standing offer or bid for a trade at the price of the standing order. Assuming that the result of a telephone conversation between the parties "splits the difference" between the standing best bid or offer and the incoming offer or bid eligible for a trade, we construct a price series by taking a simple average of the two quotes. This series is called IMBA in the text and tables.

A busy market may preclude the updating of quotes, causing some staleness in the bid and offer series. We adjust the incoming quote series in the following manner, which affects all of the price series analyzed.

The arrival of a new quote from any particular market participant cancels all existing quotes by that bank. This mimics common trading practice. In the absence of a new quotation by a given bank, the bank's current bid and offer is assumed to have a finite effective life, depending on the degree of market activity. Define the arrival rate of incoming quotes at time t, λ_t, as the total number of arrivals in a given observation interval divided by the length of the interval in minutes. The effective minute life of quotes on the screen, $\tau(\lambda_t)$, is modeled as,

$$\tau(\lambda_t) = 1/(\kappa + \gamma \min\{\lambda_t, \lambda\}).$$

The coefficients κ, γ, and λ are arbitrary, and their values depend on a subjective judgement as to the effect of market activity on the effective cancellation of quotes. The results reported here use values of $\kappa = 0.0167$,

$\gamma = 0.097$, and $\lambda = 5$. Given these values, no quotation is valid for longer than sixty minutes. This limiting value obtains when the arrival rate over the preceding hour equals $\lambda_t = 1/60$, i.e., there is no market activity except for the new incoming quote. Similarly, market activity in excess of five quote arrivals per minute results in an effective quotation life of just under two minutes. The arrival rate of five quotes per minute corresponds to the average market activity observed during peak trading periods. The average arrival rate across the trading day is roughly 2.5 quotes per minute. The results reported in the text are not very sensitive to the precise numerical specification of the rule governing this cancellation scheme. On the other hand, completely ignoring the problem induces spuriously large amounts of kurtosis in the returns distributions. For the particular parameter values employed here, the total number of transactions resulting from the 305,604 quotes is 58,644.

Finally, the lack of activity over the weekend requires some special care. We simply cancel all returns covering a span longer than one hour during weekend trading periods. This effectively removes weekend activity from the data.

REFERENCES

Admati, A. R., and P. Pfleiderer, 1988, A theory of intraday patterns: Volume and price variability, *Review of Financial Studies* 1, 3–40.

———, 1989, Divide and conquer: A theory of intraday and day of the week mean effects, *Review of Financial Studies* 2, 189–224.

Amihud, Y., and H. Mendelson, 1980, Dealership market: Market-making with inventory, *Journal of Financial Economics* 8, 31–53.

Andersen, T. G., 1992, Return volatility and trading volume in financial markets: An information flow interpretation of stochastic volatility, Working paper, J. L. Kellogg Graduate School of Management, Northwestern University.

Baillie, R. T., and T. Bollerslev, 1991, Intra-day and inter-market volatility in foreign exchange rates, *Review of Economic Studies* 58, 565–585.

Biais, B., P. Hillion, and C. Spatt, 1992, An empirical analysis of the limit order book and the order flow in the Paris Bourse, Working paper, Carnegie-Mellon University.

Bollerslev, T., R. Y. Chou, and K. F. Kroner, 1992, ARCH modeling in finance: A review of the theory and empirical evidence, *Journal of Econometrics* 52, 5–59.

Bollerslev, T., and I. Domowitz, 1991, Price volatility, spread variability and the role of alternative market mechanisms, *Review of Futures Markets* 10, 78–102.

Bollerslev, T., and J. M. Wooldridge, 1992, Quasi-maximum likelihood estimation and inference in dynamic models with time-varying covariances, *Econometric Reviews* 11, 143–172.

Brock, W., and A. Kleidon, 1992, Periodic market closure and trading volume: A model of intraday bids and asks, *Journal of Economic Dynamics and Control* 16, 451–489.

Clark, P. K., 1973, A subordinated stochastic process model with finite variance for speculative prices, *Econometrica* 41, 135–156.

Copeland, T. E., and D. Galai, 1983, Information effects on the bid-ask spread, *Journal of Finance* 38, 1457–1469.

Cutler, D. M., J. M. Poterba, and L. H. Summers, 1990, Speculative dynamics and the role of feedback traders, Working paper no. 3243, National Bureau of Economic Research.

Domowtiz, I., 1990, The mechanics of automated trade execution systems, *Journal of Financial Intermediation* 1, 167–194.

——— and H. White, 1982, Misspecified models with dependent observations, *Journal of Econometrics* 20, 35–58.

Engle, R. F., 1976, Interpreting spectral analyses in terms of time-domain models, *Annals of Economic and Social Measurement* 5, 89–109.

———, T. Ito, and W. L. Lin, 1990, Meteor showers or heat waves? Heteroskedastic intra-daily volatility in the foreign exchange market, *Econometrica* 58, 525–542.

Foster, D., and S. Viswanathan, 1990, A theory of intraday variations in volumes, variances, and trading costs, *Review of Financial Studies* 3, 593–624.

Goodhart, C. A. E., 1990, "News" and the foreign exchange market, Working paper, London School of Economics.

——— and A. Demos, 1990, Reuters screen images of the foreign exchange market: The deutsche mark/dollar spot rate, *Journal of International Securities Markets*, 333–348.

Goodhart, C. A. E., and L. Figliuoli, 1991, Every minute counts in financial markets, *Journal of International Money and Finance* 10, 23–52.

Harris, L., 1987, Transactions data tests of the mixture of distributions hypothesis, *Journal of Quantitative and Financial Analysis* 22, 127–142.

Harvey, C. R., and R. D. Huang, 1991, Volatility in the foreign currency futures market, *Review of Financial Studies* 4, 543–569.

Hausman, J., A. W. Lo, and A. C. MacKinlay, 1992, An ordered probit analysis of transaction stock prices, *Journal of Financial Economics* 31, 319–379.

Ho, T., and H. R. Stoll, 1983, The dynamics of dealer markets under competition, *Journal of Finance* 38, 1053–1074.

Jones, C. M., G. Kaul, and M. L. Lipson, 1991, Transactions, volume, and volatility, Working paper, School of Business Administration, University of Michigan, Ann Arbor.

Laux, P., and L. K. Ng, 1991, Intraday heteroskedasticity and comovements in the foreign currency futures market, Working paper, University of Texas at Austin.

Lamoureux, C. G., and W. D. Lastrapes, 1990, Heteroskedasticity in stock return data: Volume versus GARCH effects, *Journal of Finance* 45, 221–229.

Ljung, G., and G. E. P. Box, 1978, On a measure of lack of fit in time series models, *Biometrika* 65, 297–303.

Lo, A. W., and A. C. MacKinlay, 1990, An econometric analysis of nonsynchronous trading, *Journal of Econometrics* 45, 181–212.

Lyons, R. K., 1991, Private beliefs and information externalities in the foreign exchange market, Working paper, Columbia University.

Madhavan, A. N., 1992, Trading mechanisms in securities markets, *Journal of Finance* 47, 607–641.

Nelson, D. B., 1990, ARCH models as diffusion approximations, *Journal of Econometrics* 45, 7–38.

Roll, R., 1984, A simple implicit measure of the effective bid-ask spread in an efficient market, *Journal of Finance* 39, 1127–1139.

Son, G., 1991, Dealer inventory position and intraday patterns of price volatility, bid/ask spreads and trading volume, Working paper, University of Washington.

Stoll, H., 1978, The supply of dealer services in securities markets, *Journal of Finance* 33, 1133–1152.

Subrahmanyam, A., 1989, Risk aversion, market liquidity, and price efficiency, Working paper, Anderson Graduate School of Management, UCLA.

Tauchen, G., and M. Pitts, 1983, The price variability-volume relationship on speculative markets, *Econometrica* 51, 485–505.

Tygier, C., 1988, *Basic Handbook of Foreign Exchange* (Euromoney Publications Limited, London).

Wasserfallen, W., 1989, Flexible exchange rates: A closer look, *Journal of Monetary Economics* 23, 511–521.

Weiss, A. A., 1986, Asymptotic theory for ARCH models: Estimation and testing, *Econometric Theory* 2, 107–131.