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The interaction between the frequency of market quotations, spread and volatility in the foreign exchange market

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There is an empirical relationship between volatility, average spread, and number of quotations in the foreign exchange spot market. The estimation procedure involves two steps. In the first one the optimal functional form between these variables is determined through a maximization procedure of the unrestricted VAR, involving the Box–Cox transformation. The second step uses the two-stage least squares method to estimate the transformed variables in a simultaneous equation system framework. The results indicate that the number of quotations successfully approximates activity in the spot market. Furthermore, the number of quotations and temporal dummies reduce significantly the conditional heteroskedasticity effect. We also discuss information aspects of the model as well as its implications for financial informational theories. Inter- and intra-day patterns of the three variables are also revealed.

I. INTRODUCTION

It is common in the literature for variations in the arrival of 'news' in financial markets to be measured directly from the data on the volatility of prices/returns. [See, for example, Engle and Ng (1991)]. In one sense this approach assumes what needs to be tested, i.e. that 'news' drives volatility. Moreover, the ARCH effects commonly found in such financial series, [see Bollerslev *et al.* (1992)], may well represent some combination of the autoregressive characteristics of 'news' arrival, i.e. the bunching of 'news', and of 'pure' market volatility. Given the theoretical results on the mixtures-of-distributions hypothesis by Clark (1973), Tauchen and Pitts (1983), and Andersen (1991) among others, when time is measured in calendar time, the conditional variance of returns will be an increasing function of the actual number of information arrivals [see Bollerslev and Domowitz (1991)].

A number of questions follow. The first is what indicator of information arrival to use. One possibility would be to try to exploit the data available over the 'news' pages on the electronic screens, for example, Reuters AAMM page of 'news' of interest to market dealers [see Goodhart (1990), Goodhart *et al.* (1991)]. The construction of any such index would undoubtedly be somewhat subjective, and extremely laborious, but could still be worth attempting at a later stage.

Another way is to follow previous studies of mixture of distributions [see, for example, Harris (1987), Gallant *et al.* (1989) and (1990), and Laux and Ng (1991)] and use volume as a proxy for the number of information events. However, Jones, Kaul and Lipson (1991) show that volume is a noisy and imperfect proxy for information arrival, and that the *number* of transactions is a better variable in a model with a fixed number of traders. However, there are no volume data available in the forex market [see, for example Goodhart and Demos (1990)]. Instead the frequency of quote arrivals over Reuters' screens is used as the proxy for market activity. This may capture the effect of market activity on volatility, up to the extent that news is reflected in changes in current market activity.

The next question is whether it is permissible and appropriate to examine the *contemporaneous* interaction between quote arrival and volatility, or only to relate volatility to quote arrival using information available at $t-1$ and earlier. The previous literature indicates that this decision is important. The results using information on market activity, whether quote frequency or volume, at $t-1$ and earlier suggest that such data has no significant ability to predict volatility, given past data on volatility, [for example, Jones, Kaul and Lipson (1991), Lamoureux and Lastrapes (1990), Bollerslev and Domowitz (1991)]. On the other hand, Lamoureux and Lastrapes (1990) and Laux and Ng (1991) find that the use of *contemporaneous* data on market activity virtually removes all persistence in the conditional variance in their series, being daily stock returns and intra-day currency future returns respectively. Bollerslev and Domowitz (1991) doubt the validity of using contemporaneous data on the grounds of simultaneity and that the traders information set does not include contemporaneous data on market activity. Simultaneity is dealt with by using a simultaneous equation system estimation procedure. With respect to the second objection, market traders' way of life is watching the screen, so they will be virtually instantaneously aware of a change in the speed of flow of new quotes. Furthermore, it is argued that the entry of a quote on the screen must have both temporal and causal priority over volatility developments, since the latter can only be estimated *once* decisions to enter a new quote have been taken and executed. Hence the hypothesis is that, in this ultra-high frequency data set, the 'causal' linkages will be found to be stronger from quote frequency to volatility when both are taken over the same short time interval, than vice versa.

Here we examine international patterns of intra-day trading activity and some properties of the time series of returns for the Deutschemark/Dollar and Yen/Dollar exchange rates in the foreign exchange market through the interbank trade. The purpose is to provide some information useful in the further development of the microstructure of trading models and to compare the empirical results with previous ones and theoretical models already in existence.

The results in Bollerslev and Domowitz (1991) are extended in two different ways. First, certain arguments are outlined (in Section III) explaining why quote frequency data might be better entered in log, rather than in numerical, form, and we search for the best fitting transformation of the data using the Box–Cox transformation. Second, in Goodhart and Demos (1990), we argue that there are certain predictable temporal regularities in the foreign exchange market (for example, the regular release of economic data at certain pre-announced times, the passage of the market through the time zones punctuated by market openings and lunch breaks (especially in Tokyo)). Consequently temporal weekly, daily and half-hourly dummies are added to all equations. As will be shown in Section III, these two changes do make a difference to the results. The conditioning of the variables of interest on such temporal dummies allows us to distinguish between public and private information, something of great importance to informational theories of market micro-structure (see, for example, Admati and Pfleiderer (1988), Son (1991), etc.).

Although the emphasis here is on the relationship between quote frequency and volatility, since it is a less-researched area, we examine the three-fold interrelationships between quote frequency, volatility and bid-ask spreads. The positive relationship between volatility and the spread is well-known in the literature [see, for example, Ho and Stoll (1983) and Berkman (1991)]. We suggested earlier that the absence of any significant ability of prior quote frequency to predict volatility implied that volatility may have incorporated both the contemporaneous evidence from quote arrivals and other sources of information. If so, we would not expect quote arrivals, either contemporaneous or lagged, to influence spreads, given volatility.

Where, however, one might find some relationship between spreads and quote frequency would be among the constant temporal dummy variables. Whereas some sources of news are continuously unfolding, the market has a pattern of openings, lunch breaks, and closes, which might influence both quote frequency and spreads, independently of the pattern of price/return volatility. The work of Oldfield and Rogalski (1980), Wood, McInish and Ord (1985), French and Roll (1986), and Harris (1986) among others have stimulated considerable interest in documenting the pattern of stock market returns and their variances around the clock. Admati and Pfleiderer (1988), and Foster and Viswanathan (1990) offer some theoretical explanations for some of these empirical findings. Here we aim to extend this work by looking also at the temporal patterns of quote frequency and spreads. We examine the relationship between the sets of temporal dummy variables in Section IV. We conclude in Section V.

II. THE DATA SET

The continuously quoted data are divided into discrete segments in the following way. The 24-hour weekday is divided into 48 half-hour intervals and the average spread, standard deviation of the percentage first difference of the rates quoted $(\ln(e_t) - \ln(e_{t-1}))$, and the number of new quotations within this interval are recorded. In a few instances there were too few observations in a half-hour to calculate a meaningful estimate of volatility. In such cases we substituted the values for the lowest calculable observed volatility, and the accompanying spread, in a half-hour of that week. This resulted in around potentially 2500 half-hourly observations. In fact, 5 out of the 12 weeks were chosen for analysis, avoiding any weeks with public holidays in the main country participants. The results are robust to this choice.

At this point we should review some pitfalls associated with the approximation of market activity by the number of quotations. Market participants have claimed that during very busy periods traders may be too occupied in dealing through their telephones to update their screens immediately (see Goodhart and Demos (1990)). *Per contra*, when the market is dull some market participants may enter new

Table 1. *Quasi log-likelihood values as a function of the Box–Cox exponent*

	DEM				JPY		
γ	σ_t^* Log-likelihood	sp_t^* Log-likelihood	n_t^* Log-likelihood	γ	σ_t^* Log-likelihood	sp_t^* Log-likelihood	n_t^* Log-likelihood
1.0	− 1304.8	− 1675.5	− 5395.5	1.0	− 1699.8	− 1736.9	− 5202.1
0.5	− 1053.3	− 1532.9	**− 5170.2**	0.5	− 1386.8	− 1706.4	− 4894.5
0.3	− 1012.7	− 1489.6	− 5228.3	0.4	− 1353.6	− 1703.9	**− 4882.1**
0.2	**− 1008.6**	− 1470.4	− 5311.9	0.3	− 1330.3	− 1702.3	− 4894.1
0.1	− 1016.9	− 1452.6	− 5438.0	0.2	− 1316.8	**− 1701.9**	− 4934.2
0.0	− 1040.9	− 1436.2	− 5607.8	0.1	**− 1312.9**	− 1702.7	− 5005.8
− 0.5	− 1429.9	− 1375.0	− 6990.1	0.0	− 1314.9	− 1703.9	− 5110.8
− 1.0	− 2255.8	**− 1350.2**	− 8867.4				
− 2.0	− 4525.9	− 1385.2	− 13 130.0				

Note: Bold indicates the optimum γ.

quotes to generate some business. However, in general the temporal pattern of the markets may differ from the temporal pattern of the 'news' generation process. Markets often close almost entirely, for example, at weekends and over the Tokyo lunch hour, or become very busy, while some 'news' is continuously occurring. Although we would expect more 'news' always to be associated with a higher frequency of quotes, as long as some markets are in operation, the functional form of this relationship, for example, linear, log-linear, etc., remains unknown.

III. ESTIMATION AND RESULTS

The following Simultaneous Equation System (SES) is to be estimated:

$$\sigma_t = \text{Dummies} + \alpha_{12} sp_t + \alpha_{13} n_t + \alpha_{14}\sigma_{t-1} + \alpha_{15}\sigma_{t-2} \tag{1.a}$$

$$sp_t = \text{Dummies} + \alpha_{21}\sigma_t + \alpha_{23} n_t + \alpha_{24} sp_{t-1} + \alpha_{25} sp_{t-1} \tag{1.b}$$

$$n_t = \text{Dummies} + \alpha_{31}\sigma_t + \alpha_{32} sp_t + \alpha_{33} n_{t-1} + \alpha_{34} n_{t-2} \tag{1.c}$$

where σ_t, sp_t, and n_t are the standard deviation of the percentage change of an exchange rate, the average spread, and the number of quotations within the tth half-hour interval, and the system is separately estimated for the two currencies under interest, i.e. the Deutschemark and Japanese Yen, against the US dollar. As financial time series suffer from conditional heteroskedasticity effects, we include lagged dependent variables in Equations 1.a to 1.c. Moreover this helps in the identification of the system. The estimation method is two-stage least squares.[1]

The functional form of the relationship between these variables needs careful consideration. There is no apparent reason why the average spread, volatility, and number of quotations should be linearly related, rather than, say, log-linearly. On theoretical grounds both functional relationships would have the same characteristics as discussed in Sections I and II. Hence, we left the data to decide on this by using the following procedure.

We first transformed the three variables using the Box–Cox transformation. The reduced form of the SES is a restricted Vector Autoregression (VAR) of order 2; we estimated the unrestricted form for each currency for different values of the Box–Cox exponent, i.e. the following VAR(2) was estimated for different values of γ_1, γ_2, and γ_3 (the exponents):

$$\begin{bmatrix}\sigma_t^*\\ sp_t^*\\ n_t^*\end{bmatrix} = Dm. + \begin{bmatrix}\beta_{11} & \beta_{12} & \beta_{13}\\ \beta_{21} & \beta_{22} & \beta_{23}\\ \beta_{31} & \beta_{32} & \beta_{33}\end{bmatrix}\begin{bmatrix}\sigma_{t-1}^*\\ sp_{t-1}^*\\ n_{t-1}^*\end{bmatrix} + \begin{bmatrix}\delta_{11} & \delta_{12} & \delta_{13}\\ \delta_{21} & \delta_{22} & \delta_{23}\\ \delta_{31} & \delta_{32} & \delta_{33}\end{bmatrix}\begin{bmatrix}\sigma_{t-2}^*\\ sp_{t-2}^*\\ n_{t-2}^*\end{bmatrix} + \begin{bmatrix}\varepsilon_{1t}\\ \varepsilon_{2t}\\ \varepsilon_{3t}\end{bmatrix}$$

where $\sigma_t^* = (\sigma_t^{\gamma_1} - 1)/\gamma_1$, $sp_t^* = (sp_t^{\gamma_2} - 1)/\gamma_2$, and $n_t^* = (n_t^{\gamma_3} - 1)/\gamma_3$. Notice that for $\gamma_1 = \gamma_2 = \gamma_3 = 1$, and $\gamma_1 = \gamma_2 = \gamma_3 = 0$ we have the linear and log-linear forms, respectively.

In Table 1 we present the values of the quasi log-likelihood function for the transformed variables, for different, but common across the three variables, values of γ. It is immediately apparent that the optimal value of γ depends on the variable and the currency. However, notice that the

[1]We avoided Full Information Maximum Likelihood estimation on the grounds of the strong non-normality of the residuals (see below).

log-likelihood function appears to be unimodal, with respect to the parameter γ, at least for γ values between 1 and -2 for the Deutschemark, and 1 and 0 for the Yen. What we are doing here in effect is a grid search of the pseudo-likelihood function with respect to the γ parameter. Although we chose the steps of the grid to be 0.05, in Table 1 only some representative values of the log-likelihood function are reported, for two reasons. First, the likelihood function is not very flat around the optimum, with the possible exception of the Yen average spread equation, and second, because of space considerations.

The optimal γ values for the Deutschemark are $\gamma_1 = 0.2$, $\gamma_2 = -1$, $\gamma_3 = 0.5$, and for the Yen $\gamma_1 = 0.1$, $\gamma_2 = 0.2$, and $\gamma_3 = 0.4$. We did a second grid search but this time we kept one of the γs constant at its optimum value, say γ_1, and varying simultaneously the values of the other γ's, γ_2 and γ_3, around their optimal, using a step length of 0.01. For both currencies the optimum values of γ's stayed as above. Hence, it seems that neither the linear nor the log-linear functional forms are the best approximations to the data generating process functionals. However, from Table 1 it is apparent that the log-linear form is a better approximation than the linear one, with the possible exception of the number of quotations for the Deutschemark.

Diagnostic tests on this simultaneous system are reported in Appendix A. In particular, the Wu (1973) and Hausman (1978) F tests for exogeneity of the three variables, with one exception, are rejected. However, the tests for the omission of relevant lagged variables could not reject, at least for the spread equation (see Appendix A), so we included one more lag in this equation.

Consequently, we estimated the following SES by two-stage least squares. The estimates of the structural parameters and their heteroskedasticity robust standard errors are presented in Table 2.

$$\sigma_t^* = \text{Dummies} + \alpha_{12} sp_t^* + \alpha_{13} n_t^* + \alpha_{14}\sigma_{t-1}^* + \alpha_{15}\sigma_{t-2}^* \tag{2.a}$$

$$sp_t^* = \text{Dummies} + \alpha_{21}\sigma_t^* + \alpha_{23} n_t^* + \alpha_{24} sp_{t-1}^* + \alpha_{25} sp_{t-2}^* + \alpha_{26} sp_{t-3}^* \tag{2.b}$$

$$n_t^* = \text{Dummies} + \alpha_{31}\sigma_t^* + \alpha_{32} sp_t^* + \alpha_{34} n_{t-1}^* + \alpha_{35} n_{t-2}^* \tag{2.c}$$

Some important points emerge from this table. First, the results are quite robust across the two currencies, although the functional form of the variable is different. Second, notice that in the volatility equation (Equation 2.a) the average spread and the number of quotations have a strong positive effect on volatility. These positive relationships of spread-volatility and volatility-activity are well-documented facts in the literature. Ho and Stoll (1983), Berkman (1991), as well as the probit model of Hausman, Lo and MacKinley (1991) of trade by trade stock market data document the first relationship, whereas Lamoureux and Lastrapes (1990) and Laux and Ng (1991) support the second. The second relationship also supports the model of Brock and Kleidon (1990) where the link between variations in demand and the variability of prices is through variations in the bid and ask prices.

In the average spread equation (Equation 2.b) the number of observations is insignificant. This justifies our earlier hypothesis that volatility has incorporated both the contemporaneous evidence from quote arrivals and other sources of information and consequently quote arrivals do not influence spread, given volatility.

Table 2. *Estimated coefficients and standard errors of the structural system (2.2)*

			DEM $\hat{\alpha}_{ij}$			
i/j	1	2	3	4	5	6
1		9.146	0.012	0.210	-0.002	
		(5.611)	(1.656)	(3.678)	(-0.111)	
2	0.012		0.000	0.398	0.108	0.079
	(1.641)		(0.393)	(5.565)	(2.697)	(2.510)
3	-0.004	5.424		0.496	0.111	
	(-0.00)	(0.344)		(13.56)	(3.282)	
			JPY $\hat{\alpha}_{ij}$			
i/j	1	2	3	4	5	6
1		0.629	0.028	0.189	0.007	
		(5.340)	(2.189)	(4.137)	(0.227)	
2	0.291		-0.007	0.296	0.095	0.088
	(3.129)		(-0.881)	(5.597)	(2.162)	(2.683)
3	1.022	-0.805		0.457	0.038	
	(1.091)	(-0.781)		(11.58)	(1.217)	

Note: Heteroskedasticity robust t-statistics are in parentheses.

In the number of quotations equation (Equation 2.c) volatility and average spread are highly insignificant. This implies that there may be some kind of 'causation' from the number of quotations to volatility and some kind of feedback relationship between volatility and average spread. However, the number of observations is not weakly exogenous to the system as the variance covariance matrix of the residuals is not diagonal. In fact, the correlation matrix of the residuals of the system (Equation 2.a to 2.c) is presented in Table 4.

Hence, we conclude that, apart from the residual effects, volatility and average spread are simultaneously determined and there may be a feedback rule between number of quotations and volatility. However, the number of quotations affects the average spread process through volatility only. This relationship is stronger for the Yen than for the Deutschemark.

Furthermore, notice that the second lagged volatility in Equation 2.a is insignificant, and the coefficient estimate of the first lag has a very low value (around 0.2 for both currencies), which implies a very weak autoregressive conditional heteroskedasticity effect. However, this is not the case when average spread and number of observations are excluded from this equation. In such a case the OLS estimates of the first and second lag volatility, of the regression of volatility on Dummies and 2 lagged volatilities, equal 0.322 (6.079), and 0.070 (1.746) for the Mark and 0.319 (7.237), and 0.0717 (2.206) for the Yen (the robust t-statistics are in parentheses). This implies that these two variables take out a considerable amount of the conditional heteroskedasticity effect observed in exchange rate time series. This points out to the fact that heteroskedasticity type effects, which captured by ARCH or GARCH type models in a univariate setups, are mainly due to missing variables in the econometrician's information set.

Moreover, the addition of our dummy variables further reduces the second order ARCH type effect in the series. If the SES (Equations 2.a to 2.c) is estimated without the dummy variables the results exhibited in Table 3 are obtained.

Now the first lag estimated coefficient takes a considerably higher value than in the case where dummy variables are included, and the second lag coefficient becomes significant. Notice also that now in the number of quotations equation volatility has a strong negative effect, something which is also documented in Bollerslev and Domowitz (1991), where the dummy variables are excluded from their model.

To conclude this section we can say that the simultaneity and the inclusion of dummy variables capture a considerable part of heteroskedasticity type effect, observed exchange rate markets. This in effect is due to unobservable news reflected either in the bid-ask spread or in the dummy variables which are responsible for changes in traders' desired inventory positions with the result of changing spreads, according with the theories of O'Hara and Oldfield (1986) and Amihud and Mendelson (1980). These changes in spread can explain a considerable part of volatility movements, and consequently decreasing the heteroskedasticity type effects.

IV. TEMPORAL HALF-HOURLY EFFECTS

The temporal dummies capture events (publicly announced news releases, market openings and closings) whose timing,

Table 3. *Estimated coefficients and standard errors of the structural system (2.2) without dummy variables*

			DEM $\hat{\alpha}_{ij}$			
i/j	1	2	3	4	5	6
1		7.637	0.006	0.267	0.109	
		(7.213)	(2.809)	(4.897)	(3.019)	
2	0.007		0.000	0.489	0.176	0.114
	(1.651)		(1.650)	(9.243)	(4.126)	(3.770)
3	− 3.237	38.196		1.051	− 0.192	
	(− 2.155)	(1.803)		(33.73)	(− 5.692)	
			JPY $\hat{\alpha}_{ij}$			
i/j	1	2	3	4	5	6
1		0.483	0.011	0.303	0.085	
		(6.473)	(2.770)	(7.240)	(3.012)	
2	0.153		0.002	0.369	0.173	0.147
	(2.639)		(1.112)	(7.743)	(3.757)	(4.009)
3	− 2.380	2.578		0.976	− 0.233	
	(− 2.876)	(2.908)		(28.81)	(− 6.359)	

Note: Heteroskedasticity robust t-statistics are in parentheses.

though not generally their exact scale, is known in advance. Public new related to macroeconomic variables is simultaneously announced to all traders, at a time known in advance since the scheduled time of all economic related news is predetermined, and reported on another part of the Reuters system, the FXNB page. The stochastic element in such cases is the actual announcement, *not* the timing of it. In general, the majority of the US announcements are around 13:30 hours British Summer Time (BST), and the German ones around 10:00 hours BST. Consequently, the relationship between the dummy variables and the characteristics of interest to us in the market predominantly reflect response of these variables to publicly known events. *Per contra*, the relationship between these variables, after conditioning on such temporal constants, will primarily reflect private information to a somewhat greater extent.

Notice that the constant represents the last half hour of the last Friday in the sample. During this half hour all the main markets are closed and only a few traders, if any at all, input quotations. Therefore, the constant in the estimation reflects, on average, the smallest number of observations in the sample, but not necessarily the lowest level of volatility or the smallest average spread. Let us now concentrate on these dummy effects.

The estimated dummy coefficients, for both currencies and per equation, are not presented here because of space considerations.[2] Let us consider the half hour dummies first.

In graphs 1a to 3b in Figure 1 the values of the estimated dummy coefficients for both currencies are presented. They reveal an interesting feature. In the last part of the day BST time, from about the closing time of the European exchanges and until the closing time of the New York exchange, volatility is unusually high. Notice that this takes place in both currency markets.

During this period there are few, or no, economic (or other public) announcements from Europe or Asia (considering only Japan). Most US economic announcements are made before the opening of the New York Stock Exchange, at 13.30 BST. There is a small spike at the relevant half hour (27), but this remains quite small compared with the higher volatilities apparent later on in the US market day.

Hence, it seems that public news is not the explanation of this volatility increase. Furthermore, this increase seems even more difficult to explain in the light of the Admati and Pfleiderer (1988) theory. During this period we certainly have a reduction in the number of traders in the market, as only the New York exchange is in operation, so this increase can hardly be attributed to an increase in the number of liquidity traders.

There is then an apparent decrease in volatility for both currencies, during the early morning period between 1:30 and 3:30 (BST). Most of the economic-related news for the Japanese economy is announced either early in the Japanese morning, i.e. around 1:00 BST, or in the late Japanese afternoon, i.e. 6:00 BST. The same time period is characterized by high spread and screen activity. However, it appears that Japanese economic-related news has no effect on the volatility of the JPY currency. Although in line with the results of Ito and Rolley (1987), this remains peculiar. Furthermore, the same is true for the Deutschemark in relation to German economic announcements, which are mostly released either around 9:30 or 14:00 BST. Hence, it seems that only US economic news affects the variability of DEM and JPY exchange rates.

There is a further curiosity in the half-hourly dummies which is worth mentioning. During the Tokyo lunch time break (4:00–5:00 BST) there is a dramatic decrease of volatility coupled with an increase in spread and a decrease in the number of quotations in the first half-hour period (between 4:00–4:30 BST), followed by an increase in volatility coupled with a decrease in spread which cannot be explained by public information theories. Perhaps traders who come back early from lunch take 'wild' positions to make their early return worthwhile. On the other hand this volatility increase could be a statistical artefact due to the small number of quotations during that period; that is, a few observations out of 'equilibrium level' can have a dramatic increase in the sample variance of the rate.

The increase of average spread during the beginning of the Tokyo (4:00 BST) lunch hour for both currencies could be attributed to that traders during the lunch hour widening their spreads to protect themselves from any unexpected news, whereas when they return to their desks the average spread returns to normal.

For both markets 7:00 BST seems to be an unusually high spread period. This coincides with the opening of the European market and the closing of the Asian one; possibly European traders want to protect themselves from potential superior information that their Asian counterparts could possess. However, this is less marked in the JPY market. This opposes the Admati and Pfleiderer (1988) model, where spread is lowest at the beginning of the trading day, due to liquidity considerations, and in line with the Foster and Viswanathan (1990) model where spread is highest at the start of the day. Another high spread period for the DEM market is around 14:00 BST, shortly after the release of US macroeconomic news. It is also the common time for coordinated interventions to occur [see Goodhart and Hesse (1992)]. As at the same time there is some small increase in the volatility of the market the spread increase can be attributed to the traders, fear of central bank interventions.

The busiest period of the day in terms of the number of quotations, measured by the half-hourly dummies, is the return in activity after the Tokyo lunch-break and around

[2]See Table 5 is Demos and Goodhart (1992).

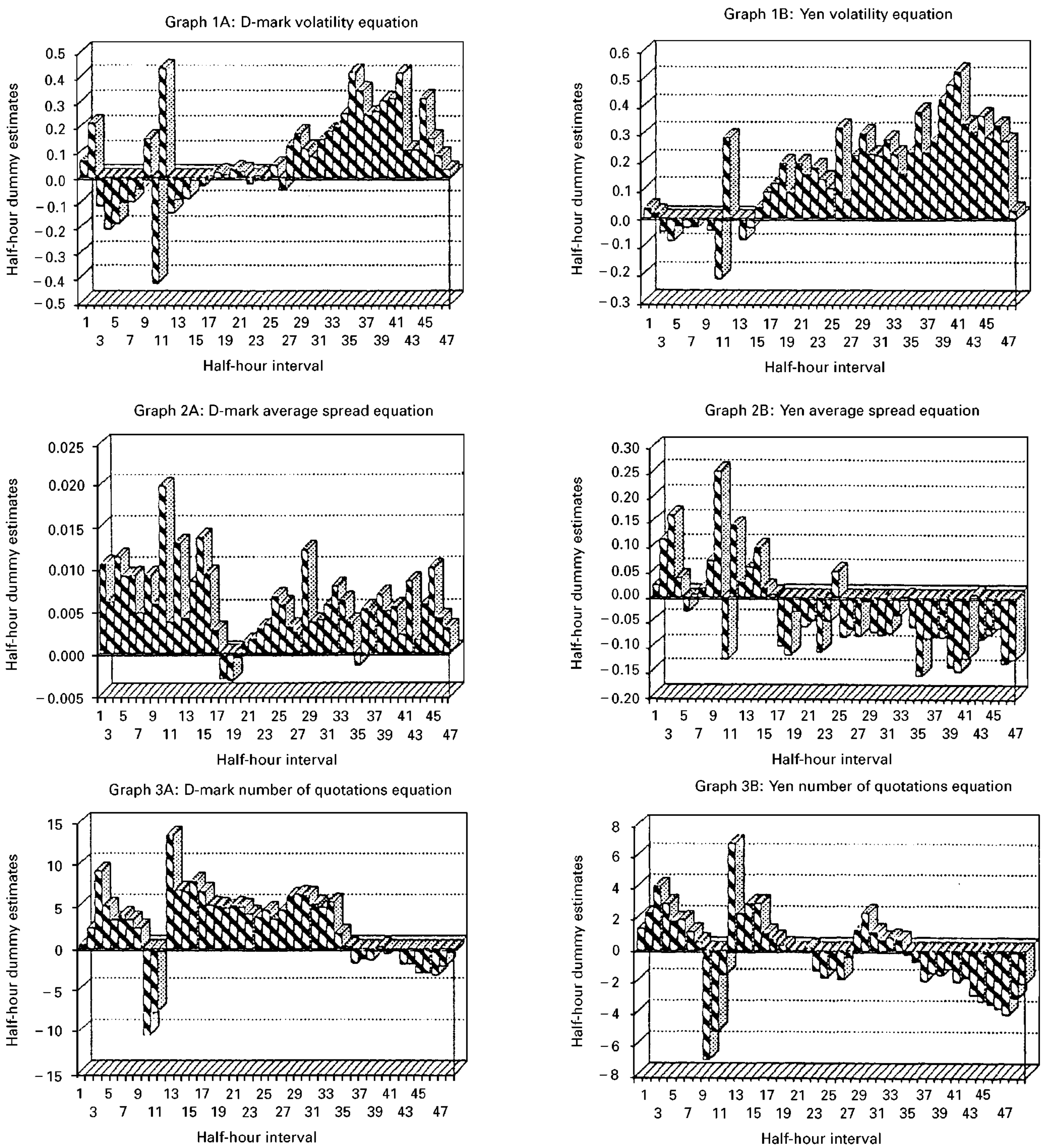

Fig. 1. *Graphs of volatility, average spread, and number of quotations equations*

5:30–6:00 BST, whereas the least busy is the Tokyo lunch hour for both currencies. After the burst of activity in the post Tokyo lunch-break, activity declines until there is a smaller secondary peak when New York opens, between 13.30 and 14.30 BST, (27–29 on our graphs), before London (Europe) closes. Thereafter activity (the number of quotations) falls steadily as the US markets grind to a halt, before Australia opens the new day.

The increased spread during periods of high market activity in both markets is best explained by the model of Subrahmanyan (1989), where more trading by informed risk-averse traders brings about lower liquidity and higher

Table 4. *Correlation matrix of the residuals for Equations 2.a–2.c*

	DEM			JPY		
	(2.a)	(2.b)	(2.c)	(2.a)	(2.b)	(2.c)
(2.a)	1			1		
(2.b)	− 0.267	1		− 0.502	1	
(2.c)	0.158	0.023	1	− 0.074	0.185	1

costs. Furthermore, the higher spread towards the end of the trading day, observed in the Deutschemark market but not in the Japanese Yen market, is predicted by the dealer market model of Son (1991), where risk-averse traders avoid trading close to the end of their day to avoid overnight inventory holdings.

There are few signs of any significant pattern in volatility between the days of the week, except for some indications of higher volatility in the Yen on Thursdays, and also positive but insignificantly so for DEM. The average spread was, however, significantly higher on Fridays than earlier in the week, with some tendency for it to be lowest on Thursdays and Wednesdays. This is roughly the inverse to the daily pattern for the frequency of quote arrivals (activity), which is lowest on Friday, and tends to peak in mid-week, Tuesday and Wednesday.

The weekly dummies during the period showed a pattern of steadily increasing market activity from week to week. The final week (Week 5) was not only extremely active, but exhibited a marked and highly significant increase in spread size. Volatility also increased in the final week, but the increase was much less significant.

V. CONCLUSIONS

We have assessed the behaviour of the spot foreign exchange market quotations in terms of volatility, average spread, and the number of quotations within half-hour intervals, as well as certain informational aspects of these processes. It seems that a log-linear relationship among these three processes is a considerably better approximation to the true data generating process functional form, than the linear one; however, it is by far worse than the functional form presented here.

A new variable was introduced: the number of observations within a specific time interval. This variable plays an important role in the determination of volatility and average spread, either directly or through the error terms. The contemporaneous correlation of the number of quotations and volatility leads us to hypothesize that the former process could be a proxy for the volume of trade, or for the number of transactions in the spot FOREX market, for which data are unavailable. This is in line with studies in stock market volume and volatility data [see Gallant, Rossi, and Tauchen (1990), and Lamoureux and Lastrapes (1990)].

It turns out that informational theories can only partially explain the facts documented here. Although, high trading and volatility at the opening of markets can be explained along the lines of the Admati and Pfleiderer (1988) theory,[3] the different behaviour of the two currencies in different markets at the same (and different) time periods points towards the need to take into account local and currency-specific behaviour. The same can be said for the models of Foster and Viswanathan (1990), Subrahmanyan (1989), and Son (1991).

An important result of this paper is that the inclusion of half-hourly dummies, and taking account of simultaneity between volatility, average spread, and number of quotations, considerably reduces the GARCH type effects in the conditional variance of these two exchange rates. What remains of such GARCH effects can then probably be attributed to private information and the uncertainty associated with it.

Finally, having fitted weekly, daily and half-hour dummies, we can identify inter- and intra-day patterns of activity, volatility and average spread. Some of these, for example, the impact of the Tokyo lunch hour, we have previously documented. Others are already well known in markets, for example, the rise in spreads and decline in activity on Fridays. But we were surprised by the finding of the continuing high volatility, in both currencies, throughout the period of US market opening, despite steadily falling activity, which we had expected. Much of the public information on economic news in the US is released at, or before, the market opening, so exactly what keeps volatility so high during the afternoons in the US is a mystery to us.

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[3]Strictly speaking, however, the Admati and Pfleiderer (1988) model applies to individual traders and to markets with well-defined opening and closing times.

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APPENDIX A

For the optimal γ's obtained, from the procedure described above, we tested for omission of relevant lags [see Spanos

(1986)], specifically two more, in the VAR formulation. The F statistics per currency and variable were the following: 2.25, 5.03, and 1.43 for the Deutschemark and 1.88, 4.271, and 3.81 for the Yen ($F(6, \infty)_{1\%} = 2.64$). For 10-order serial correlation of the residuals, the F statistics were 2.08, 2.52, and 1.13 and 1.70, 2.82, and 1.34 for the Deutschemark and Yen respectively ($F(10, \infty)_{1\%} = 2.32$). It seems that at least for the spread equation having only two lags does not capture the systematic dynamics. Hence, in the VAR formulation one more lag is added.

The F-statistics for two more lags, this time, are: 1.25, 0.98, and 1.65, and 1.47, 2.60, and 3.04, for the Mark and Yen respectively. However, the 10-order serial correlation F-statistics are highly significant for both currencies. This is probably due to overfitting in the volatility and number of quotes equations. Consequently, we re-estimated the VAR imposing zero coefficients to the third lag of volatility and number of quotations. The 10-order serial correlation statistics now are: 1.54, 1.38, and 1.23, and 1.62, 2.31, and 1.66 for the two currencies, suggesting that indeed overfitting was the cause of spurious serial correlation. The omission of two more lags, in the systematic dynamics of the VAR are now 1.57, 0.86, and 2.13 for the Deutschemark and 1.49, 2.22, and 3.89 for the Yen. Although the systematic dynamics for the number of quotations, for the Yen only, indicates that more lags are needed, and provided that this is not the case with the Deutschemark we decided to stay with this specification.

The Jarque-Bera (1980) normality tests on the VAR residuals stand at 2445.0, 696.6, and 185.3 for the Mark and 777.3, 529.6, and 125.9 for the Yen, implying a massive rejection of the null hypothesis. Furthermore, the one-sided Lagrange Multiplier test for ARCH type effects [see Demos and Sentana (1991)] again massively rejects the null of conditional homoskedasticity. Notice that in the normality test using linear of log-linear form the statistics had, more or less, two to three times the values reported above. A question arises immediately on the validity of the distributions, mainly of the various statistics that are used. However, provided that the usual regularity conditions hold, that is, the existence of higher moments for the distribution of the errors, the usual arguments for the asymptotic validity of the tests apply.[4]

The exogeneity Wu (1973) Hausman (1978) F statistics are 5.51, 4.10, and 5.95, and 4.60, 2.75, 5.80 for the Mark and Yen respectively. Hence with the exception of the average spread in Yen the exogeneity of the other variables is rejected. The Basmann (1974) test for the overidentified restrictions does not reject the null hypothesis as it stands at 1.57, 2.19, and 1.52 for the Mark and 1.95, 0.56, and 0.93 for the Yen. This is an indication that the specification of the system is correct (see Spanos (1986)).

[4]Notice that even in small samples it is not clear if the two-stage least square estimator over or underestimates the normal probability [see Knight (1986)].