# Bid-Ask Spreads in Foreign Exchange Markets: Implications for Models of Asymmetric Information

David A. Hsieh

Allan W. Kleidon

October 1994

**Suggested running head:** "Foreign Exchange Bid-Ask Spreads"

## About the Authors:

**David A. Hsieh** is Professor of Finance and Economics at the Fuqua School of Business, Duke University.

**Allan W. Kleidon** is Vice President at Cornerstone Research and a Visiting Professor at the School of Law, Stanford University.

**Acknowledgements:**

Support for this research has been provided by Cornerstone Research. We are grateful for helpful comments from Jeffrey Frankel, Paul Pfleiderer, Antti Suvanto, currency traders at Citibank and at Wells Fargo-Nikko Investment Advisors (Jeffrey Hord and Vikas Srivastava), two anonymous referees, seminar participants at the Haas School of Business, University of California, Berkeley, and participants at the Conference on *The Microstructure of Foreign Exchange Markets* in Perugia, Italy, July 1994.

## 1. Introduction

The term "market microstructure" was coined in 1976 by Mark Garman to define "moment-to-moment trading activities in asset markets" (1976, Abstract). With the stated goal of providing insight and testable implications regarding the transaction-to-transaction nature of realistic exchange processes, Garman examines dealership and auction models of market makers where the stream of market orders from a collection of market agents is depicted as a stochastic Poisson process. The resulting insights concern bid-ask spreads (based on standard micro-economic analysis), inventories of market makers, and the effects of some market power on the part of market makers.

A more recent microstructure literature is based on information asymmetries among economic agents. In a recent literature review, Admati (1991) defines the area of market microstructure as "the literature on asset markets with asymmetric information and especially on trading mechanisms" (p. 347); Garman is noted as an example of "earlier market microstructure literature" in which "[i]nformation issues were not typically modelled" (1991, fn. 11, p. 355). Two reasons are given for the popularity of asymmetric information models: policy implications of different trading processes, as exemplified by the 1987 crash, and empirical results such as various patterns in trading volume, variances and returns over the trading day. The belief is that better insights into both issues will be achieved by examining information asymmetries. Moreover, observed empirical results are believed to "call for theoretical explanations beyond what can be obtained by traditional models (in which informational asymmetries are not present)" (Admati 1991, p. 348).

In some ways, foreign exchange data have institutional features that are ideal for testing these now "standard" asymmetric information models. The market is very liquid and is linked around the world by computerized information systems, and the commodity is essentially the same in all markets. Standard information models have been applied to foreign exchange data in Bollerslev and Domowitz (1993), particularly to the behavior of bid-ask spreads and volume around the open and close of trading in regional markets. Bollerslev and Domowitz conclude (p. 1422) that data for smaller banks "which operate mainly within regional markets with well-defined market openings and closings" show the relationship between trading activity and spreads that is implied by standard asymmetric information models.

In this paper, we further examine how well standard asymmetric information models can explain the behavior of volatility, bid-ask spreads and volume around the open and close of trading in foreign exchange markets.[1] We conclude that the standard information models are unable to explain these data.

Our analysis differs from most previous studies in that we examine the implications of standard information models for the behavior of data *across* markets that are open simultaneously, rather than looking at markets in isolation. In particular, a feature of standard information models is that high volatility is associated with trades by privately informed traders whose trading activity incorporates their information into prices and quotes. Within this class of model, if new information results in high volatility of quotes for a trader located in London, then the quotes for a trader who is physically located in New York but who observes the London quotes will also show high volatility.

We exploit the fact that foreign exchange transactions occur virtually around the clock, with overlap between the trading day for traders in London and New York. Consequently, open of trade in New York and close of trade in London correspond to times when the other market has been trading for some time. We find that high volatility that shows up at the open in New York and the close in London appears to be unrelated to the concurrent volatility in the other market, *even though both sets of quotes appear on exactly the same trading screens at exactly the same time.*

This volatility cannot be due to new information reaching one market but not the other, within the standard information models. Either these markets that are ostensibly closely linked are segmented in important ways not recognized in standard models, or some phenomenon other than the incorporation of private information must be responsible for the behavior of quotes. Given the high degree of integration of the international foreign exchange market, we conclude that the observed periodicity of volatility is not due to the incorporation of private information as envisioned by standard asymmetric information models. One way of stating the problem is that if no new information is reaching the international foreign exchange market—which is implied by the absence of unusual volatility in quotes generated by traders in one physical location—then quotes generated by traders in another market show excess volatility relative to that implied by standard information models.

This is a not a new phenomenon. For example, the crash of October 1987 is an example of a large change in stock prices that does not appear to be caused by new information reaching the market as a whole. However, a recent class of model has been developed that explains such phenomena as the crash in terms of imperfect information aggregation and learning by market participants, rather than new information reaching the market as a whole. These models differ from standard asymmetric information models by relaxing the assumption that each trader has perfect knowledge about the structure of the market, that is, about the preferences and beliefs of all traders in the market.[2]

While this is a different type of model from standard asymmetric information models, it is possible that at least some of the observed behavior in foreign exchange markets may be attributable to this type of information asymmetry. We examine this possibility below, after closely examining the standard asymmetric information models. It appears that some form of learning about the market structure is important at the start of trading, which results in wide and volatile quotes when traders first enter the market. This process may be as informal as the posting of wide quotes with little expectation of trading during the initial period of learning.

At the close of trading, standard information models are again unable to explain the foreign exchange data. We conclude that inventory management by market makers in the closing market appears the most likely explanation.

The paper proceeds as follows. Section 2 discusses the institutional features of our data and presents our empirical results. Section 3 examines the standard asymmetric information models of intraday price and volume of Admati and Pfleiderer (1988) and Subrahmanyam (1989, 1991), and the current application of these models to foreign exchange data in Bollerslev and Domowitz (1993).[3] Section 4 examines alternate explanations of the results in section 2, namely recent learning models based on asymmetric information and other market microstructure models that place more emphasis on the roles of market power and inventory management of market makers. Section 5 contains concluding remarks.

## 2. Data and Results

This section examines the behavior of spreads and quote volatilities across different regional foreign exchange markets at the same point in time. We demonstrate that a key implication of standard asymmetric information models is *rejected* in foreign exchange data, namely that periods of high variance correspond to periods of high concentration of informed trading. When one regional market has high variance (that is, open and close of the regional market with concurrent high bid-ask spreads), other markets simultaneously have *low* variance (and low bid-ask spreads), even though the traders from different markets are connected by computer terminals with all quotes appearing simultaneously on all terminals. In section 3, we interpret these results as showing that whatever the explanations for these phenomena—and we suggest possibilities in section 4 below—they are not consistent with current standard models of asymmetric information.

### 2.1 Data

The foreign exchange market can be roughly divided into two groups.[4] The first group comprises market makers, or the interbank market, which accounts for most foreign exchange trading.[5] Market makers deal with each other through a very active computerized market that trades virtually around the clock, either directly or through inter-dealer brokers. The second group comprises the retail market or customers who approach a local broker or bank and are offered retail foreign exchange quotes by that retail bank.

The interbank foreign exchange market, from which our data are obtained, comprises a network of major trading banks throughout the world that are linked interactively via computer screens (either Reuters or Telerate systems). We use data from the Reuters indications system, which transmits computerized quotes among interbank dealers. When a trading bank individually updates its quotes, the new quotes directly appear on the screens of all traders around the world. Actual trades are consummated via telephone,[6] and price and volume for direct inter-dealer trades are not publicly revealed. Some information about brokered inter-dealer trades, namely price, quantity, and whether the trade is at the bid or the ask, is publicly disseminated to dealers via an intercom system. Major trading banks often perform both interbank and retail roles, with a dedicated forex desk within the bank linked to the interbank market, and with retail customers who are offered quotes that consist of the dealers' interbank quotes plus an additional markup.

The Deutschemark/dollar data we use were originally captured from a Reuters data feed by Charles Goodhart, and cover the 82 days from April 9 to June 30, 1989. These are the same data used by Bollerslev and Domowitz (1993), and they provide valuable descriptions of the characteristics of these data.[7] For our purposes, we concentrate on two markets, namely London and New York, but our analysis applies to the other markets documented in Bollerslev and Domowitz. Figures 1a and 1b document the time periods in which significant trading activity takes place in London and New York respectively. These figures give the average number of quote arrivals on Reuters' screens, per five-minute intervals, from traders based in London and New York.[8] Each location has activity beginning around 7.00 a.m. (local time) to about 6.00 p.m. (local time).[9]

Figure 2 integrates the London and New York data by converting the Eastern Standard Time (EST) New York times to Greenwich Mean Time (GMT) and plotting both figures 1a and 1b together. As noted by Bollerslev and Domowitz (1993, p. 1426), trading activity (as measured by the number of quote arrivals) in London begins high, declines until New York opens, then increases until close of London trade. Activity in New York roughly follows that of London, but continues strongly after the London close as New York becomes the major open market.

We wish to highlight several aspects of these data that make them excellent for studying models of asymmetric information. First, the interbank market is the closest to an ideal 24-hour market of which we know. It is very liquid, especially by comparison with stock markets, in terms of both volume of trade and number of traders; individual traders have continuous access to the market via computer terminal; and some trader is active virtually around the clock (including the markets in the Far East). Second, the commodity is essentially the same in all markets: the Deutschemark and dollar are the same irrespective of trader location, and settlement issues are trivial by comparison with, say, transactions on the NYSE versus the International Stock Exchange (ISE) in London (see Burnham 1998, p. 21).

Third, the facts of 24-hour trading and the very size and nature of the foreign exchange markets suggest that standard models of asymmetric information may find it difficult to explain persistent temporal patterns, since there may be less systematic private information in these markets compared with, say, a small NYSE listed stock that has few followers. Lyons (1993b) concludes that interpretation of "information" in the foreign exchange market must be broader than that in standard models of equity markets, since there are no "insiders" in the foreign exchange market. Our discussion of learning models in section 4 provides such a broader concept of information.

### 2.2 Results

*London and New York: Individual markets*

We first document that volatility in the foreign exchange markets follows the same U-shape pattern from open to close of trade as on, say, the NYSE. This is important because it is precisely this result that supports the conclusions of Admati and Pfleiderer (1988) and Subrahmanyam (1989) that there is heavy activity by informed traders at open and close of trade on the NYSE, which results in the higher variances of returns at those times.

Return variances are calculated as follows. The day is first divided into one-minute intervals. At the end of each minute, the last quote (bid/ask) is averaged. If no new quotes occur during that minute, the observation is deleted. Between two minutes (if both have quotes), the one-minute rate of return is computed as the discrete rate of change of the average bid/ask between the two minutes. The standard deviation of each half hour (beginning at 7.30 a.m. local time) is computed as the standard deviation of these one-minute returns during the interval. For robustness, we present the medians of these half hourly standard deviations over all days in our sample.

Figures 3a and 3b plot these average (median) standard deviations per half hour interval, from 7.30 a.m. (local time) to 6.00 p.m. for London and New York respectively. The results are striking. The average variances are much higher at open and close in both markets than during other times of the trading day, confirming the apparent U-shape in volatility that has been previously documented in other markets.[10] Figures 4a and 4b present the average spreads (in pfennig per dollar) by minute over the trading periods indicated by trading activity in figures 1a and 1b above, for London and New York respectively. These figures confirm the general U-shaped pattern of spreads particularly documented in Bollerslev and Domowitz for smaller regional banks (1993, p. 1428 ff.).

*London and New York: Integrated markets*

Figure 5 shows the standard deviations of both London and New York returns on the same (GMT) time scale. There appears to be no correspondence between the striking volatility patterns across these two markets, which are virtually instantaneously linked in terms of quote information.

Not surprisingly given the results in figure 5, figure 6 shows that changes in the bid-ask spread documented for London and New York separately do not provide any coherence when viewed at the same time across markets. While the average spread is roughly equal in London and New York when both markets are open, there is no apparent effect of the high spreads associated with the open or close of one market on the other market.

Table 1 presents a test of the difference in spreads between London and New York, by fifteen minute intervals from noon GMT to 5.30 p.m. GMT. The test assumes that samples are uncorrelated, so that the t-statistic for the difference of average spreads in each interval is downward biased if there is in fact positive correlation across the samples (which would be expected if information impacted both sets of quotes throughout the day). The results confirm the impressions from figure 6, and demonstrate that the (indicated) spreads in New York are consistently significantly higher than those in London, except for London close when London spreads are higher than earlier in the London trading day and on average are higher than those in New York.

Table 2 tests for the difference between quote midpoints in London and New York, as opposed to the spreads. Although table 1 shows that the indicated spreads in New York are significantly higher than those in London except at London close, table 2 shows that this pattern does not carry over to mid-quotes. Although on average the London mid-quotes are greater than the New York mid-quotes, the difference is typically not statistically significant, at least assuming uncorrelated samples.

Table 3 examines the difference between mid-quote to mid-quote variances for London and New York, again by fifteen minute intervals beginning at noon GMT. The results from figure 5 are supported in table 3. From noon until 3.15 p.m., the variance in New York consistently exceeds that in London with the largest average variances in New York at the start of New York trading (although not all periods are individually significant at conventional levels based on the conservative assumption of uncorrelated samples).[11] However, the variance in London increases towards the close of London trading, and significantly exceeds that in New York in the later part of the London trading period. The (conservative) t-statistics are strongly significant at conventional levels in all periods between 4.00 p.m. and 5.30 p.m. (GMT) (the t-statistics range from 2.64 to 5.53). Even in the last fifteen minute interval (to 5.45 p.m.) in which there were only twelve observations in London, the t-statistic is 1.73. Thus these results clearly document a change in variance in one market that is not simultaneously observed in the other market.

The cross-market variance results in figure 5 and table 3, and the cross-market spread results in figure 6 and table 1, constitute a challenge for standard asymmetric information models as applied to foreign exchange data.

## 3. Current Asymmetric Information Models

This section examines the standard asymmetric information literature as applied to the open and close of trade in foreign exchange markets. The general importance of asymmetric information has long been recognized. Bagehot (1971) argues that the market maker loses in trades with better informed traders, so that trades with uninformed liquidity traders must make sufficient profit to cover those losses plus costs. This notion is formalized in subsequent work [see Admati (1991)], the most relevant for our current purposes being Admati and Pfleiderer (1988) and Subrahmanyam (1989, 1991). Bollerslev and Domowitz (1993) explicitly interpret much of the foreign exchange behavior we discuss in terms of the models of Admati and Pfleiderer and Subrahmanyam.[12]

An initial problem with this literature is an inability of the theoretical model of Admati and Pfleiderer (1988), and the extension of this model by Subrahmanyam (1989, 1991), to simultaneously account for the observed empirical phenomena of volume, volatility and bid-ask spreads on the NYSE (the market these models were originally intended to explain).[13] We then demonstrate that the cross-market foreign exchange results from section 2 above are inconsistent with standard asymmetric information models.

### 3.1 Admati and Pfleiderer (1988)

A model of endogenous trading volume is provided by Admati and Pfleiderer (1988), who extend Kyle (1984). They assume three types of agents:

informed traders, who will trade only on terms advantageous to them given their superior information; discretionary liquidity traders, who must trade over a given day, but who choose when to trade during the day on the basis of trading costs, i.e., they trade in those periods of lowest cost; and non-discretionary liquidity traders who must trade at a given time during the day regardless of cost. Trading costs, in this model, arise solely because of the activity of the informed, whose profits are paid by the uninformed liquidity traders.

Given their assumptions, Admati and Pfleiderer show that it is possible to obtain concentrations of volume at arbitrary trading times because in equilibrium these high volume periods attract both informed traders and discretionary liquidity traders. The informed are attracted because there will be more uninformed liquidity traders behind whom they can camouflage their trades. The discretionary liquidity traders are attracted because, in this model, the increased activity of informed traders implies sufficiently increased competition among them that the cost of trading to the uninformed is *lowered* relative to other periods.

Admati and Pfleiderer relate their results to observed empirical behavior, especially to volume and variance at the open and close of a day's trading on the NYSE, and "show that the patterns that have been observed empirically can be explained in terms of the optimizing decisions of these traders" (1988, p. 4). Their primary motivation is the high volume and concurrent high variance at open and close. Volume is explained by their concentration equilibrium outlined above; high variance follows directly from the increased activity by informed traders at open and close, since more (previously private) information is thus incorporated into prices.

### 3.2 Subrahmanyam (1989, 1991)

The key result in Admati and Pfleiderer (1988), namely that increased activity by informed traders lowers the costs to the uninformed who must pay the price of the presence of the informed, is not intuitively obvious. Subrahmanyam (1989, 1991) builds on the model of Admati and Pfleiderer, and shows that their result depends on the assumption of risk neutral informed traders. If the informed traders are risk averse, then increased activity on their part can increase the trading costs of liquidity traders. Subrahmanyam (1989, p. 18) cites Foster and Viswanathan (1989) as showing that the adverse selection component of bid-ask spreads is highest at the beginning of the day, which "contrasts with the model of Admati and Pfleiderer [1988], which predicts that spreads should be *lowest* at the beginning of the day" (emphasis in original). Brock and Kleidon (1992, section 4.1) also provide evidence that appears inconsistent with the key result in Admati and Pfleiderer, since spreads follow the same U-shape as volume: highest volume is associated with highest, not lowest, costs.[14]

Subrahmanyam (1989) interprets this result as consistent with his extension of Admati and Pfleiderer to the case of risk averse informed traders, since then more trading by informed traders results in lower market liquidity and higher costs. To do this, he requires (p. 17) the additional assumption that "more individuals are informed at the beginning of the day than at other times during the day." For this model to be a full explanation of the relation between spreads and volume, he presumably requires that the informed also trade more heavily at close.

### 3.3 Bollerslev and Domowitz (1993)

Bollerslev and Domowitz (1993) examine the same data as in this paper, namely continuously recorded quotes on the Deutschemark/dollar exchange rate in the interbank foreign exchange market. They document quote arrivals and bid-ask spreads over the trading day, across geographical locations and across trading participants. The analytical focus is on two main areas: first (which is most relevant for this paper), an evaluation of the predictions of the asymmetric information models of Admati and Pfleiderer (1988) and Subrahmanyam (1989), and second, time series modeling of means and conditional variances.

Bollerslev and Domowitz conclude (p. 1439) that their evidence "is encouraging with respect to the ability to validate and discriminate between theoretical models of trading activity using intraday information on foreign exchange trading." They suggest that periodic non-discretionary liquidity trading around open and close will intensify the results of Admati and Pfleiderer, while round the clock trading will weaken them, and conclude that the U-shaped pattern of trading activity from open through close, well documented for the NYSE and addressed by Admati and Pfleiderer (1988), is apparent only in the European markets (p. 1426, fn. 8).

Bollerslev and Domowitz also find that for traders who restrict their trading to regional markets with well defined openings and closings (as opposed to international firms with traders in multiple regional markets), the activity pattern (quote volume) "typically shows a U-shape, as does the distribution of their own spreads over the course of the day" (p. 1428). Since these traders "operate more like the stock market traders usually modeled in much of the theoretical literature, with behavior influenced by openings and closings" (p. 1429), Bollerslev and Domowitz interpret this evidence as confirming the model of Admati and Pfleiderer (1988), although they note (p. 1439) that the "daily patterns of the spread and market activity suggest risk-averse behavior on the part of these traders." This modification is tied to "Subrahmanyam's (1989) extension of the Admati and Pfleiderer model to include risk-averse behavior [which] predicts that more trading by informed risk-averse participants brings about higher costs" (p. 1426, fn. 9).

### 3.4 Foreign exchange quote data and standard information models

We conclude that the asymmetric information models of Admati and Pfleiderer and Subrahmanyam are *not* consistent with the foreign exchange data on spreads and volatility, for two reasons. First, close examination of Subrahmanyam's extension of the Admati-Pfleiderer model shows that although he can account for high spreads at times of high informed trading, the cost is that he loses the major result of the Admati-Pfleiderer model, namely the concentrated trading equilibrium relied on by Admati and Pfleiderer to account for simultaneous high volume and high volatility. Second, the results from section 2 above show that volatilities (and spreads) across markets that trade simultaneously do not show the congruence implied by either the Admati-Pfleiderer or Subrahmanyam models.

On the first point, note that Subrahmanyam's model implies that discretionary liquidity traders who can time their trades will avoid the high cost, high volume periods which he links to high levels of informed trading. However, this breaks the concentration of trading relied on in Admati and Pfleiderer's equilibrium. This in turn makes it difficult to explain the observed high volume in terms of discretionary liquidity traders and informed traders, since the former will avoid the high-cost open and close, and the number of informed traders must be "sufficiently small" (1989, p. 18) for the result to go through. Further, if the increased volume were due to a very large increase in the number of informed traders (sufficient to both offset the departure of discretionary liquidity traders and account for the total increase in volume), one wonders who takes the other side of their trades, especially since they receive correlated signals in this model.

Presumably the burden falls, once again, on the luckless non-discretionary liquidity traders who in these models have zero elasticity of demand and must trade at these times regardless of price or cost. That is, the empirical results on spreads and volume, that the Admati-Pfleiderer and Subrahmanyam models attempt to explain, imply that within those models there must be an increase in non-discretionary liquidity trading at open and close sufficient to offset the departure of discretionary traders in the face of higher transactions costs. Admati and Pfleiderer (1988, p. 34) conjecture that the orders of non-discretionary traders may cluster around open and close because of market closure; however, this is not part of their formal model, and they rely on such periodic demand as simply a timing catalyst for their endogenous clustering that requires low trading costs at open and close to attract discretionary traders.

The second problem with these asymmetric information models relates to the cross-market results from section 2 above. These results show that the observed behavior in spreads and variances cannot be explained within standard information models. It is true that looking at the two markets individually, the variance results appear similar to those from the NYSE used to motivate the asymmetric information model of Admati and Pfleiderer. At first blush, then, these results may appear to provide confirmation of the conclusion that activity at open and close of trading in foreign exchange markets is heavily influenced by concentrations of informed traders at those times, resulting in high variances.

The results obtained from looking at London and New York separately are highly misleading, however, in terms of evidence concerning any tracks left in the data by privately informed traders. Recall that these quotes appear directly on the Reuters' screens of traders in all locations. Assume that the high variance (and high spread) at close of trade in London is indeed caused by an unusually high concentration of informed traders at that time, which in turn causes rapid changes in quotes and consequently high variance. Traders in New York observe directly and simultaneously these London quote revisions that are ostensibly caused by the incorporation of previously private information. Since the commodity is the same whether the quotes are posted in London or New York, it must be the case that the incorporation of new information into the London quotes must virtually simultaneously show up in New York quotes, resulting in simultaneous high variance in New York quotes.

The results in table 3 and figure 5 clearly refute this implication. Note that the New York opening, which is ostensibly replete with private information causing the New York variance of returns to rise dramatically, causes scarcely a ripple on the London market! Similarly, the London market closes with dramatic local effects in terms of variance, but with no effect on New York. Similarly, table 1 and figure 6 show an apparent lack of integration across these two markets with respect to spreads.

## 4. Evaluation of Results

We regard the results from section 3 as striking evidence that whatever is causing the patterns in variances and spreads at open and close of trading in the foreign exchange market, it is *not* the incorporation of previously private information through the heavy trading of informed traders at open and close of trading in London and New York. This is particularly evident from the comparison of volatility patterns across London and New York in figure 5 and table 3 above.

We consider two main alternative explanations for these results. First, we consider a broader class of information models that has recently been proposed to explain related forms of apparent excess volatility in stock prices, namely models that relax the assumption in standard information models that traders have perfect knowledge about the preferences and beliefs of other traders in the market. These new models, based on imperfect information aggregation and subsequent learning by market participants, can be linked to experimental results in the behavioral literature, and have proven successful in accounting for such difficult phenomena as the Crash of October 1987. The second explanation we consider, which is particularly relevant for behavior at the close of a market, returns to inventory models such as Garman (1976).

### 4.1 Models of imperfect information aggregation: Open of trade

Our results at open of New York and close of London trading show that no new information is reaching the international foreign exchange market as a whole, since there is an absence of unusual volatility in quotes generated by traders in London when New York opens, and conversely at London close. One way to view these results is that quotes generated by traders in the volatile market show excess volatility relative to that implied by standard information models.

Others have noted the difficulty in explaining foreign exchange data in terms of standard information models. For example, Frankel and Froot (1990) emphasize heterogeneity of expectations across traders in foreign exchange markets, and suggest (p. 182) three possible implications of the high trading volume in these markets for price movements: 1) greater depth means more efficient processing of fundamental information; 2) there is no relation between trading volume and prices since the market is "already perfectly efficient;" and 3) there may be "excessive volatility" caused by trading based on "noise" rather than "news." Frankel and Rose (1994) explore the third possibility in some detail, with emphasis on the possibility of "endogenous speculative bubbles" in foreign exchange markets.

The special nature of our cross-market data implies a high hurdle for potential explanations, since such an explanation must account for both the systematic behavior within markets and the lack of congruence across markets around open and close. Thus, for example, if the explanation is to be "noise" rather than "news," it appears that London is not affected by noise when New York opens with high volatility; but at London close, the roles are reversed, with London displaying high volatility but New York now immune from any noise affecting London. This appears to be more complicated than implied by the noise-trading models cited in Frankel and Rose (1994), or by models of learning currently applied to foreign exchange markets such as Lewis (1989a, 1989b).

One recent approach that shows promise in this context focuses on imperfect, though rational, information aggregation.[15] There are two extreme views on price formation. One assumes that all private information is instantly aggregated and revealed to market participants through prices. The other assumes that price changes are capricious and irrational. One attempt to find a middle ground assumes that prices are formed as some average of these two types of behavior, an approach similar to the noise trading models cited in Frankel and Rose (1994, p. 37). The approach of imperfect information aggregation also supplies a middle ground between the extremes, but in a very different way.

It is well known from behavioral laboratory experiments that, under certain conditions, asset prices can be readily generated that display systematic deviations from those predicted by fully revealing rational expectations models. These deviations display both apparent excess volatility and the characteristics often associated with speculative bubbles. The conditions needed to generate these phenomena in experimental laboratories are revealing: market participants must lack common knowledge about other traders preferences or beliefs, or there must be insufficient traded instruments to theoretically allow traders to invert from prices to infer information. Significantly, if traders have common knowledge about preferences and beliefs, then the consistent result is that prices quickly converge to the fully revealing rational expectations equilibrium, if there are sufficient traded assets given the sources of information uncertainty, and if the traders have trading experience in the market.[16]

While standard information models typically assume common information among market participants about traders' preferences and beliefs, we regard this assumption as unrealistic in many settings, including the foreign exchange market. When traders first begin trading at the open of their local market, a commonly described issue is that they need to get the "feel" of the market at that time.[17] The most important elements of this "feel" comprise the participants in market at that point in time and what their trading behavior has been in the immediately prior trading period.

Clearly current prices are not sufficient statistics for these items. Traders attempt to obtain this information by contacting traders who have been trading for some time; for example, New York traders will have contacts in London (not necessarily in the same bank) who they will call to obtain a sense of the current market. Our interpretation of this phenomenon is consistent with the importance of knowledge about the preferences and beliefs of other traders to allow information aggregation across traders. In the more limited view of an individual trader, the question is the interpretation of current trading behavior in the market. For example, is a request for a bid on a certain sized trade likely to be followed by the same trader for another? If so, then that will affect the terms offered for the first trade.

Significantly, traders describe that until they have got the feel of the market, they are uncertain of their "view," and hence, for example, whether they will be going long or short one or other currency in their early trading during the day. This translates into initial high spreads, with rapidly changing quotes as traders develop their view for the current trading period.

This, of course, appears to correspond to the evidence we present in section 2 above at open of trade. The market that has been trading for some time (London, at New York open) does not show any "excess volatility" relative to surrounding times, and the new traders (in New York) rapidly get the feel of the market, i.e., assimilate important information about the current market structure that is not contained in the current price. While there is little documented evidence about the mechanisms traders use to get the feel of the market, conversations with traders indicate that they include perusal of overnight information from various sources beyond the trading history of the particular currency being traded, as well as more formal arrangements with counterparts at overseas banks who agree to provide specific information about the market to the "novice" who is just starting to trade. One possibility consistent with our data (and not addressed by standard information models) is that the new dealers set wide spreads while they gather this information, and then narrow the spreads once they are ready to trade.

However formal or informal the mechanism for obtaining information about the market structure, the level of spreads and volatility of quotes settle down once traders get the feel of the market, and the markets trade in an integrated fashion until the next major disruption—the close of trading on one of the markets.

### 4.2 Inventory based models: Close of trade

A large proportion of foreign exchange trading, including most of that done by smaller, regional banks, is "day trading," in which traders start and end the day with flat positions. While this does not cause any particular problems at the start of the day, since positions can be accumulated during the trading day which has just begun, the inventory problem for day traders becomes increasingly acute as the close of trading approaches. In the limit, a trader who *must* close out a position by the end of the day has increasingly inelastic demand to trade, and will be more willing to accept a relatively poor price to accomplish the trade.[18]

The effects of inventory on prices and quotes are well discussed in market microstructure literature beginning with Garman (1976).[19] Recent empirical work in equity dealer markets in London (see Hansch, Naik and Viswanathan 1993) and the U.S. (see Chan, Christie and Schultz 1994) document strong inventory effects, and Lyons (1993b) documents inventory effects in the foreign exchange market. Discussions with traders in the foreign exchange market confirm that high quote volatility and spreads at close is linked by traders to the activities of day traders who are attempting to close out their positions.[20]

## 5. Conclusions

In this paper we have explored the implications of foreign exchange markets for alternate models of intraday price and volume behavior. There are empirical difficulties in reconciling current asymmetric information models with stock price data in individual markets, but it is possible for some form of these models to be consistent with NYSE prices and volume, assuming that liquidity traders have strong demand to trade at open and close for reasons that are not motivated within the information models. Our choice of the foreign exchange market is motivated by the ability to test whether any form of the current asymmetric information models can explain prices and volumes in this market.

The advantages of foreign exchange data are that the market extends around the clock, and traders from any location have equal access via computer terminal to the posted quotes of all traders from all locations. If new information is the cause for revisions in quotes for traders in, say, London, then those quote revisions are immediately indicated to all other traders. Moreover, since there is an overlap between the trading days of traders in London and New York, we can observe whether the quote behavior is integrated in the fashion implied by the asymmetrical information models.

The results are inconsistent with these models. If London and New York are examined individually, they display the same patterns of spread and volatility from "open" to "close" as does the NYSE, which may indicate similar forces in each market. However, when New York foreign exchange traders begin their day, with attendant high volatility and spreads, London has been trading for hours and is still trading. There is no impact on London quotes, in either volatility or spreads, of the striking New York quote behavior. Similarly, although London "closes" its day with high variances and high spreads, this does not cause a ripple on the quotes of New York traders. This is inconsistent with standard sources of asymmetric information being the fundamental cause of this behavior.

Our primary conclusion is that the current models of asymmetric information appear inadequate to explain our results. This raises questions concerning their application in other markets as well. Indeed, our findings are not limited to quotes in the foreign exchange market. Kleidon and Werner (1992) demonstrate that similar results apply to U.K. stocks that are cross-listed on London and New York exchanges, and that consequently trade simultaneously in a similar fashion to the foreign exchange trading we document here. It appears that we must turn to explanations other than current information models if we are to account for the behavior of prices and volumes in both stock and foreign exchange markets.

We suggest two possible explanations for the empirical results documented in section 2. First, we place importance at open of trade on learning by traders about the structure of the market, particularly concerning the identity and behavior of other traders. This can be linked to both behavioral experimental results, and to the results in recent literature that examines the implications for information aggregation of a lack of common knowledge among traders concerning the preferences and beliefs of market participants. During the period when traders pursue various mechanisms to learn the feel of the market, spreads may be set sufficiently wide to avoid trading at an informational disadvantage.

Second, at close of trade, much of the activity in the closing market documented in section 2 may be due to the inventory related activities of traders at market close, especially for the large group of day traders who must close their positions by the end of trading.

While these explanations seem plausible—and indeed are confirmed by foreign currency traders—further investigation is warranted.

## Footnotes:

1. Trading patterns at open and close of trade have been extensively studied within asymmetric information models, primarily with respect to the New York Stock Exchange [NYSE], but also in the context of cross-country listings and foreign exchange. See, e.g., Admati and Pfleiderer (1988), Subrahmanyam (1991), Freedman (1989), Barclay, Litzenberger and Warner (1990), and Bollerslev and Domowitz (1993). For an excellent survey of the literature, see Admati (1991).
2. These issues are addressed in Gennotte and Leland (1990), Jacklin, Kleidon and Pfleiderer (1992), Kleidon (1992), Romer (1993), and Kleidon (1994).
3 . Foster and Viswanathan (1990) present a related asymmetric information model which focuses on interday rather than intraday variations in price and volume. Although it can be argued that foreign exchange trading is not tied to any particular "day," our current focus is on behavior between open and close of usual trading hours for traders within the geographical markets of London and New York. Foster and Viswanathan examine the behavior of trading *across* days, particularly the effects of weekends on Monday trading.
4. For an excellent description of the markets, see Burnham (1991). See also Goodhart (1990), Goodhart and Figliouli (1991), Lyons (1992, 1993a, 1993b), and Bollerslev and Domowitz (1993).
5. Lyons (1993a, p. 2), citing the New York Federal Reserve Bank, states that over 80% of trading volume is between market makers.
6. Lyons (1993b) examines data for a single market maker from the Reuters Dealing 2000 System that allows screen trading, although direct telephone

communication was necessary for all traders when our data were collected. Since our approach requires cross-market comparisons, the new data set is insufficient for our purposes. It will be useful to replicate our study using data from the new Reuters system, if sufficient data ultimately become available.

7. The data were kindly forwarded to us by Tim Bollerslev and Ian Domowitz. For details of the data capture, error screens, and data characteristics, see Goodhart (1990) and Goodhart and Figliouli (1991).

8. We exclude quotes from Saturday and Sunday, since there is almost no trading on these days (except the last hour on Sunday).

9. There are isolated quotes at times outside this interval, but they are negligible in frequency, and we ignore them in subsequent analysis. Note also that in London there is one period shortly before 6.00 p.m. (GMT) in which there are no quotes; this is reflected in figures 4(a) and 6 by a "zero" spread at that time.

10. Note that since we delete observations if no quote update occurs, and since we require consecutive observations to calculate a one-minute rate of return, there will be typically fewer observations for any given time interval than one observation per minute times the number of days in the sample. In particular, there are fewer observations in our sample at the open and close of trading than during periods of active trading. Table 3 presents formal tests of the differences in variances.

11. The earliest intervals in New York (and the latest intervals in London) also have few observations; see fn. 10 above.

12. Lyons (1993a, 1993b) develops microstructure models in the context of the foreign exchange market, but does not examine cross-market data as in Bollerslev and Domowitz (1993).

13. Much of this discussion follows Brock and Kleidon (1992, section 4.3).

14. The model of Admati and Pfleiderer (1988) and Subrahmanyam (1989,1991) assumes sequential batch auctions rather than the continuous auctions associated with bids and asks on the NYSE. However, Admati and Pfleiderer regard their results as applying to the volume behavior on the NYSE, and Subrahmanyam (1989) explicitly equates the costs in Admati and Pfleiderer (which are the same as in his model) with bid-ask spreads. We follow this approach. Further, as Grossman and Miller (1988,p.628) point out, transactions costs should be measured by the difference between the price paid now versus the price expected to be paid by waiting; but if the average spread falls after opening and rises at close, one would expect a *priori* that a given liquidity trader would expect higher transactions costs in such periods.

15. For detailed discussion of this approach, see Kleidon (1994). This general approach has been examined in the context of foreign exchange markets by Crnja (1993).

16. For details, see Kleidon (1994, Section 2).

17. This is not restricted to the foreign exchange market. This phenomenon has been consistently described to us in conversations with both equity and foreign exchange traders.

18. Brock and Kleidon (1992) exploit differences in trading demand at open and close to predict higher spreads at these times if a market maker such as a

monopolist specialist has the ability to price discriminate at these times of inelastic demand to trade. This idea may have some application in foreign exchange markets, particularly with respect to quotes by regional banks to customers who have peak foreign exchange trading demands at open and close.

19. See also Amihud and Mendelson (1980), Ho and Stoll (1981, 1983), O'Hara and Oldfield (1986), and Son (1991).

20. A related feature of the New York close is the decrease in depth of the market as traders stop trading, with consequent increase in spreads.

## References


Admati, A.R. 1991. The Informational role of prices: A review essay. *Journal of Monetary Economics* 28: 347-361.

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

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

Bagehot, W. (pseud.). 1971. The only game in town. *Financial Analysts Journal* 27: 12–14, 22.

Barclay, M.J., R.H. Litzenberger, and J.B. Warner. 1990. Private information, trading volume, and stock-return variances. *Review of Financial Studies* 3: 233–253.

Bhattachary, U. and M. Spiegel. 1992. Are noisy prices caused by noisy traders? Theory and evidence. Unpublished manuscript, Columbia University, Graduate School of Business: May.

Bollerslev, T. and I. Domowitz. 1993. Trading patterns and prices in the interbank foreign exchange market. *Journal of Finance* 48: 1421–1443.

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

Burnham, J.B. 1989. Marketmakers, speculators and customers: The U.S. foreign exchange market. Working paper No. 130. Center for the Study of American Business, Washington University, St. Louis.

Chan, K.C., W.G. Christie, and P.H. Schultz. 1994. Market structure and the intraday pattern of bid-ask spreads for Nasdaq securities. Unpublished manuscript. Fisher College of Business, Ohio State University.

Crnja, Z. 1993. Environmental uncertainty in the foreign exchange market. Thesis, Department of Economics, Stanford University.

Foster, F.D. and S. Viswanathan. 1989. Variations in Volumes, Spreads and Variances. Research paper 88–108. Fuqua School of Business, Duke University.

Foster, F.D. and S. Viswanathan. 1990. A theory of the interday variations in volume, variance, and trading costs in securities markets. *Review of Financial Studies* 3: 593–624.

Frankel, J.A. and K.A. Froot. 1990. The rationality of the foreign exchange rate: Chartists, fundamentalists, and trading in the foreign exchange market. AEA Papers and Proceedings. *American Economic Review* 80: 181–185

Frankel, J.A. and A.K. Rose. 1994. An empirical characterization of nominal exchange rates. University of California, Berkeley. A chapter for *The Handbook of International Economics.* G. Grossman and K. Rogoff, Editors.

Freedman, R. 1989. A theory of the impact of international cross-listing. Unpublished manuscript, Graduate School of Business, Stanford University.

Garman, M.B. 1976. Market microstructure. *Journal of Financial Economics* 3: 257–275.

Gennotte, G. and H. Leland. 1990. Market liquidity, hedging and crashes. *American Economic Review* 80: 999–1021.

Glosten, L.R. and P.R. Milgrom. 1985. Bid, ask and transaction prices in a specialist market with heterogeneously informed traders. *Journal of Financial Economics* 14: 71–100.

Goodhart, C. 1990. 'News' and the foreign exchange market. Discussion paper No. 71. London School of Economics Financial Markets Group.

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

Grossman, S.J. and M.H. Miller. 1988. Liquidity and market structure. *Journal of Finance* 43: 614–633.

Hansch, O., N. Naik, and S. Viswanathan. 1993. Trading profits, inventory control and market share in a competitive dealership market. Unpublished manuscript. Fuqua School of Business, Duke University.

Ho, T. and H.R. Stoll. 1981. Optimal dealer pricing under transactions and return uncertainty. *Journal of Financial Economics* 9: 47–73.

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

Jacklin, C., A.W. Kleidon, and P. Pfleiderer. 1992. Underestimation of portfolio insurance and the crash of October 1987. *Review of Financial Studies* 5: 35–63.

Kleidon, A.W. and I.W. Werner. 1992. Round-the-clock trading: Evidence from UK cross-listed securities. Unpublished, Graduate School of Business, Stanford University.

Kleidon, A.W. 1992. Market and environmental uncertainty, in: P. Newman, M. Milgate, and J. Eatwell, Editors. *The New Palgrave Dictionary of Money and Finance* 2 (Macmillan Press Limited, London): 651–654.

Kleidon, A.W. 1994. Stock market crashes. Forthcoming *Finance Handbook,* R. Jarrow, V. Maksimovic, and W.T. Ziemba, Editors., North Holland: January

Kyle, A.S. 1984. Market structure, information, futures markets, and price formation, in: G.G. Storey, A. Schmitz, and A.H. Sarris, eds., International Agricultural Trade: Advanced Readings in Price Formation, Market structure, and Price Instability. (Westview Press, Boulder and London) 45–64.

Kyle, A.S. 1985. Continuous auctions and insider trading. *Econometrica* 53, 1315–1335.

Lewis, K.K. 1989a. Can learning affect exchange-rate behavior? The case of the dollar in the early 1980's. *Journal of Monetary Economics* 23: 79-100.

Lewis, K.K. 1989b. Changing beliefs and systematic rational forecast errors with evidence from foreign exchange. *American Economic Review* 79: 621-636.

Lyons, R.K. 1992. Private beliefs and information externalities in the foreign exchange market. Unpublished manuscript, Columbia University: March.

Lyons, R.K. 1993a. Optimal transparency in a dealership market with an application to foreign exchange. Unpublished manuscript, University of California, Berkeley: September.

Lyons, R.K. 1993b. Tests of microstructural hypotheses in the foreign exchange market. Finance Working Paper No. 230. University of California, Berkeley: August.

O'Hara, M. and G.S. Oldfield. 1986. The microeconomics of market making. *Journal of Financial and Quantitative Analysis* 21: 361–376.

Romer, D. 1993. Rational asset-price movements without news. *The American Economic Review* 83: 1112–1130.

Son, G. 1991. Dealer inventory position and intraday patterns of price volatility, bid/ask spreads and trading volume. Unpublished manuscript, Department of Finance, University of Washington.

Subrahmanyam, A. 1989. Risk aversion, market liquidity, and price efficiency. Unpublished, Anderson Graduate School of Management, University of California, Los Angeles.

Subrahmanyam, A. 1991. Risk aversion, market liquidity, and price efficiency. *Review of Financial Studies* 4: 417–441.

# List of Tables and Figures

**Tables (including notes):**



**Figures:**

**Table 1**

## Test of Difference in Spreads, London and New York

(by 15 minute interval)

| Time (GMT) | Spread[a] (# Obs) London | | New York | | t-stat[b] |
|---|---|---|---|---|---|
| Noon | 0.0669 | (873) | 0.1000 | ( 5) | -2.34 |
| 12:15 | 0.0659 | (905) | 0.0763 | (57) | -2.34 |
| 12:30 | 0.0668 | (836) | 0.0725 | (222) | -3.10 |
| 12:45 | 0.0657 | (867) | 0.0751 | (258) | -5.61 |
| 10:00 | 0.0677 | (958) | 0.0710 | (367) | -2.25 |
| 1:15 | 0.0706 | (964) | 0.0757 | (482) | -3.05 |
| 1:30 | 0.0789 | (1059) | 0.0808 | (470) | -0.93 |
| 1:45 | 0.0735 | (1168) | 0.0821 | (549) | -5.99 |
| 2:00 | 0.0725 | (1091) | 0.0799 | (524) | -4.95 |
| 2:15 | 0.0735 | (1153) | 0.0823 | (596) | -5.80 |
| 2:30 | 0.0728 | (1118) | 0.0775 | (620) | -3.54 |
| 2:45 | 0.0727 | (1105) | 0.0795 | (699) | -5.28 |
| 3:00 | 0.0742 | (1197) | 0.0816 | (712) | -5.70 |
| 3:15 | 0.0759 | (1207) | 0.0836 | (783) | -5.89 |
| 3:30 | 0.0758 | (1184) | 0.0854 | (833) | -7.34 |
| 3:45 | 0.0784 | (1128) | 0.0846 | (890) | -5.09 |
| 4:00 | 0.0840 | (811) | 0.0832 | (1042) | 0.63 |
| 4:15 | 0.0831 | (642) | 0.0837 | (1065) | -0.44 |
| 4:30 | 0.0841 | (477) | 0.0837 | (1104) | 0.28 |
| 4:45 | 0.0859 | (343) | 0.0852 | (1151) | 0.42 |
| 5:00 | 0.0868 | (166) | 0.0833 | (1183) | 1.66 |
| 5:15 | 0.0909 | (46) | 0.0833 | (1124) | 1.71 |
| 5:30 | 0.0792 | (12) | 0.0863 | (1088) | -0.99 |

Note: [a] Mean spread in London ($S_{LON}$) and New York ($S_{NY}$), times 100.

[b] t-statistic for ($S_{LON} - S_{NY}$), assuming uncorrelated samples.

## Table 2

### Test of Difference in Mid-Quotes, London and New York

(by 15 minute interval)

| Time (GMT) | Mid-Quote[a] (# Obs) London | | New York | | t-stat[b] |
|---|---|---|---|---|---|
| Noon | 1.9508 | (873) | 1.9496 | ( 5) | 0.07 |
| 12:15 | 1.9504 | (905) | 1.9553 | (57) | -0.73 |
| 12:30 | 1.9461 | (836) | 1.9414 | (222) | 1.18 |
| 12:45 | 1.9472 | (867) | 1.9383 | (258) | 2.44 |
| 1:00 | 1.9466 | (958) | 1.9425 | (367) | 1.28 |
| 1:15 | 1.9430 | (964) | 1.9421 | (482) | 0.31 |
| 1:30 | 1.9424 | (1059) | 1.9377 | (470) | 1.57 |
| 1:45 | 1.9412 | (1168) | 1.9401 | (549) | 0.39 |
| 2:00 | 1.9386 | (1091) | 1.9332 | (524) | 1.88 |
| 2:15 | 1.9393 | (1153) | 1.9384 | (596) | 0.33 |
| 2:30 | 1.9411 | (1118) | 1.9361 | (620) | 1.83 |
| 2:45 | 1.9420 | (1105) | 1.9354 | (699) | 2.52 |
| 3:00 | 1.9423 | (1197) | 1.9408 | (712) | 0.58 |
| 3:15 | 1.9418 | (1207) | 1.9359 | (783) | 2.38 |
| 3:30 | 1.9423 | (1184) | 1.9423 | (833) | 0.00 |
| 3:45 | 1.9447 | (1128) | 1.9396 | (890) | 2.10 |
| 4:00 | 1.9370 | (811) | 1.9381 | (1042) | -0.43 |
| 4:15 | 1.9370 | (642) | 1.9360 | (1065) | 0.38 |
| 4:30 | 1.9392 | (477) | 1.9393 | (1104) | -0.03 |
| 4:45 | 1.9466 | (343) | 1.9378 | (1151) | 2.73 |
| 5:00 | 1.9431 | (166) | 1.9395 | (1183) | 0.81 |
| 5:15 | 1.9477 | (46) | 1.9430 | (1124) | 0.63 |
| 5:30 | 1.9549 | (12) | 1.9448 | (1088) | 0.61 |

Note: [a] Mean Mid-Quote [(Bid + Ask) / 2] for London ($MQ_{LON}$) and New York ($MQ_{NY}$).

[b] t-statistic for ($MQ_{LON} - MQ_{NY}$), assuming uncorrelated samples.

## Table 3

# Test of Difference in Mid-Quote to Mid-Quote Variance, London and New York

(by 15 minute interval)

| Time (GMT) | Standard Deviation[a] (# Obs) London | | New York | | t-stat[b] |
|---|---|---|---|---|---|
| Noon | 0.0253 | (873) | 0.0442 | ( 2) | -1.40 |
| 12:15 | 0.0203 | (905) | 0.0905 | (30) | -1.27 |
| 12:30 | 0.0206 | (836) | 0.0445 | (202) | -2.56 |
| 12:45 | 0.0174 | (867) | 0.0280 | (253) | -3.72 |
| 10:00 | 0.0241 | (958) | 0.0301 | (367) | -1.56 |
| 1:15 | 0.0276 | (964) | 0.0327 | (482) | -1.50 |
| 1:30 | 0.0477 | (1059) | 0.0727 | (470) | -1.62 |
| 1:45 | 0.0310 | (1168) | 0.0429 | (549) | -2.11 |
| 2:00 | 0.0330 | (1091) | 0.0397 | (524) | -1.52 |
| 2:15 | 0.0329 | (1153) | 0.0408 | (596) | -2.19 |
| 2:30 | 0.0293 | (1118) | 0.0348 | (620) | -2.41 |
| 2:45 | 0.0301 | (1105) | 0.0315 | (699) | -0.63 |
| 3:00 | 0.0321 | (1197) | 0.0385 | (712) | -1.57 |
| 3:15 | 0.0333 | (1207) | 0.0374 | (783) | -1.42 |
| 3:30 | 0.0317 | (1184) | 0.0309 | (833) | 0.53 |
| 3:45 | 0.0336 | (1128) | 0.0308 | (890) | 1.35 |
| 4:00 | 0.0372 | (811) | 0.0278 | (1042) | 4.90 |
| 4:15 | 0.0375 | (642) | 0.0284 | (1065) | 4.01 |
| 4:30 | 0.0437 | (477) | 0.0276 | (1104) | 4.46 |
| 4:45 | 0.0451 | (343) | 0.0266 | (1151) | 5.53 |
| 5:00 | 0.0453 | (166) | 0.0261 | (1183) | 5.21 |
| 5:15 | 0.0652 | (46) | 0.0258 | (1124) | 2.64 |
| 5:30 | 0.0853 | (12) | 0.0265 | (1088) | 1.73 |

Note: [a] Standard Deviation of Mid-Quote changes for London ($SD_{LON}$) and New York ($SD_{NY}$), times 100.

[b] t-statistic based on method of moments test for equality of the variances, assuming uncorrelated samples.

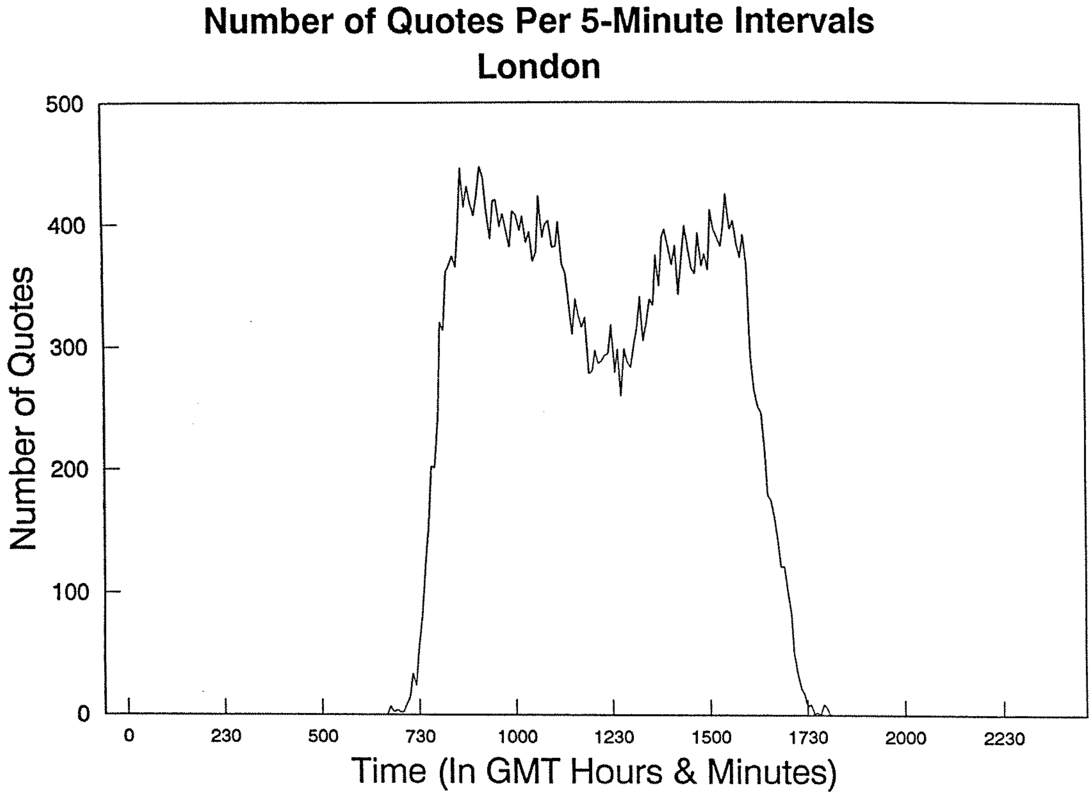



Figure 1(a)

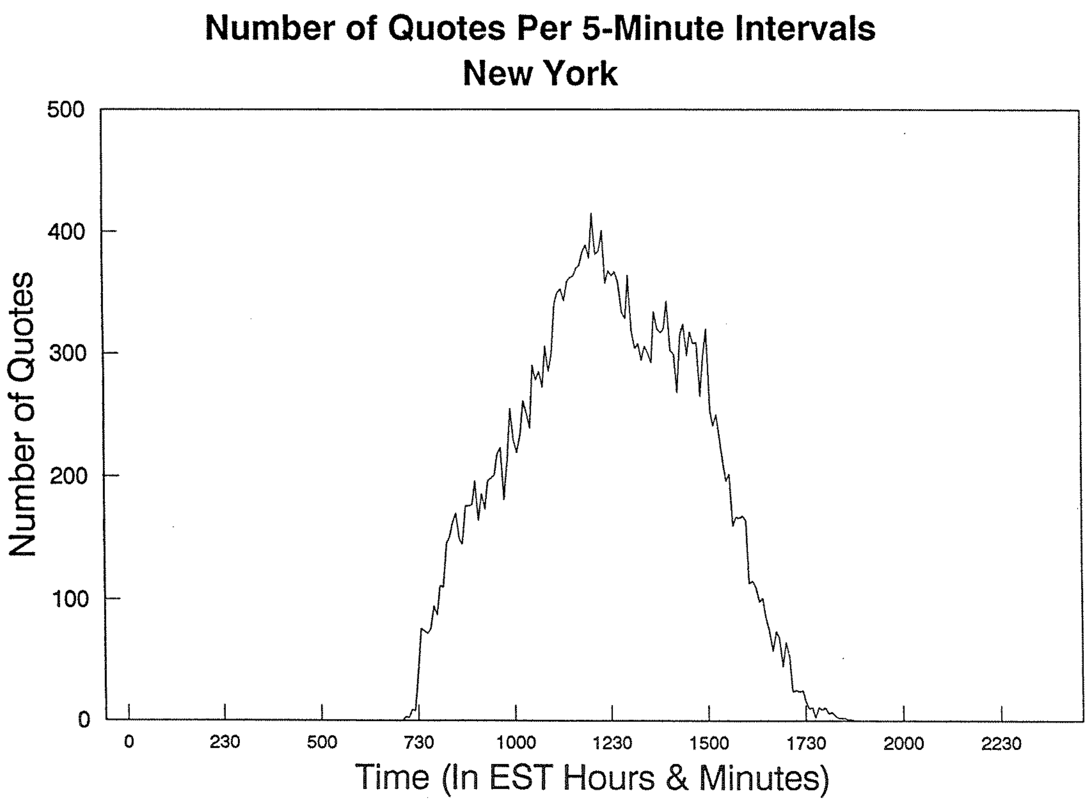



Figure 1(b)

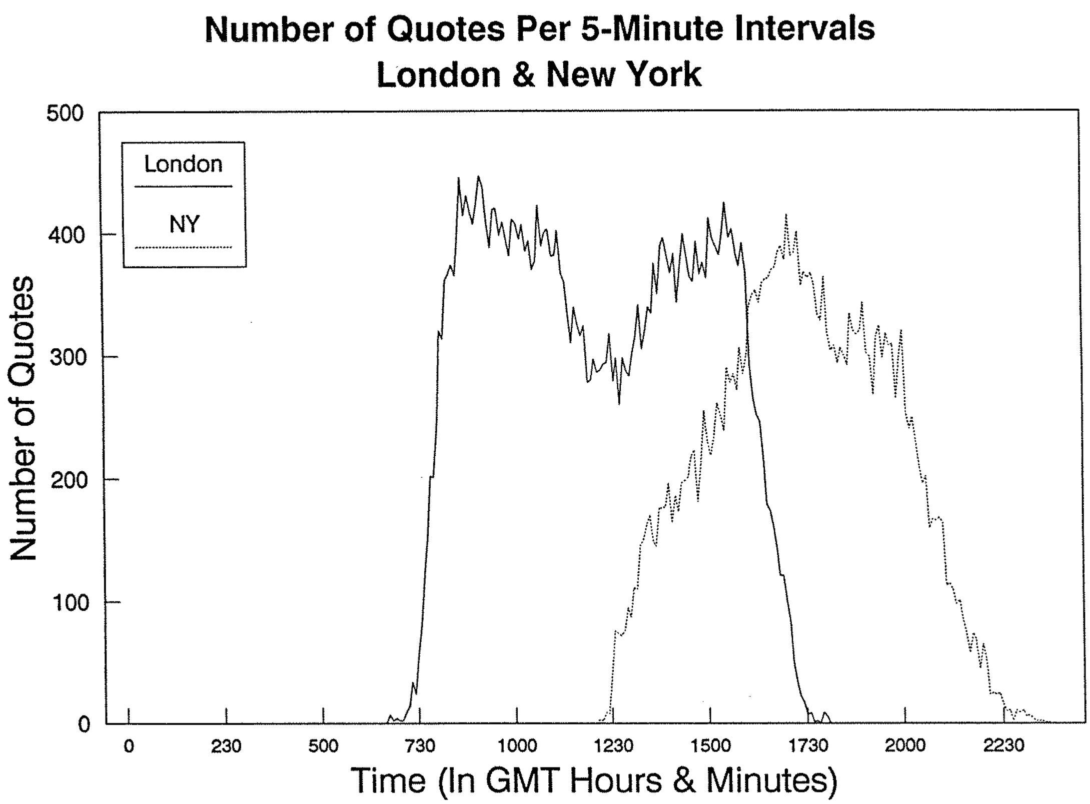

Number of Quotes Per 5-Minute Intervals
London & New York
London
NY
Number of Quotes
500
400
300
200
100
0
0
230
500
730
1000
1230
1500
1730
2000
2230
Time (In GMT Hours & Minutes)

**Figure 2**

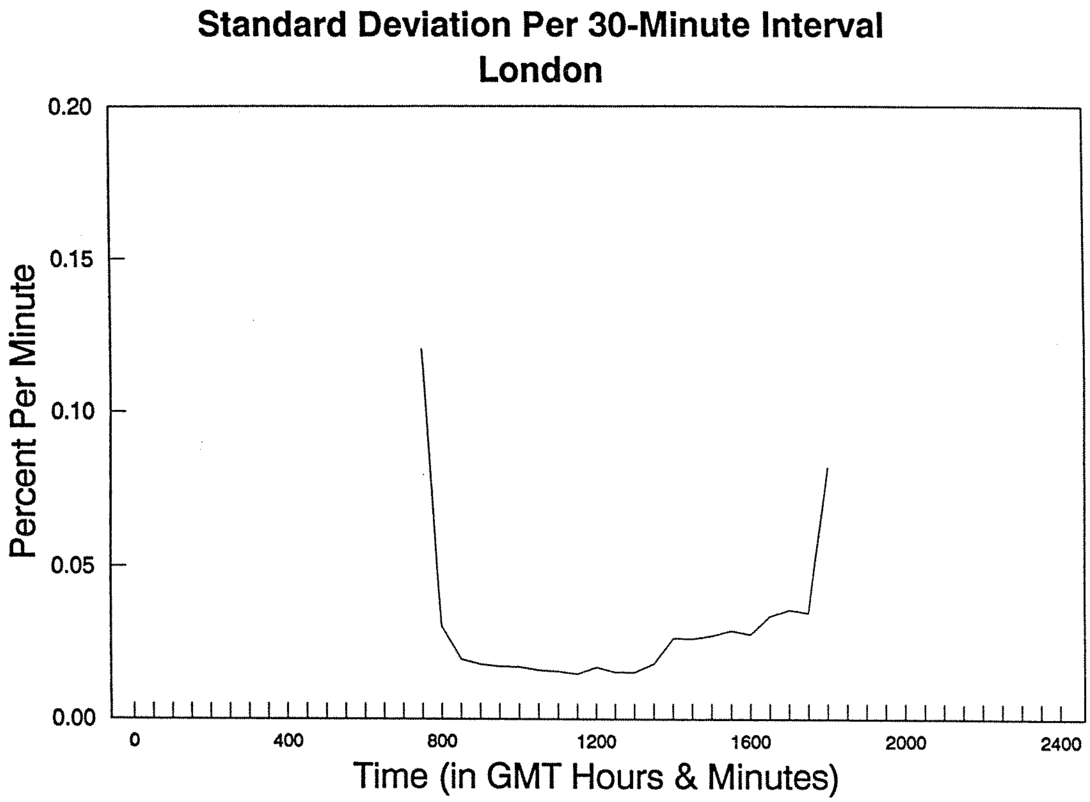



Figure 3(a)

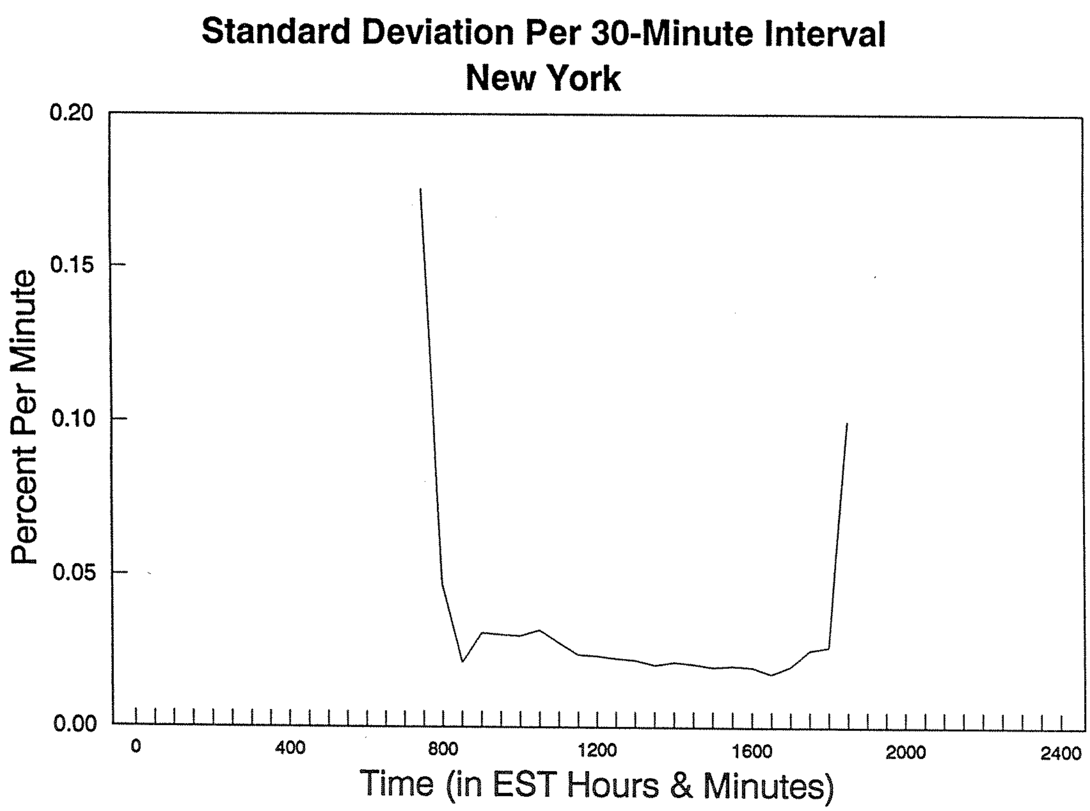



Figure 3(b)

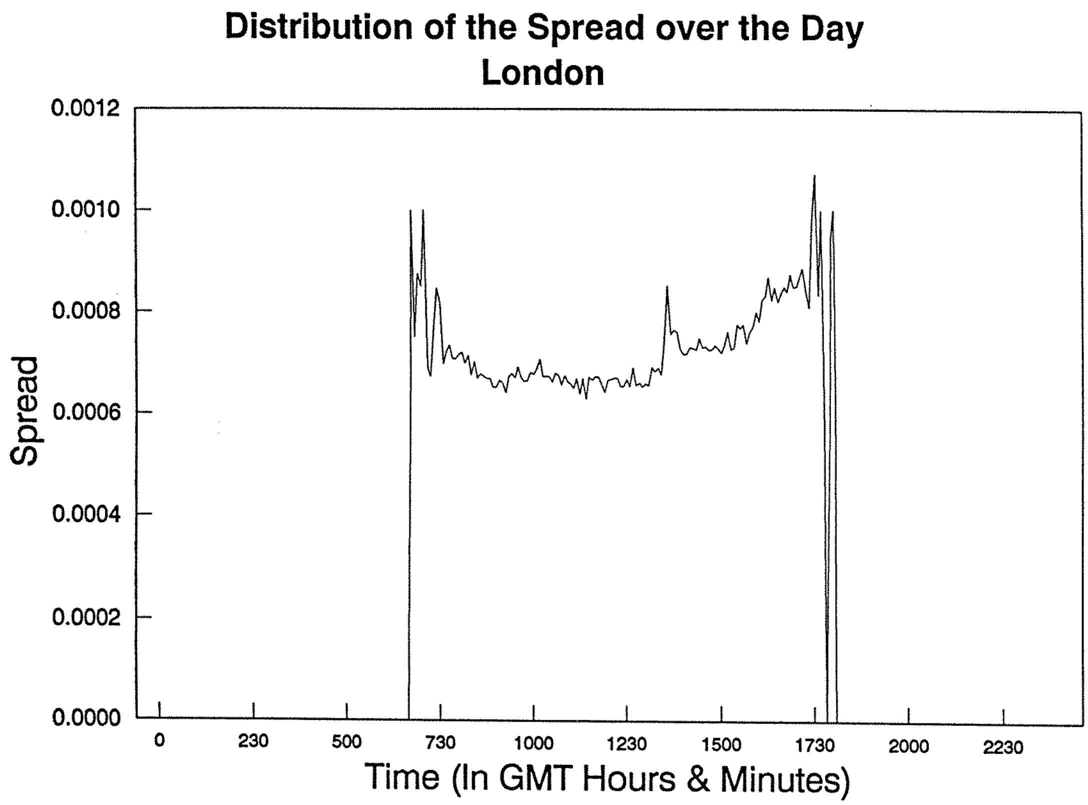



Figure 4 (a)

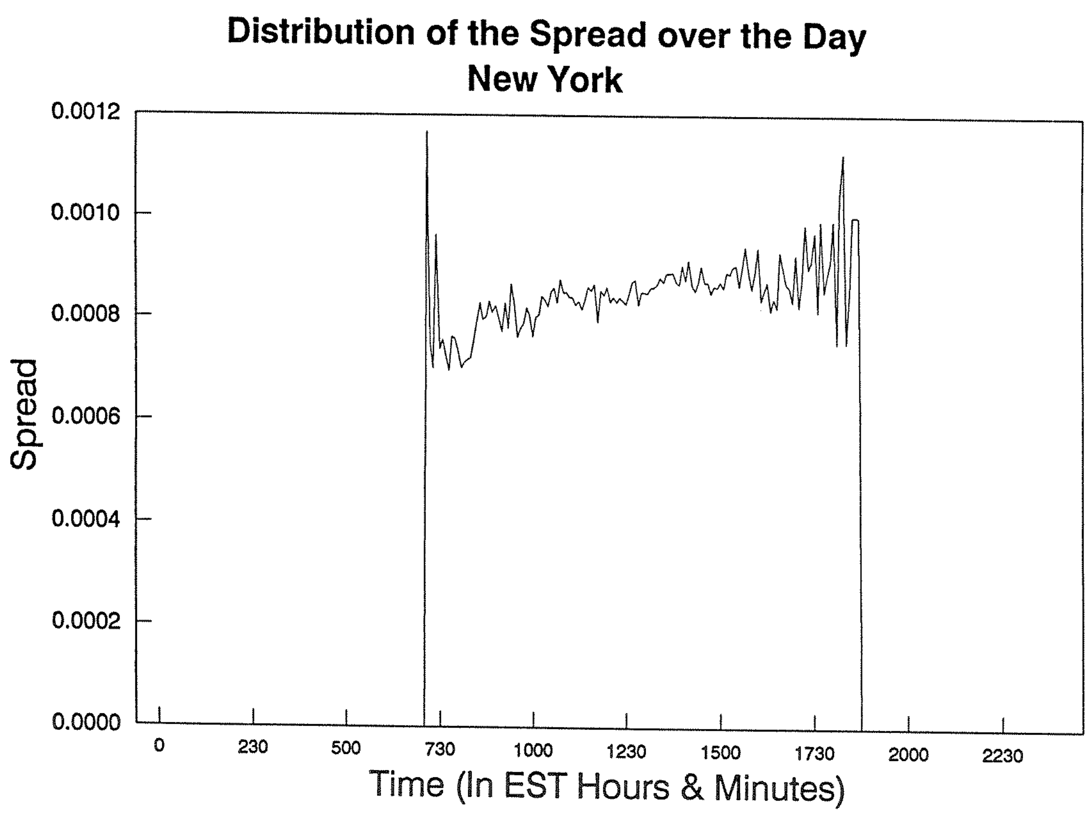



Figure 4 (b)

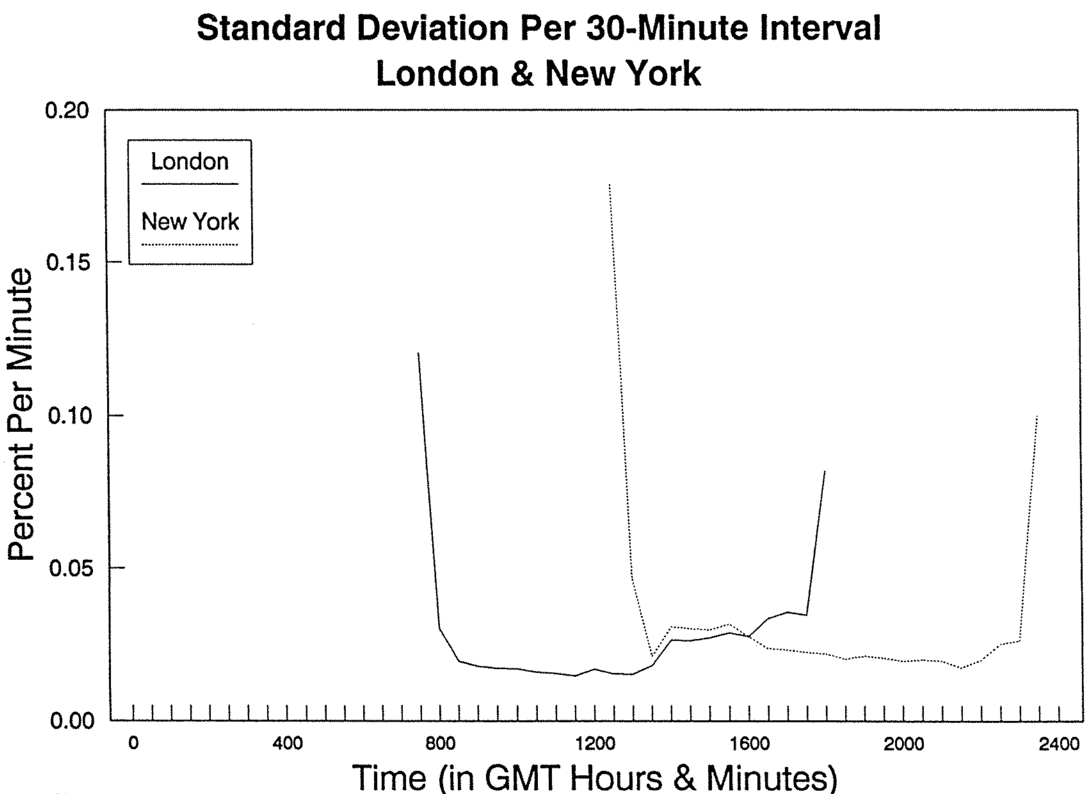

Standard Deviation Per 30-Minute Interval
London & New York
Percent Per Minute
0.20
0.15
0.10
0.05
0.00
London
New York
0
400
800
1200
1600
2000
2400
Time (in GMT Hours & Minutes)

Figure 5

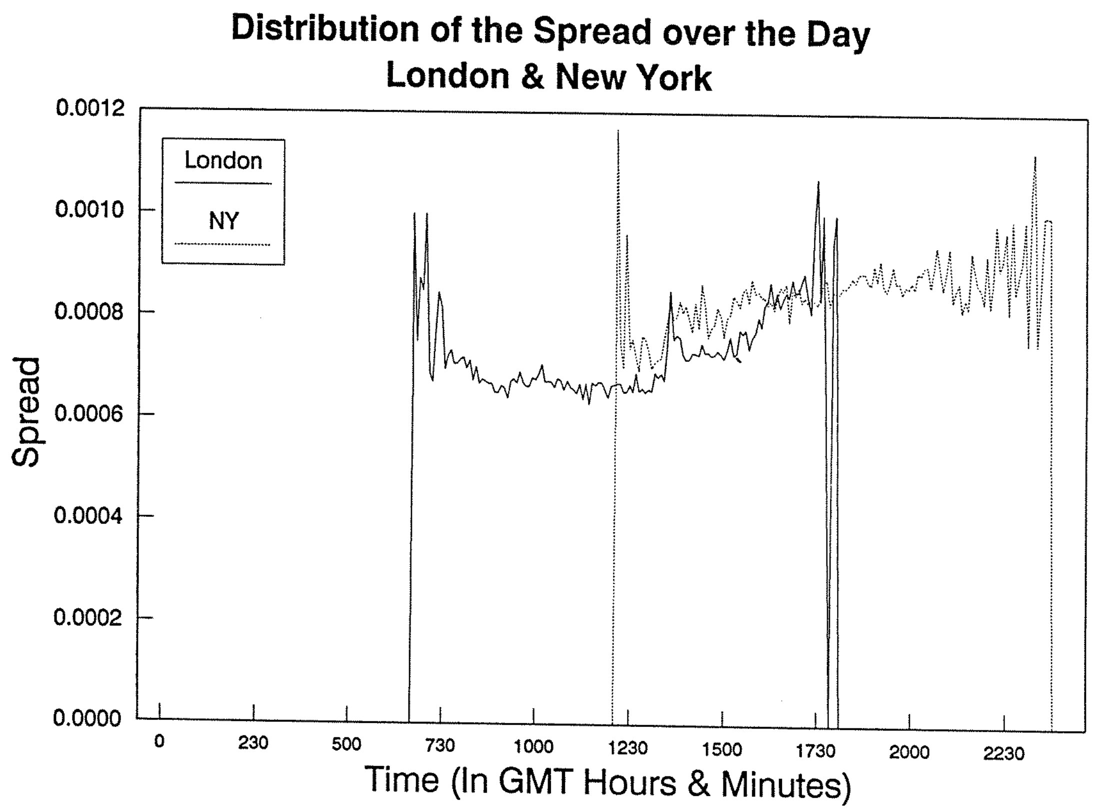
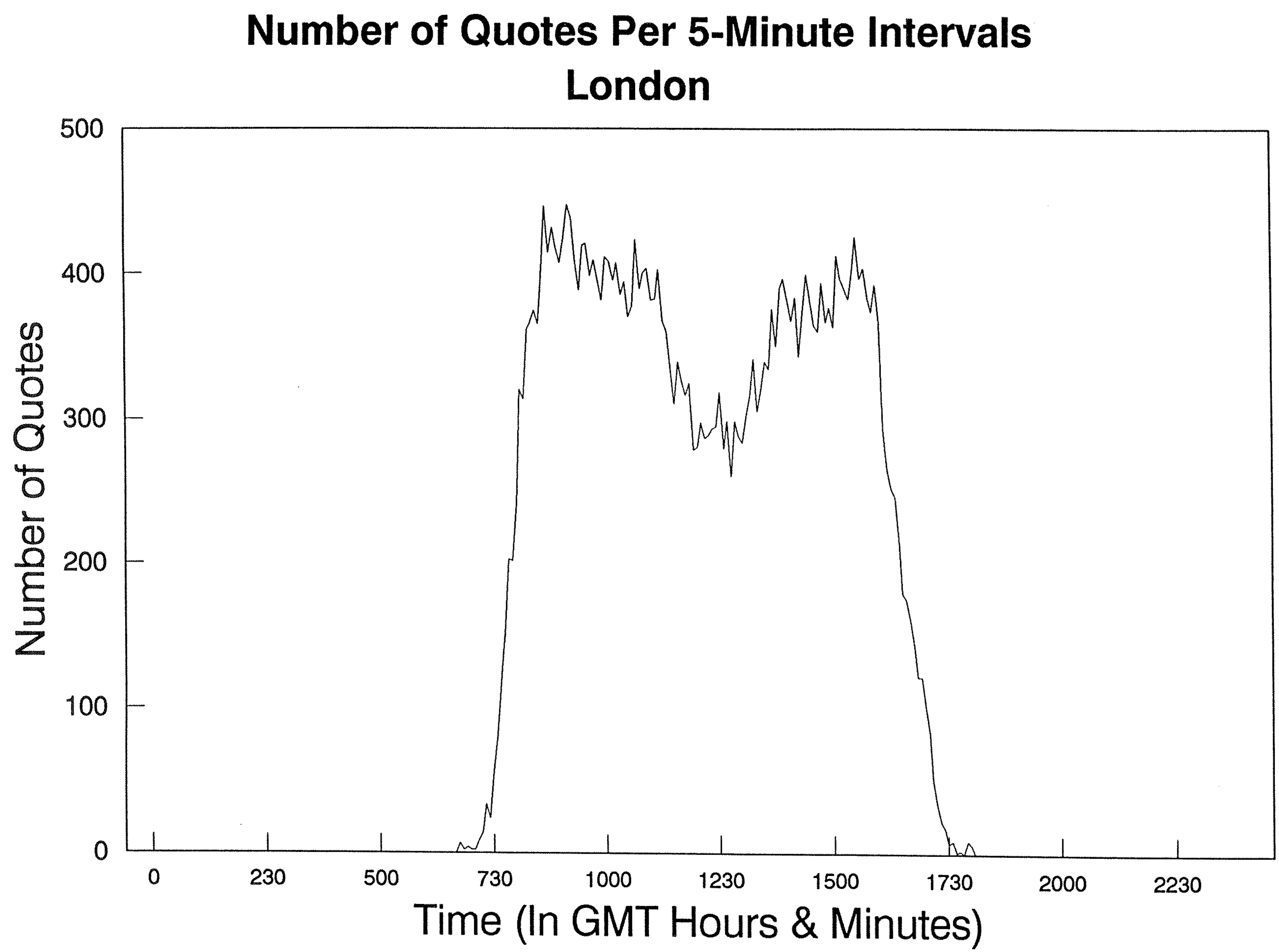
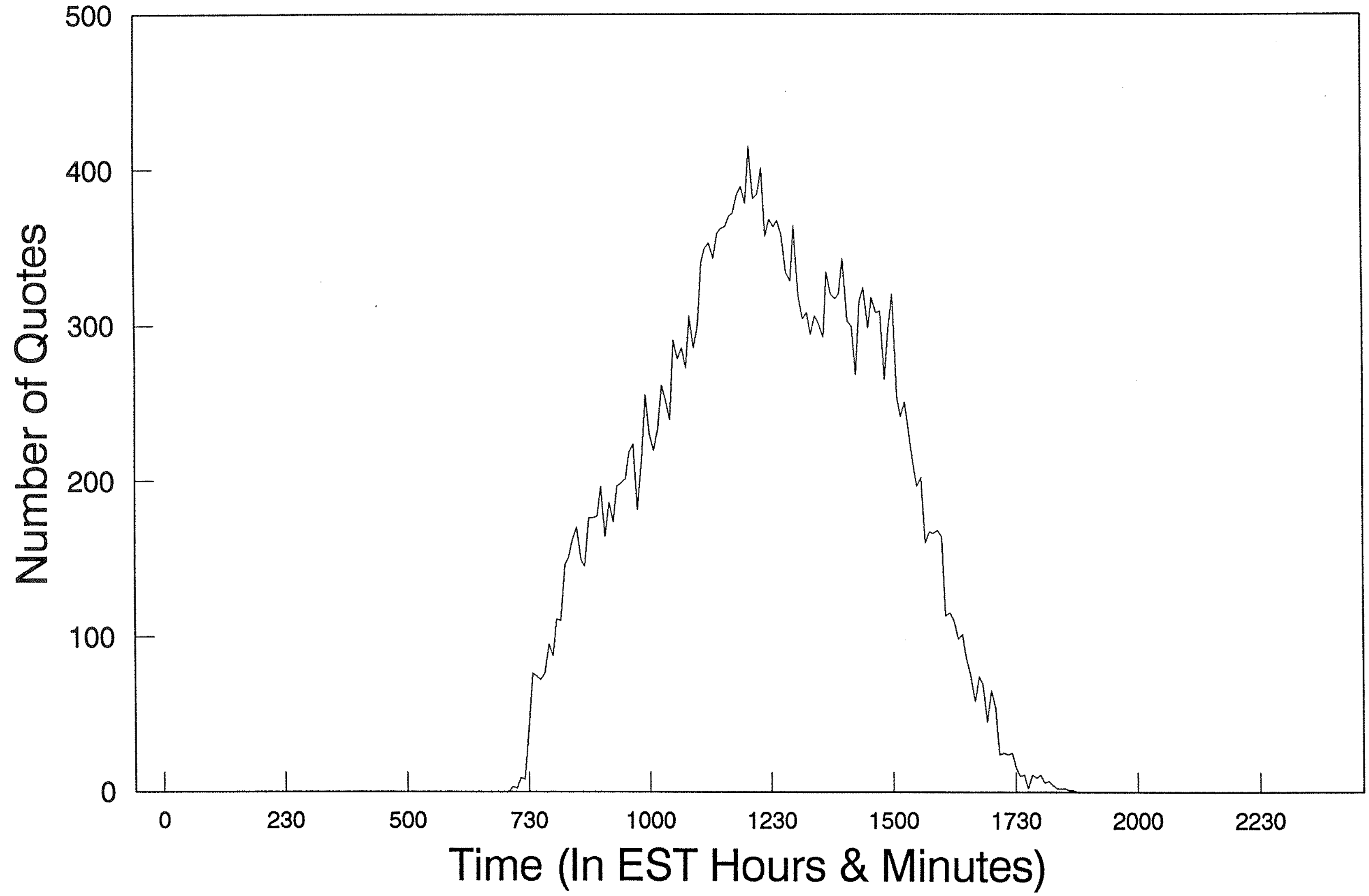

Distribution of the Spread over the Day
London & New York
London
NY
Spread
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
0
230
500
730
1000
1230
1500
1730
2000
2230
Time (In GMT Hours & Minutes)

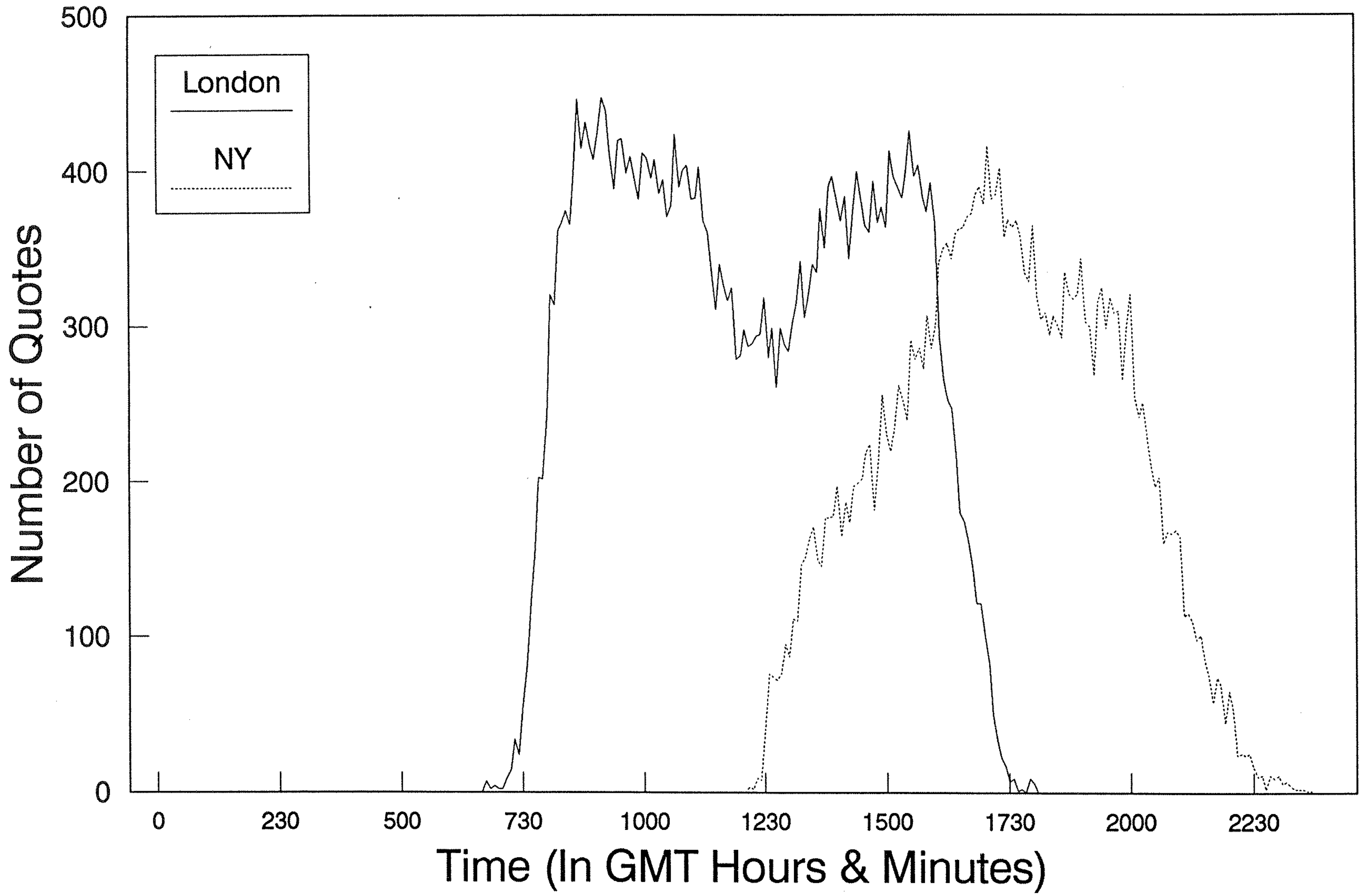
**Figure 6**


Number of Quotes Per 5-Minute Intervals
London
500
400
300
200
100
0
Number of Quotes
0
230
500
730
1000
1230
1500
1730
2000
2230
Time (In GMT Hours & Minutes)

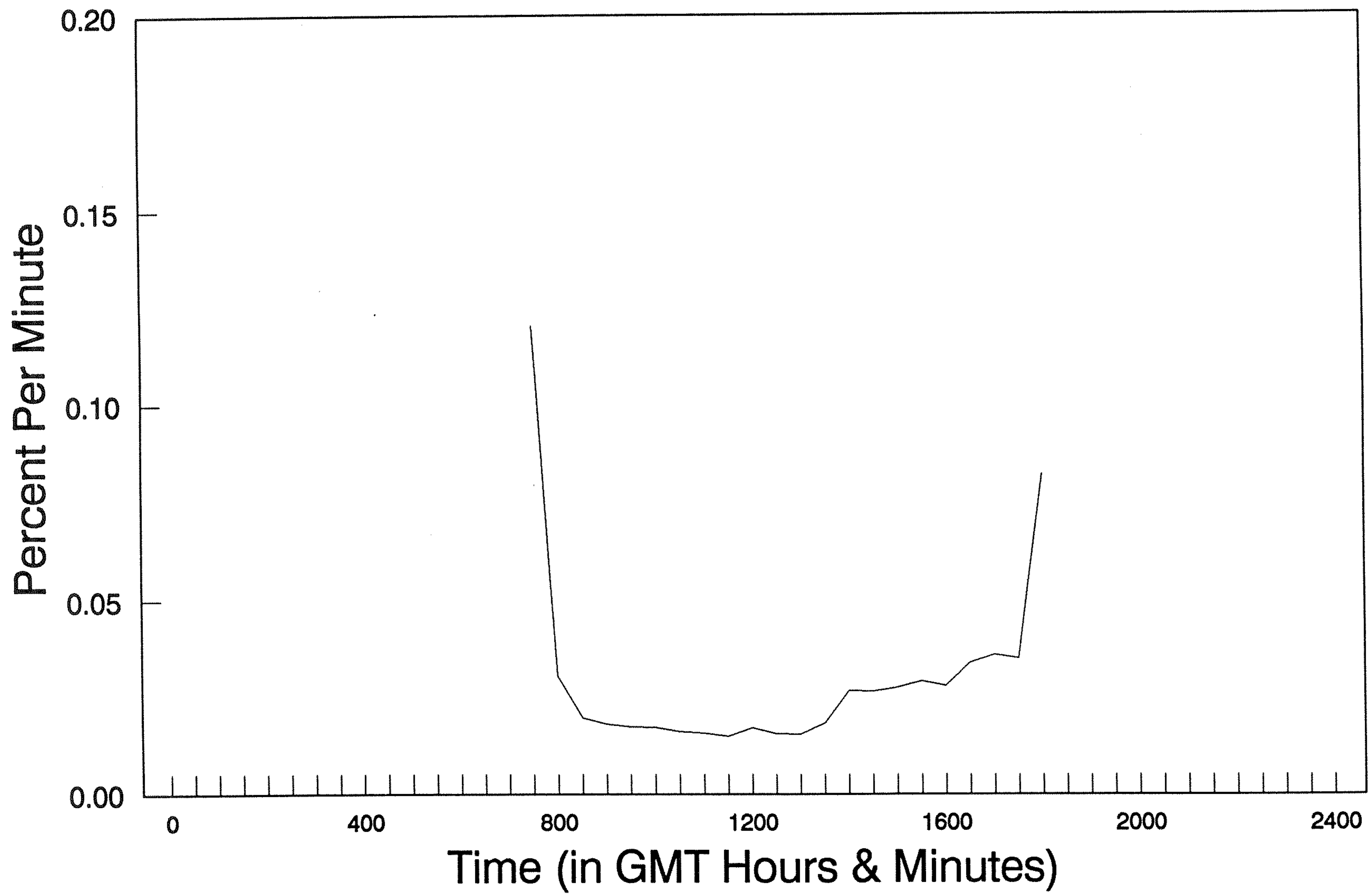
## Number of Quotes Per 5-Minute Intervals
## New York



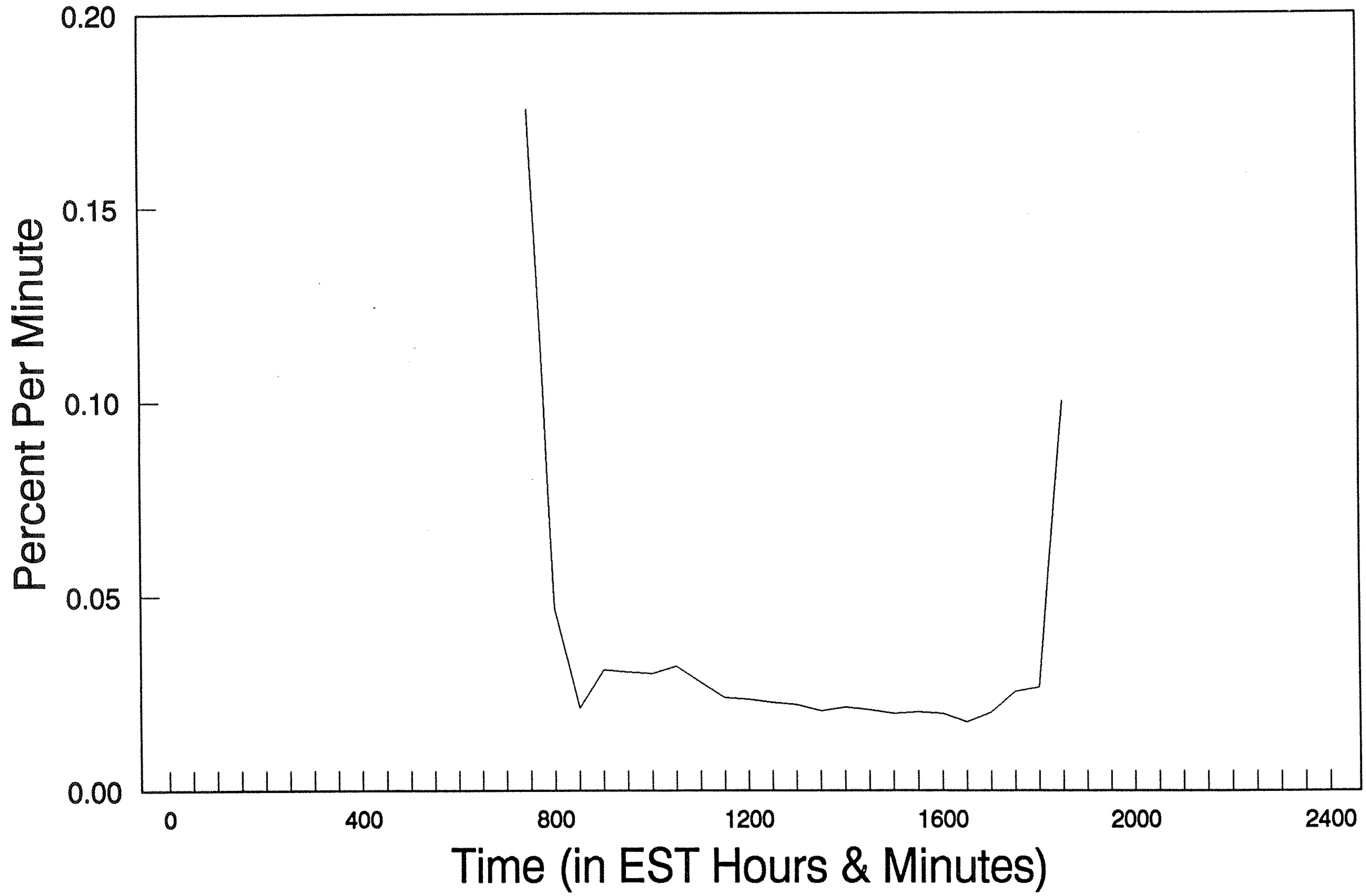
## Number of Quotes Per 5-Minute Intervals London & New York



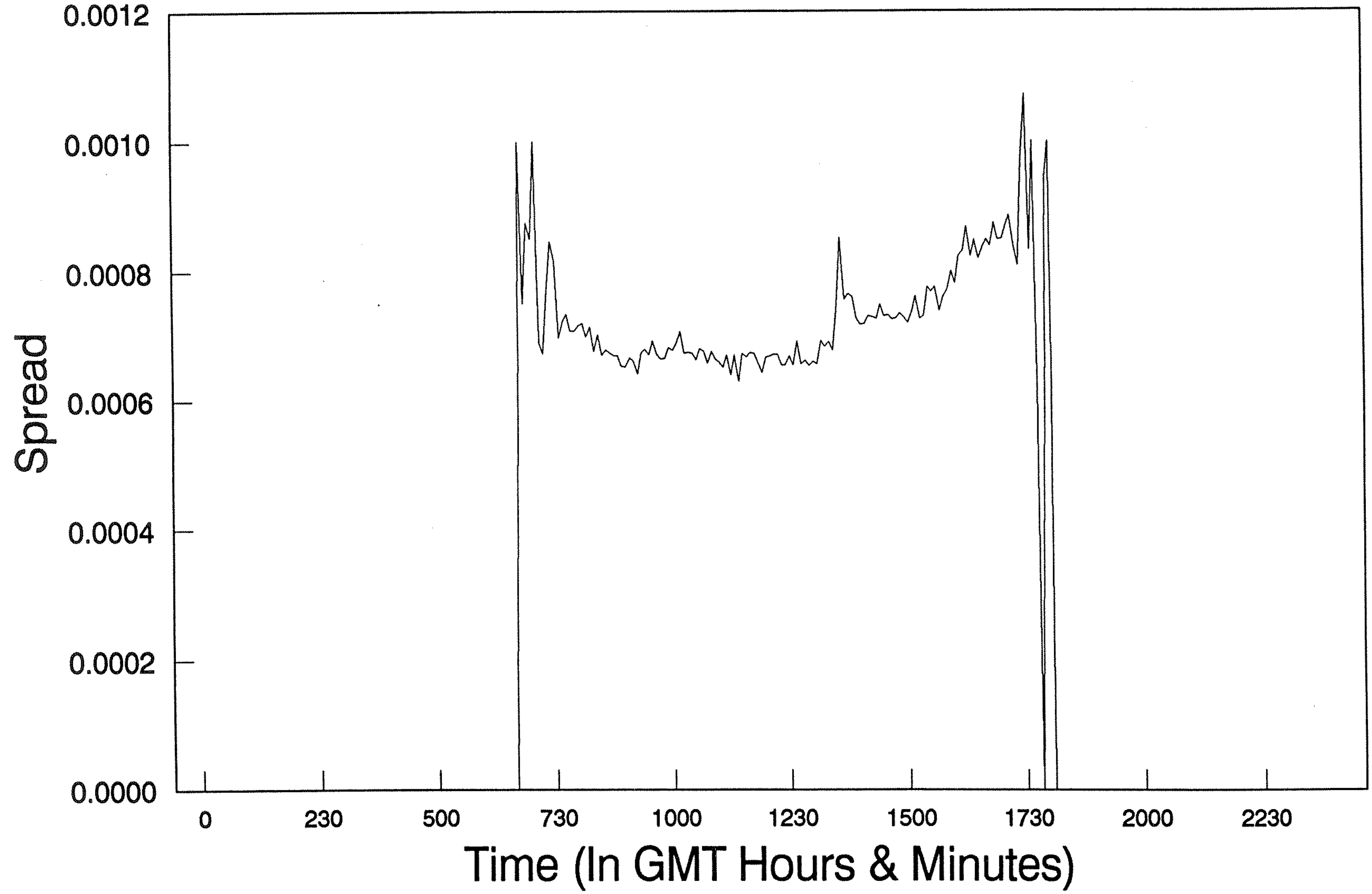
## Standard Deviation Per 30-Minute Interval
## London



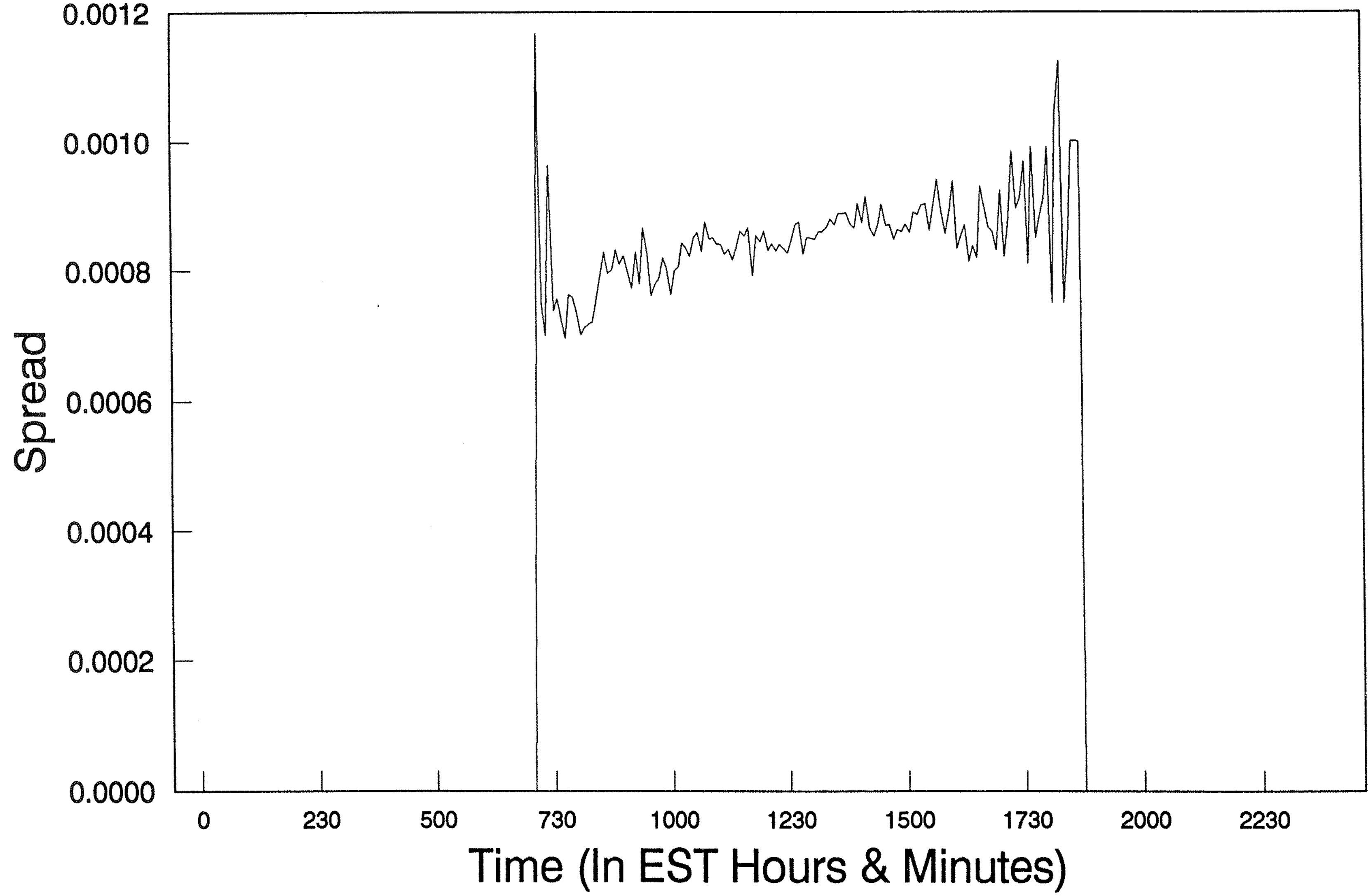
## Standard Deviation Per 30-Minute Interval
## New York

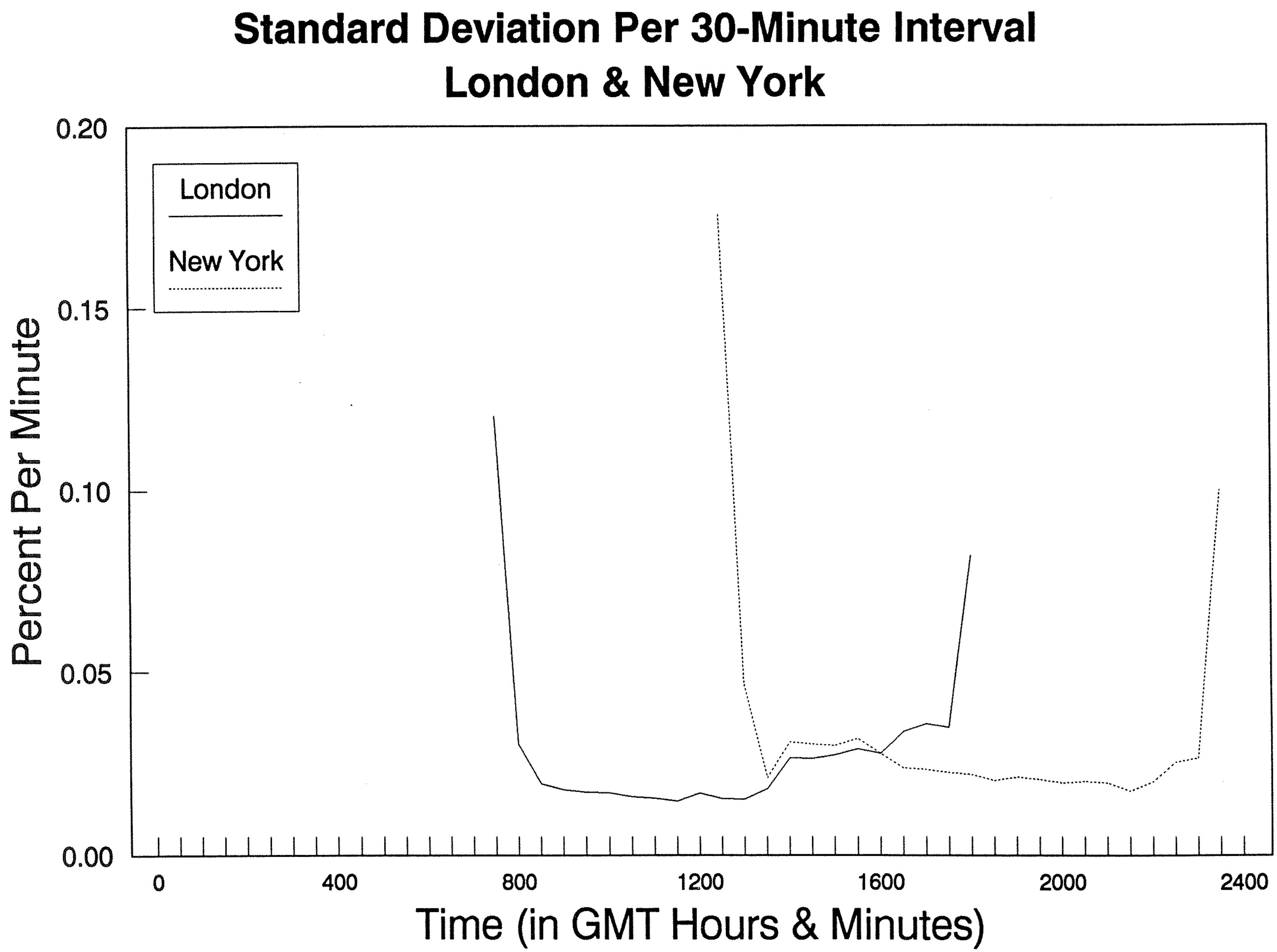


## Distribution of the Spread over the Day
## London



## Distribution of the Spread over the Day
## New York




Standard Deviation Per 30-Minute Interval
London & New York
London
New York
Percent Per Minute
0.00
0.05
0.10
0.15
0.20
0
400
800
1200
1600
2000
2400
Time (in GMT Hours & Minutes)

## Distribution of the Spread over the Day
## London & New York