# Intra-day Seasonality in Activities of the Foreign Exchange Markets: Evidence from the Electronic Broking System[*,☆]


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**Abstract:**

This paper examines intra-day patterns of the exchange rate behavior, using the “firm” bid-ask quotes and transactions of USD-JPY and Euro-USD pairs recorded in the electronic broking system of the spot foreign exchange markets. The U-shape of intra-day activities is confirmed for Tokyo and London participants, but not for New York participants. Activities (deals and price changes) do not increase toward the end of business hours in the New York market, even on Fridays (ahead of weekend hours of non-trading).  It is generally observed a negative correlation between the number of deals and the width of bid-ask spread during business hours, but in the first business minutes of Tokyo, bid-ask spread and activities have high correlation. It is also found that the concentration of transaction during overlapping business hours between Tokyo and London markets (London and New York markets) may arise from heterogeneous expectations among participants from different regions, that is waking up of participants of the next region in time line of the day.

JEL: F31, F33, G15

## 1. Introduction

The foreign exchange market remains sleepless. Someone is trading somewhere all the time—24 hours a day, (almost) 7 days a week. Analyzing the behavior of the exchange rate has become a popular sport of international finance researchers, while global financial institutions are investing millions of dollars to build a real-time computer trading scheme. High-frequency, reliable data are the key in finding robust results for researchers or profitable schemes for businesses.

The objective of this paper is a modest one, namely to examine intra-day patterns of market activities—frequency of quote revisions, transaction volumes, and bid-ask spread—of the dollar/yen and the euro/dollar spot exchange rates using a newly available data of the electronic broking system for the spot foreign exchanges. The intra-day seasonality is in itself interesting but it serves as a basis for further theoretical and empirical analysis.[1]

The spot foreign exchange markets have evolved in recent years, and, by now, the overwhelming majority of the spot foreign exchanges are transacted through the global electronic broking systems—the EBS and Reuters D3000. The data, provided by the EBS, consist of global electronic broking bid-ask quotes, lowest given and highest paid transaction prices, and transaction volumes for three years starting January 01, 1999 at the frequency of every one minute.[2] The EBS data set has advantage over the frequently-used, indicative quotes of a foreign exchange market tick-by-tick data set, such as FXFX of Reuters, in at least two important aspects. First, the quotes in the EBS data set are "firm", in that banks that post quotes are committed to trade at those quoted prices, when they are "hit".[3] In contrast, the indicative quotes of FXFX screen are those input by dealers for information only, without any commitment for trade. Indicative quotes are much less reliable than firm quotes in capturing the whole picture of a market reality. Second, transactions data available in the EBS data set is simply not available in the FXFX screen. Although exact trading volumes are not disclosed, transactions counts (counts of seconds that had at least one transaction) and trade

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[1] In an earlier paper of ours, Ito and Hashimoto (2004), we have analyzed intraday patterns without data set of trade volume shares, which will be described later. This paper is an improved version of our earlier paper with an additional data set, with the same objective.

[2] The data set was provided for fee by the EBS Co., for the use at the University of Tokyo, Research Center for the Advanced Science and Technology. The authors are grateful to EBS for such an arrangement.

[3] See Goodhart and O'Hara (1997: p.78) for general discussions on the difference between the indicative and firm quotes.

volume shares (a percentage share of trading volumes in one minute) are available in the EBS data set.

The contribution of this paper to the literature is three-fold. First, the paper presents a careful description of intra-day seasonality, using the electronic broking data consisting of "firm" quotes and deals as well as trade volume shares, taking into account time zone and daylight saving time of major markets, and national holidays. Second, we found the existence of U-shape pattern in activities and trade shares in both Tokyo and London markets, but no daily U-shape patterns in New York market. It is generally observed a negative correlation between the number of deals and the width of bid-ask spread, but in the first business minutes of Tokyo, bid-ask spread and activities have high correlation, compared to in the following hour. Third, the concentration of transaction during overlapping business hours between Tokyo and London markets (London and New York markets) arises from the price discrepancy due to the asymmetric information among markets.

With respect to intraday seasonality, volume and volatility are found to move together whereas the spread moves the opposite way. In FX market, activity is highest in ordinary business hours of all three markets, but there is no increase at the end of the day. This is contrast to the equity markets where activity is U-shaped with a rise at the end of the day as well as at the beginning. Another big difference between FX and equity markets is the correlation coefficient of the spread and activities (deals and price revisions). The paper finds that the spread is narrower during the hours of high activities, and this is opposite of the conventional wisdom of the equity markets.

The rest of this paper is organized as follows: Section 2 describes the data. Section 3 is a main part of this paper, establishing intra-day seasonality of activities. In section 4, various tests are conducted to establish the patterns, Tokyo opening effects, revealed in the data. Section 5 examines the London and New York opening effects. In section 6, we construct a theoretical model to explain how the overlapping business hours enhance the inter-regional trade. Section 7 concludes the paper.

## 2. The EBS data

### 2.1. EBS electronic broking system

Almost all spot exchange rate transactions of major currencies are now done by electronic broking systems, EBS and Reuters D-3000. The state of the global foreign exchange market is available from a market survey by central banks conducted under coordination of the Bank for International Settlements (BIS), once every three years. In different categorization, the trades between dealers who report to the BIS surveys have declined substantially.[4]

> "*This can in part be explained by the growing role of electronic brokers in the spot interbank market. The use of electronic brokers implies that foreign exchange dealers generally need to trade less actively among themselves.*" (BIS (2002; p.7).)

This trend means that "hot potatoes" (Lyons (1997)) are less important now, and a cool supercomputer is increasingly important. In other words, dealers' tactics to transform order flows from the corporate sector into the interbank market may be less influential than before, and the dealers' behavior in posting firm bids and asks through the electronic broking system is more influential then before.[5]

The EBS is a provider of trading technology, and the quotes and transactions are shown continuously, 24 hours a day. The EBS trader's screen shows the "firm bid" and "firm offer", the bid and offer that are committed to trade if someone on the other side is willing to trade at that price.[6]

The EBS has a strong market share (in absolute terms and in comparison to Reuters D-3000) in the dollar/yen rate and the euro/dollar rate and it is said to cover more than 90% of the dollar/yen and euro/dollar trade.[7] Therefore, it is safe to assume that almost all electronically brokered spot deals of these two currencies are represented in the data set.

[4] However, from the preliminary report of the most recently conducted survey of April 2004, there are indications that spot trades of major currencies have increased between 2001 and 2004. See, a summary of such a trend on the EBS home page: http://www.ebs.com/products/spot.asp.

[5] Our interviews (in November 2003) with banks with substantial foreign exchange trading in London reveals that they have reduced in the last few years the degree of discretion of dealers and shifted proprietary trading to the specialized section. Computer models have replaced dealers' instincts.

[6] For the general reference on the microstructure of the foreign exchange market, see Goodhart and O'Hara (1997), Lyons (1995) and Lyons (2001). For earlier work that used the electronic broking system, see Goodhart, Ito and Payne (1996) and Goodhart and Payne (1996) have used the data obtained from Reuter D2000-2 that is predecessor of D3000.

[7] Reuters have significant market shares in exchanged related to sterling, Canadian dollar, and Australian dollars.

The EBS system facilitates, as part of the dealing rules, each institution to control its bilateral credit lines. Namely, each EBS-linked institution sets credit lines (including zero) against all other potential counter-parties. Therefore, an institution faces a restriction of bid, offer, or deal from other institutions. When bid and offer rates are posted for the system, they are not necessarily available to all participants of the EBS system. The EBS-registered trader's screen shows the best bid and best offer of the market and best bid and best offer for that particular institution. In normal times, the best bid of the market is lower than the best offer of the market. Otherwise, some institution that has positive credit lines with both institutions on the bid and ask sides will be able to make profits by arbitrage.

As part of facilitating an orderly market, EBS requires any newly linked institution to secure a sufficient number of other banks that are willing to open credit lines with the new comer. A smaller or regional bank may have fewer trading relationships, thus not as many credit relationships. Then the best bid and ask for that institution may be different from the best bid and ask of the market. A smaller or regional bank may post more aggressive prices (higher bids or lower asks) because they will have relatively fewer credit relationships, implying that they will see fewer dealable prices generally.

### 2.2. The EBS Data Set[8]

The EBS has made available two sets of data, the price data set and the trade volume share data set. Both data sets include information on the dollar/yen and the euro/dollar currency pairs from January 1, 1999 to December 31, 2001. The price data set is the first to become available for the researchers on the firm quotes in high frequency.[9] It contains information of, among others, best bid, best ask, deal prices done on the bid side (lowest given) and deal prices done on the ask side (highest paid).[10] Moreover,

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[8] The data set is a proprietary information of EBS. The usage is restricted to those who are affiliated at the University of Tokyo.

[9] Data are of the 1-second time slice. The system records, at every second, bid, offer, deals that are posted and carried out in the world-wide EBS system. Bid and offer rates are recorded at the end of time slice. For example, bid and offer rate at xx hour, yy minute, zz second. Fluctuations of the bid and offer rates within the second (in the time slice) are not recorded and cannot be inferred. It is theoretically possible that bid and offer rates move up and down within the second, but not shown in the data set. Deal rates are recorded on the basis of Highest Paid and Lowest Given in the 1-second time slice.

[10] The deal (on either side) recorded at zz second includes those that took place between zz-1 second to zz second. When there are multiple trades within one second, "lowest given price" and "highest paid price" will be shown. A highest paid deal means the highest price hit (done) on the ask side within one second and the lowest given deal means the lowest price hit (done) on the bid side within one second.

the EBS price history shows whether the deal is done on the bid side (the bid was taken) or the ask side. It does not contain information on the volume of transactions associated with bid, offer, or deal. The trade volume data set is the first to become available on the actual trading volumes in high-frequency. It includes relative trade volume shares that are the share of trade volumes (one-second slice) relative to the total trading volumes in that day. The EBS global system consists of three regional computer sites, based in Tokyo, London, and New York, and it matches orders either within the site or across different sites. Each region covers Europe, North America, and Asia, respectively. The three regions are often abbreviated as LN, NY, and TY regions in this paper. The intra-regional deal of LN, for example, consists of deals whose maker and taker are both from London region. And inter-regional deal of LN&NY consists of deals whose maker and taker are from two different regions of London and New York.

The basic characteristics of the data used in this study are shown in Table 1. “The number of price changes” means the number of quote changes on either side of the bid-ask quotes or both at the same time.[11]

Table 1-1

Table 1-2 shows the three-year average of relative daily volume percentages of the yen-dollar and the euro-dollar deals. Deal traffic patterns are described in terms of intra-regional deals as well as inter-regional deals. The relative deal volume of six pairs of three markets is shown as percentage of the total daily volume by region. Originally the percentage is shown in the one-minute timeslice basis. Then, in the analysis, it is hourly aggregated.

The first three rows show percentages of intra-market deals of London, New York, and Tokyo. The next three rows show the three inter-regional pairs of three regions. The Relative Trade Share by region is the postulated share based on our calculation, in order to see the shares of deals that can be attributable to a particular region. It is calculated by adding the intra-regional deal share and the sum of halves of inter-regional deals. For example, the yen trade share in Tokyo market is the sum of the Tokyo intra-regional share, half of the Tokyo-NY, and the half of the Tokyo-London deal shares. In other

[11] Price changes could be generated by new entries of quotes, withdrawal of former quotes or disappearance of the quote due to “hits”. The difference between “the number of price changes” and the sum of “the number of price changes on the bid side” and “that on the ask side” is the number of quote changes on both sides simultaneously.

words, one LN-TY transaction is divided into 0.5 Tokyo region deal and 0.5 London region deal.

Table 1-2

There are two salient features that emerge from this table. First, there is a home-market advantage, namely the yen is traded more by Tokyo financial institutions (Tokyo-Tokyo deals, Tokyo-London deals, in particular) and the euro is traded more by London financial institutions (London-London deals, London-New York deals, in particular). In total, 42% of yen trades are attributable to the Tokyo financial institutions (30 % for London), and 54% of euro trades are attributable to the London financial institutions (14% for Tokyo). The New York institutions participate in the deals less than the Tokyo institutions for the yen and less than London institutions for the euro transactions. Second, the overlapping business hours encourage inter-regional transactions. For both the yen and the euro, the London-New York deal share is the highest, and the Tokyo-New York deal share is the lowest. This reflects that business hours in London and New York overlap more than three active business hours, while Tokyo and New York does not share any business hour.

## 3. A First Look at the Intra-day Patterns

### 3.1. Definition of Activity during the day

The intraday patterns have been explored in many papers before.[12] For example, Admati and Pleiderer (1988) provided a theory to explain why the concentration of trading and high volatility could happen in a day endogenously using the model where there are two types of traders, liquidity traders and informed traders. Andersen and Bollerslev (1997, 1998) and Baillie and Bollerslev (1990) show the patterns of intraday volatility and then proceed to examine the dynamics of volatility clustering and other properties. However, except for Goodhart, Ito, and Payne (1996) and Goodhart and Payne (1996), all papers use indicative prices. Moreover, the period for analysis is typically for several months. This paper establishes the facts with firm quotes and deals, that are far better in describing the market than indicative prices. The sample period extends to three years, with a second as a frequency.

[12] Many papers are contained in a conference volume on the High Frequency Data in Finance, edited by Baillie and Dacorogna (1997).

In this section, the hourly changes in the market activities and bid-ask spread are examined. As for market activities, we will take the number of price changes (the number of seconds where price changes are recorded) and the number of deals (the sum of bid-side deals and ask-side deals) in each hour of the day, averaged over a particular period (mostly over a year) with a differentiation of the standard and daylight saving time.[13] The hourly bid-ask spread is averaged over the period (e.g., for one year). These indicators of market activities are calculated for each GMT Hour (Hour 0 to 23), and then averaged over a certain period.

We also use the *relative volume share of an hour*, which is defined as hourly aggregated relative volumes in that day. The hourly trading volumes measured in the aggregate deals in the contract numbers, with each contract being one million of the base currency (the first currency in the currency pair name), is divided by the total trading volume of the day.

The difference between the deal count and the trading volume share is two fold. The deal count is the number of seconds in which there is one deal or more. Therefore a second that experienced the deal may contain more than one deal and one deal may mean one million US dollars or several millions of US dollars. The trading volumes are the total amount of deals, but expressed in the share within the day.

A higher level of activities means a larger number of price changes, and a larger number of deals. This is due to the fact that the number of price changes by dealers tends to increase when more (heterogeneous) participants are in the market; when more news become available; when the most competitive participant (who posts best bid and ask) is reacting to news and market develops quickly; and when the bids and asks are hit more often (so that the best bids or asks are knocked out). The number of deals tends to increase when more participants with different expectations are present in the market (so that someone sells while someone buys at the same price); and when more news that can be interpreted differently become available.

The bid-ask spread tends to become narrower when more participants are in the market

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[13] Note that the number of price changes and the number of deals in the data set may not exactly match the total number of price changes and deals in the EBS system, because the data set is in terms of the one-second slice. If there are more price changes and deals within one second, the recorded numbers are less than the true numbers. The original data set is by second. Therefore, the maximum number of deals or price changes in one hour is 3,600.

(that is, market is deep) and when expectations are relatively homogeneous.

### 3.2. Standard Time and Daylight Saving Time

Since daylight saving time is adopted in London and in New York, the GMT hours corresponding to the local business hours of London and New York shift by one hour during their respective summer season. Table 2 summarizes the GMT hours and corresponding Local time of the three major markets.

Table 2

In the following, aggregation for the year is divided into the two periods:[14]

Daylight Saving (Summer) Time: First Sunday of April-last Sunday of October,
Standard (Winter) Time: January-last Sunday of March, the next working day of the last Sunday of October-December.

Note that we eliminate the one-week period in the spring when Europe is under the Summer Time but the US is not. Also excluded from the sample are Saturdays, Sundays, and days in which one of the three markets is closed for national holidays.

### 3.3. Intraday Activity Patterns

**Price changes and Deals**

Figures 2-1 and 2-2 show the intraday (Hour 0-23) pattern of the activities and the bid-ask spread of the USD-JPY pair and Figures 2-3 and 2-4 show those of the Euro-USD pair.

Figures 2-1 and 2-2 reveal several interesting features. First, a high correlation between the "number of price changes" and the "number of deals" is found in the yen-dollar foreign exchange market. Second, there are three peaks in the number of price changes and the number of deals in a day. In summer, peaks of the activity of USD-JPY pair are seen at Hour 0, Hours 6-7 and Hours 12-14; and in winter, Hour 0, Hour 8, and Hours 13-15. Third, we find three troughs in a day. In summer: Hour 3; Hours 10-11; and Hour 21: and in winter, Hour 3, Hour 11, and Hour 22. Fourth, the

[14] Daylight saving time in 1999 was from April 4 to October 31 in the United States; from March 28 to October 31 in the United Kingdom; in 2000, from April 2 to October 29 in the United States, and from March 26 to October 29 in the United Kingdom; and in 2001, from April 1 to October 28 in the United States and from March 25 to October 28 in the United Kingdom.

bid-ask spread is narrower during the first half of the day, then it becomes wider after Hours 16-17 and peaks at Hours 21-22.

In general, the bid-ask spread tends to be negatively correlated with the number of deals (or price changes): The three troughs of the number of deals (or price changes) mostly correspond to three peaks of the bid-ask spread. One deviation is the Hour 0, when the bid-ask spread is higher than other business hours in Tokyo (except lunch hour at Hour 3) but the number of deals (or price changes) is at the one of the peaks; that is, unlike other times, a positive correlation.

Figure 2-1-Figure 2-2

The decrease in activities during the Tokyo lunch hour is remarkable. There used to be regulations that prohibited the interbank foreign exchange trading during the lunch hour in Tokyo. Although the regulation was lifted in December 1994, the tradition seems to continue—history seems to matter.[15]

Figures 2-3 and 2-4 show hourly-aggregated Euro-USD activities that correspond to the earlier figures for the USD-JPY pair. Similar observations emerge. First, a high correlation between the "number of price changes" and the "number of deals" is found. Second, as for the number of price changes and deals, three peaks on the hours similar to those of the USD-JPY pair, in a day are found, with one distinctive feature. The height of the first peak, Hour 0, is much lower for the Euro-USD pair than the USD-JPY. It is remarkable that during the peak hours in the London morning and the overlapping hours of London afternoon and New York morning, the number of deals (the sum of those on the bid and ask sides) exceeds that of price changes. This is evidence that the market is thick enough that many deals did not result in the price change. Third, we find three troughs in a day: at Tokyo lunch hour, London lunch hour, and at Hour 21-22. Fourth, the bid-ask spread is narrow during the London business hours. It becomes wider after Hours 16-17 and peaks at Hours 21-22.

[15] Historically, the interbank foreign exchange transactions had a lunch break (regulatory shutdown) during the lunch hours. When the regulation was removed, the activities during the lunch hour increased at the expense of those before and after; the net effect was higher. See Ito, Lyons, and Melvin (1998) and Covrig and Melvin (2005). Then, in the afternoon and market-ending hours of Tokyo market, activity again increases in terms of relative transaction volume: it peaks around Hours 5-6.

Figure 2-3 2-4

In sum, comparing the USD-JPY and Euro-USD tradings, intraday activities show very similar patterns, with the following notable exceptions. First, there seems to be a "home-market advantage". That is, activities of the Tokyo market relative to the London market are higher for the USD-JPY and lower for the Euro-USD. In fact, the heights of the three peaks for the yen are roughly equal, but, for the euro, the height of the peak during the Tokyo opening hour is distinctively low. The Tokyo market (or to be precise, the Asian market in general) is not significant in the euro trading. Second, the Euro-USD market is particularly deep in London morning and even deeper in the London afternoon hours that overlap with the New York morning. This is shown in the number of deals exceeding the number of price change during London business hours. Such a characteristics is not generally observed in the USD-JPY trading (only once at Hour 8 in the 1999-2001 summer).

**Trade volume**

In the above analysis based on counts of deals and quote changes, In the price data set, we cannot attribute the activities to specific locations (or, to be precise, market participants in the region). An example is whether a surge in activities in the Tokyo mid-afternoon hours and London morning hours can be attributed to activities of the Tokyo participants or the London participants. Fortunately, the data set of the trading volume shares has the label of participants (regional names) for the trading shares.

The relative trading volume shares of deals that can be attributable to participants of a particular region for the USD-JPY pair are shown in Figures 3-1 and 3-2. The volumes of yen trades done by Tokyo financial institutions and London financial institutions clearly show the U-shape patterns, respectively, whereas yen trade by New York financial institutions shows a single peak pattern. The peak of volume shares by the Tokyo participant (Hour 0) is higher than that by the London participants (Hours 7-8) or that by the New York participants (Hours 14-15). Tokyo participants remain in the market, although with low shares, during the London and New York business hours. The Tokyo participants start to trade the yen in the 7am Tokyo time (Hour 22), although a sudden surge at 9am is quite remarkable. The trading volume share by Tokyo financial institutions at 8am (Hour 23) is higher than that during the London business hours. The New York peak volume share is higher than that of the London volume share (Hour 12-13). The London and New York participants are quite dormant in the yen trading during the London business hours.[16]

Figure 3-1- 3-2

Figures 3-3 and 3-4 show the relative trading volume shares for the EURO-USD pair.

It is immediately clear that the share of euro trades by the Tokyo participants is quite small. Although there is a U-shape pattern in the euro trading by the Tokyo participants, the shape and height of the U-shape is quite different from that for the yen-dollar trading. The Tokyo participants' share of Euro trading compared to that of the yen-dollar trading is low, and unlike the yen-dollar trading, the euro-dollar trading show that the trading share in the late afternoon hours (Hour 7 in the summer, Hour 6 in the winter) is higher than that of the beginning of the market (Hour 0). This shows that, for the euro trade, the Tokyo participants have to wait for London participants to find counterparties, whereas they can find among themselves the trading counterparties for the yen trade. In other words, for the yen-dollar trades, the Tokyo market has new information becoming available and heterogeneous reactions to the news generate trading, but for the euro trades, the Tokyo market relatively lacks news or has homogeneous participants.

Figure 3-3, 3-4

The trading shares of the London participants are particularly high for the euro market during the two peaks (Hours 8 and 13-15 in winter; Hours 7 and 12-13 in summer). The trading shares of the New York participants show only a single peak (Hour 15 in winter and Hour 14 in summer). For the euro-dollar trading, the London participants' peak is higher than the New York participants' peak, while for the yen-dollar trading, the peak of the London participants' share is lower than the New York participants' share during the overlapping hours (Hours 13-15). Even for the euro trading, the London and New York participants are almost non-existent in the Tokyo business hours.

In sum, the trading volume share data show the following five salient features. First, a U-shape intra-day activity pattern is confirmed for the Tokyo and London market

[16] The data set we used in our earlier study, Ito and Hashimoto (2004), did not distinguish the regional origins of the deals, and therefore the regional attribution remains only a conjecture.

participants, but not for the New York market participants.[17] The lack of a U-shape activity for New York market participants is a new finding in the microstructure literature.[18] Second, there is a home-market bias in the foreign exchange market: the activity share for the yen trading is the highest by the Tokyo participants at the opening hours of the Tokyo market, while for the euro trading, the highest is by London participants during the overlapping hours of London afternoon and New York morning. Third, the relative trading share of the Tokyo market participants for the euro trading is significantly lower than the London or New York participants even in their peak hour. Fourth, the London and New York participants are quite dormant in their trading during the Tokyo market hours, while the Tokyo participants maintain some trading activities during the London business hours, both for the yen and euro trading. Fifth, comparing the number of seconds that include at least one deal (Figures 2-1 through 2-4) and the volume shares (aggregate of three regional participants, or a vertical sum of three points for each hour in Figures 3-1 to 3-4) quite similar patterns are found. Three peaks during the day for the yen-dollar trading, and two high peaks and one low peak for the euro-dollar trading.

## 4. Tests of Well-known Intra-day Seasonality Pattern

The number of market participants varies from one day to next, and from one hour to next within the day. There are conventional wisdoms regarding the depth of the market, market activities, and the bid-ask spread. When many market participants are participating in the market, the market is commonly called deep. When many participants with very different background and forecasts are present in the market, deals tend to occur. When there are many participants in the market, spreads tends to be narrower and trades do not change the best quotes. These common senses can be quantitatively tested and shown using our data.

### 4.1 Hypotheses

Here, several hypotheses regarding intra-day patterns, such as the opening hour effects of the three markets, the Monday morning effect, and a (lack of) U-shape pattern are examined. The switch between the winter time and the daylight saving time will be

[17] The U-shape pattern was originally documented for the stock market. In the exchange market, see Hsieh and Kleidon (1996), and Ito, Lyons, and Melvin (1998).

[18] For the empirical test and survey of the U-Shape pattern in financial markets, see, for example, Harris (1986), Foster and Viswanathan, (1993), Ito, Lyons and Melvin (1998), and Andersen and Bollerslev (1998).

exploited to identify opening hour effects of the London and NY markets apart from the GMT hour effects. Also a hypothesis that the bid-ask spread is narrower (wider) when the activity is higher (lower, respectively) is tested formally.

It is theoretically expected that the bid-ask spread is negatively correlated with either the number of price (firm quote) changes or the number of deals. When many participants are present in the market, then the price changes will be frequent, and at the same time, spreads will become narrower. For the hours where the number of deals is high, it may also be expected that spreads are narrower. Thus, the following relationships can be examined.

$$Spread_{(t)} = constant + a_1 * number\ of\ price\ changes_{(t)} + \varepsilon_{(t)}\ ,$$
$$Spread_{(t)} = constant + b_1 * number\ of\ deals_{(t)} + \varepsilon_{(t)}.$$

However, there may be an exception to this relationship. When the Tokyo market opens after a long break, such as a weekend, the bid-ask spread may be wider because market participants are unsure about the market conditions and other participants' positions, while the numbers of deals and quote revisions may be higher, as some participants have to carry out some accumulated orders from customers.

**4.2 Are Tokyo Opening Hours Special?**

First of all, let us test a hypothesis that the opening hour of the Tokyo market has special characteristics, because it follows a few hours of extremely low activity. The bid-ask spread and the number of price changes is assumed to have a stable relationship throughout the day, except for the first business hour of the Tokyo market. Then the model examined is as follows:

$$Spread_{(t)} = constant + (a_1 + H0dum) * number\ of\ price\ changes_{(t)} + \varepsilon_{(t)}\ ,$$
$$Spread_{(t)} = constant + (b_1 + H0dum) * number\ of\ deals_{(t)} + \varepsilon_{(t)}.$$

Presumably, the larger the number of entries (quotes, deals), the smaller the spread, and therefore $a_1$ ($b_1$) is expected to be negative. *H0dum* is an hour 0 dummy, taking the value 1 when the quote is recorded in the period of Hour 0 (Tokyo 9am) and 0 otherwise. The expected sign of coefficient is positive. The explanatory variable, the relative volume, is also included in each of regression in order to control for the effect of transaction volume on the spread. Estimation results are shown in Table 4-1 (USD-JPY pair) and in Table 4-2 (EURO-USD pair). A separate regression is conducted for each of the three years, and using the number of price changes (Panel A) or the number of deals (Panel B).

Table 4-1 Table 4-2

As for the USD-JPY trade, shown in table 4-1, the statistically significant and negative coefficients of $a_1$ and $b_1$, as expected, are found. That is, when market is deep (when the number of price (quotes) changes is large and deals done are large), the bid-ask spread tends to be narrower. The *H0dum* is estimated significantly positive only for a regression model with number of deals on spread in 1999 and whole sample for USD-JPY pair. Others are either negative or insignificantly positive.

The result for the Euro-USD trade is almost the same as is the case with the yen-dollar trade. In Table 4-2, a predicted negative relationship between number of price change and spread and between deals and spread is found, except for an insignificant relationship between the number of price change and the bid-ask spread for the whole sample and 1999 samples. The coefficients of *H0dum* are not estimated as significantly positive.

The hypothesis of a special first hour effect, a positive correlation between the spread and activities—namely, the Tokyo opening effect, is not strongly supported in the regressions.

### 4.3 Does Monday Opening Effect exist in the FX market?

Even though the effect of opening hours on activity is not significant, it is still worth checking the Monday morning effect because Tokyo market opens for the first time of the week after a long weekend break. If orders accumulated during the weekend (about 35 hours) is much larger than those accumulated during the overnight gap (2-3 hours) between New York close and Tokyo open, then the first hour of Tokyo on Monday (Hour 0 in adjusted GMT) may be different, most likely with a much higher activity, from that hour on any other day of the week.

Here, the effect of Monday morning is examined using the Monday Hour 0 dummy in the following regression model:

$$Spread_{(t)} = const + (a_1 + MonH0dum)*number\ of\ price\ changes_{(t)} + \varepsilon_{(t)},$$
$$Spread_{(t)} = const + (b_1 + MonH0dum)*number\ of\ deals_{(t)} + \varepsilon_{(t)}.$$

*MonH0dum* takes 1 when the price changes (deals) is put in at Monday Hour 0 and 0 otherwise. The expected sign of coefficient $a_1$ ($b_1$) is negative, and that of *MonH0dum* is positive. Again, in order to control for the effect of transaction volume on the spread, the relative volume is also included as an explanatory variable in each regression.

Regression results for USD-JPY pair are shown in Table 4-3. The coefficients of $a_1$ and $b_1$ are estimated significantly negative, as expected. The hypothesis of Monday morning effect on the number of price changes does not seem supported in Panel A. The regression result of the spread on number of deals, in Panel B, is slightly different. The Monday Hour 0 dummy is estimated positive in the full sample and in 2000 (at 5% significance level) and in 1999 (at 10%). The finding of Monday morning effect on deal activities suggests that the market participants carry out some accumulated orders over the weekend in the first hour of the week, the Monday Tokyo morning at Hour 0, despite the relatively wide bid-ask spread. Table 4-4 for the Euro-USD trade shows negative coefficients of $a_1$ and $b_1$, except for $a_1$ for estimation in 1999 as well as the full sample period. The Monday opening effect is not estimated significantly positive at all.

Table 4-3 Table 4-4

Overall, the results suggest the existence of Monday opening effect only for USD-JPY deals in both 1999 and 2000, but we found no Monday morning effect in explaining the spread by the foreign exchange activities in other estimation periods.

The disappearance of the Tokyo opening effects and Monday morning effects in the FX market in recent years are probably due to the enhanced computerised trading systems that have increased liquidity in the market most of the times of day. For the last several years, many financial institutions, from small hedge funds to big banking groups, have invested in computer programs that automatically signal buy and sell orders responding to changes in market trends and execution of such trades becomes easier with electronic broking systems. The widespread use of computer trading systems may have contributed to the elimination of the particular intraday patterns.

**5. London and New York opening effects**

Finally, we test the effect of opening hours of London and New York markets using one of the following specifications:

$$y_{(t)} = \beta{*}D_1 + \gamma{*}D_2 + \varepsilon_{(t)},$$

where y is one of the three variables, number of price changes, the number of deals, or the bid-ask spread; and $D_1$ and $D_2$ are dummy vectors. The relative volume is included as an explanatory variable to represent the depth of the market. $D_1$ consists of dummy variables representing Hour 0 to Hour 23 to control the hour of the day effects. $D_2$ are dummy vectors that examine opening and lunch hours over and above the GMT hour effect, as will be explained below. Opening hours of London and New York can be identified separately from the GMT hour dummies because the opening hour shifts by one hour between summer and winter. Since the Tokyo market does not observe the daylight saving time, the Tokyo local time does not shift against GMT hour, and therefore we use the dummy vector $D_2$ that identifies the London opening, London lunch, and New York opening over and above k hours after the Tokyo opens regardless of the daylight saving time. Here, $D_2$ can be written as follows:

$$D_2 = \left|\begin{array}{cccc|cccc} 0 & & 0 & 1 & 0 & 0 & & 0 \\ & O & & 1 & 0 & & O & \\ 0 & & 0 & 1 & 0 & 0 & & 0 \\ \hline 0 & & 0 & 0 & 1 & 0 & & 0 \\ & O & & 0 & 1 & & O & \\ 0 & & 0 & 0 & 1 & 0 & & 0 \end{array}\right|.$$

The $D_2$ variables include the following open and lunch hour dummy variables. For example, as lunch breaks in London seem to begin at GMT Hour 10 in summer and GMT Hour 11 in winter, the London lunch dummy takes the following expression:

$$\text{LN lunch} = \begin{cases} 1 \text{ at Hour 10 in summer} \\ 1 \text{ at Hour 11 in winter} \\ 0 \text{ otherwise.} \end{cases}$$

Since $dy / dD_2 = \gamma$ is independent from other explanatory variables, it simply depicts the effect of London lunch (London opening, NY opening) over and above the GMT Hour effect.[19]

In running regressions, opening hours of two major markets are considered along with the London lunch time. Therefore, the London opening dummy takes the form:

$$\text{LDN open 1} = \begin{cases} 1 \text{ at Hour 7 in summer} \\ 1 \text{ at Hour 8 in winter} \\ 0 \text{ otherwise.} \end{cases}$$

Since a large jump of quote entries between hour 5 and hour 6 in summer (which corresponds to the London 5 and 6 hour in the morning) and between hour 6 and hour 7 in winter is in some cases found in Figures 2-1 to 2-4, we consider the case where the London market opens at Hour 6 in summer and Hour 7 in winter.

$$\text{LDN open 2} = \begin{cases} 1 \text{ at Hour 6 in summer} \\ 1 \text{ at Hour 7 in winter} \\ 0 \text{ otherwise,} \end{cases}$$

It is not exactly clear from the Figures which hour is the New York opening hour, and therefore we consider three types of the New York opening dummies as follows:

$$\text{NY open 1} = \begin{cases} 1 \text{ at Hour 14 in summer} \\ 1 \text{ at Hour 15 in winter} \\ 0 \text{ otherwise,} \end{cases}$$

$$\text{NY open 2} = \begin{cases} 1 \text{ at Hour 13 in summer} \\ 1 \text{ at Hour 14 in winter} \\ 0 \text{ otherwise,} \end{cases}$$

$$\text{NY open 3} = \begin{cases} 1 \text{ at Hour 12 in summer} \\ 1 \text{ at Hour 13 in winter} \\ 0 \text{ otherwise,} \end{cases}$$

[19] The test is conducted including three other sets of dummies: London opening(version 2) = 1 at Hour 6 in summer, 1 at Hour 7 in winter, and 0 otherwise; NY open (version 2)= 1 at Hour 14 in summer, 1 at Hour 15 in winter, and 0 otherwise; NY open (version 3)= 1 at Hour 13 in summer, 1 at Hour 14 in winter, and 0 otherwise. The results are not reported to save space, but it is found that each of the London opening, London lunch, and NY opening has a significant effect on both price changes and spread, and that the opening (lunch) hours significantly shift with the daylight saving time.

**Regression results**

Regression results for the USD-JPY pair are shown in Table 5-1. Panel A shows the result of Number of Price Changes. The results generally show that the Hour dummy variables are significant most of the time. The London open dummies, London lunch dummy, and New York open dummies are all significant and positive. The results indicate that the London opening effect and New York opening effect, after controlling for the GMT Hour effect and the trading volume effect, are clearly identified. The number of price changes are estimated approximately 25-30% larger during opening hours than other business hours. The London lunch dummy is estimated significantly negative as expected.

The middle panel summarizes regression results of the number of deals. The GMT hour effects are significant, and the opening hours of London and New York as well as London Lunch hours are significant and have expected signs. The number of deals becomes 35-43% larger during the opening hours.

The bottom panel shows the regression result of the spread. Results show that the GMT hour dummy variables as well as London Lunch effect are significant in all of the regressions, whereas London and New York opening effects are insignificant in 2000 and 2001. The spread is estimated more than 3% narrower during the opening hours. In particular, it drops by more than 6% during New York opening hours. The opening hour effects are significantly negative in 1999, indicating that the spread becomes narrower at the beginning of London and New York markets. However, coefficients of opening are found insignificant in 2000 and in 2001. This suggests that it is difficult to infer from the movement of the spread when the London and New York market opens in 2000 and 2001. The width of spread is not significantly different from other hours even during the opening hours of London and New York. Contrary to the opening hour effects, London lunch hour is estimated significantly positive in all regressions. The result means the evidence of wider spread during lunch break.

Table 5-1

Regression results of the Euro-USD pair are shown in Table 5-2. The result of regression of the Number of Price Changes is provided in the upper panel. The results show that the Hour dummy variables, as well as the London open dummies, London lunch dummy and New York open dummies are significant.

The middle panel in Table 5-2 provides the results of the Number of Deals. All of the coefficients are significant and have expected signs.

The result of Bid-ask Spread is summarized in the bottom panel. Although the Hour dummies are all significant, London and New York opening dummies and London lunch dummies are insignificant in most cases. In contrast to the result of USD-JPY pair, the width of spread is not significantly different from other business hours even during the opening hours of London and New York.

Table 5-2

Both the lack of the upswing of the U-shape in the afternoon for the trading activities and the insignificant market open effects on bid-ask spread in New York market may be due to the recent widespread practice of continuous trading and better control of inventory. The U-shape, in particular the increase in the afternoon, is often regarded as willingness to trade in order to control inventory ahead of a long break (between the days or over the weekend). However, the widespread use of the trading systems like the EBS system and the computer programs made it much easier for dealers and proprietary traders to find market rates and counterparties even in other regions of the world regardless of the local hours and to manage inventories continuously. This may have contributed to the disappearance of the pick up of the activities toward the end of the business hours in New York, and little changes of the bid-ask spread during the business hours from Tokyo, London, and New York.[20]

## 6. Overlapping Business Hours enhance the Inter-regional

In this section, we construct a simple theoretical model in order to explain why trading volumes (trading shares in a day, or the number of deals, within a fixed interval of time are concentrated during a certain period of time in a day, and banks in the different regions trade each other. We have identified three peaks of high trading volumes in the day: the Tokyo opening hours, overlapping business hours of Tokyo and London markets, and overlapping hours of London and New York markets. From empirical findings on intraday patterns of asset prices, it is commonly found that in particular time

[20] We thank Rich Lyons for his suggestion of this interpretation.

periods within a day (1) there is a concentration of trading, (2) returns and price changes become more variable, (3) higher trading volume corresponds to higher return variability, (4) there are both inter-regional trading and intra-regional trading during the overlapping business hours. A model of trading through an FOREX electronic broking system is constructed that would predict those stylized facts in the earlier sections of this paper.

The Simple Setup

At the beginning of the business hours of each region, retail customers of each region place their buy or sell limit orders via banks, based on their private information. Then, banks transmit those to the electronic broking system, like EBS. For example, at the beginning of the Tokyo business hours (9am), Tokyo customers place limit orders, and banks, either add their own orders or not, transmit customer orders to the electronic broking system. Then in turn, the system will match buy and sell orders in a batch trading (simultaneous clearing at a single price). Basically, the orders are lined up as a demand function and a supply function. The electronic broking system, just like an auctioneer of the Walrasian model, will match the orders at the equilibrium price. See Figure 6-1.

In the early afternoon hours, the trading volumes are very low, because there is little news and new customer orders. Orders that were not matched during the Tokyo business hours are still active, but do not match in the market. These leftover orders from the Tokyo market will be carried over to the London time for possible execution. Let us denote the closing price of the Tokyo market by $p^{tkc}$. The non-trading is depicted as Figure 6-2.

The London customers receive their own information and place limit orders in the London opening hours. The carried-over Tokyo orders are added to the new London orders. Let us assume that Tokyo (London) customers place order through Tokyo (London, respectively) banks. It is also assumed that Tokyo customers are unaware of London customers' information, and keep their orders in the market.

If the demand and supply functions of the London orders produce the same price with $p^{tkc}$, then there will be no inter-regional trade (trading between Tokyo bank and London bank). If the London clearing price is different from $p^{tkc}$, then some Tokyo demand (or supply) will be matched with London customer orders. It can be shown under a fairly general condition that the further the London clearing price is from the Tokyo closing price, the higher is the share of the inter-regional trading. Therefore, there should be a positive correlation between the absolute value of the spread between the Tokyo and London closing prices and the share of the inter-regional trading volumes (in relative to the intra-regional trading of the market that just opens). The London market clearing with some trading being inter-regional trading is shown in Figure 6-3. Therefore, the more the London equilibrium price diverges from the Tokyo equilibrium price, the higher is the ratio of inter-regional trades to the intra-regional trades.

Let us consider the following demand and supply curves in FX market. Suppose that the supply of dollar and demand for dollar in Tokyo market are shown as the followings.

$$S_t^{TK} = \alpha_0^{tk} + \alpha_1^{tk} p \quad \text{and} \quad D_t^{TK} = \beta_0^{tk} + \beta_1^{tk} p ,$$

where $S^{TK}$ is the supply function of the dollar in Tokyo market, $D^{TK}$ is the demand function of the dollar, and $p$ is the price. The market clearing price and the equilibrium transaction volume are represented as

$$p_t^{TK,c} = \frac{\beta_0^{tk} - \alpha_0^{tk}}{\alpha_1^{tk} - \beta_1^{tk}} \quad \text{and} \quad q_t^{TK,c} = \frac{\alpha_1^{tk}\beta_0^{tk} - \alpha_0^{tk}\beta_1^{tk}}{\alpha_1^{tk} - \beta_1^{tk}} .$$

Similarly, the London market equilibrium price and transaction volume, only consists with London orders, are calculated as follows.

$$p_t^{LN} = \frac{\beta_0^{\ln} - \alpha_0^{\ln}}{\alpha_1^{\ln} - \beta_1^{\ln}} \quad \text{and} \quad q_t^{LN} = \frac{\alpha_1^{\ln}\beta_0^{\ln} - \alpha_0^{\ln}\beta_1^{\ln}}{\alpha_1^{\ln} - \beta_1^{\ln}}$$

Considering the fact that the all of the transactions in London market is orders in London market plus the leftover from the Tokyo market. If the London opening price is higher than Tokyo clearing price, then customer orders in Tokyo which was not done during Tokyo business hours is added in London supply curves.

$$S^{LN} = \begin{cases} \alpha_0^{\ln} + \alpha_1^{\ln} p & \text{if } p^{LN} < p^{TK,c} \\ \alpha_0^{\ln} + \alpha_1^{\ln} p + S^{TK,R} & if \;\; p^{LN} \geq p^{TK,c} \end{cases}$$

where $S^{TK,R}$=$S^{TK}$-$q^{tk,c}$ is the supply of dollar carried-over from the Tokyo market and

$$S_t^{TK,R} = \frac{\alpha_1^{tk}(\alpha_0^{tk} - \beta_0^{tk})}{\alpha_1^{tk} - \beta_1^{tk}} + \alpha_1^{tk} p.$$

Similarly, the demand curves in London market consists with London orders plus leftover orders from Tokyo market if the London opening price will be lower than Tokyo clearing price.

$$D^{LN} = \begin{cases} \beta_0^{\ln} + \beta_1^{\ln} p & \text{if } p^{LN} > p^{TK,c} \\ \beta_0^{\ln} + \beta_1^{\ln} p + D^{TK,R} & \text{if } p^{LN} \leq p^{TK,c} \end{cases}$$

where $D^{TK,R}$=$D^{TK}$-$q^{tk,c}$ is the demand for dollar carried-over from the Tokyo market and

$$D_t^{TK,R} = \frac{\alpha_1^{tk}(\alpha_0^{tk} - \beta_0^{tk})}{\alpha_1^{tk} - \beta_1^{tk}} + \beta_1^{tk} p.$$

Now, consider the case, $D^{LN}(p = p^{TKc}) > S^{LN}(p = p^{TKc})$ or $p^{ln}$>$p^{tk,c}$. The London market clearing price, derived from the equilibrium, $S^{LN}$=$D^{LN}$, is

$$p_t^{LN,c} = \frac{1}{\alpha_1^{\ln} + \alpha_1^{tk} - \beta_1^{tk}} \left( -\alpha_0^{\ln} + \beta_0^{\ln} - \frac{\alpha_1^{tk}(\alpha_0^{tk} - \beta_0^{tk})}{\alpha_1^{tk} - \beta_1^{tk}} \right).$$

Then, the transaction volume that emerges from only London orders, $q^{LN,LN}$, is

$$q_t^{LN,LN} = \alpha_0^{\ln} + \frac{\alpha_1^{\ln}}{\alpha_1^{\ln} + \alpha_1^{tk} - \beta_1^{tk}} \left( -\alpha_0^{\ln} + \beta_0^{\ln} - \frac{\alpha_1^{tk}(\alpha_0^{tk} - \beta_0^{tk})}{\alpha_1^{tk} - \beta_1^{tk}} \right)$$

The Tokyo carried-over transaction, namely the Tokyo-London transaction, $q^{TK,LN}$, is

$$q_t^{TK,LN} = \frac{\alpha_1^{tk}(\alpha_0^{tk} - \beta_0^{tk})}{\alpha_1^{tk} - \beta_1^{tk}} + \frac{\alpha_1^{\ln}}{\alpha_1^{\ln} + \alpha_1^{tk} - \beta_1^{tk}} \left( -\alpha_0^{\ln} + \beta_0^{\ln} - \frac{\alpha_1^{tk}(\alpha_0^{tk} - \beta_0^{tk})}{\alpha_1^{tk} - \beta_1^{tk}} \right).$$

This can be simplified as follows:

$$q^{TK,LN} = \alpha_1^{TK}(p^{LNc} - p^{TKc})$$

Then, the inter-regional share as a ratio to the total transaction volumes in London, denoted by $IRShare^{LN}$ is written as a function of prices as follows:

$$IRShare^{LN} = \frac{q^{TK,LN}}{q^{TK,LN} + q^{LN,LN}} = \frac{\alpha_1^{TK}(p^{LNc} - p^{TKc})}{\beta_0^{LN} + \beta_1^{LN} p^{LNc}}$$

It is easy to show that the inter-regional trade share is an increasing function of $p^{LNc}$ holding $p^{TKc}$ constant (because it is given when the London market opens).

$$\frac{dIRShareLN}{dp^{LNc}} = \frac{\alpha_1^{TK}(\beta_0^{LN} + \beta_1^{LN} p^{TKc})}{\{\beta_0^{LN} + \beta_1^{LN} p^{LNc}\}^2} > 0$$

Then the larger $p^{ln}$-$p^{tk,c}$, the larger the intra-inter share. The model shows that the larger the price changes between Tokyo and London (to be precise between the open of the London morning and close of Tokyo), the larger inter-regional (Tokyo-London) trading volumes (in relative to total London trading volumes).

Similarly, if carried-over trades from London customers are added to New York, then the larger the price changes between London and New York, more inter-regional trades will occur in the morning hours of New York.

Estimation

We will test a theoretical prediction that the more price movement from the beginning of the overlapping hours to the end of overlapping hours, the higher become the share of inter-regional trade to the total trade during those hours.
The regression model we use is as follows:

$$IRShare_t = b * gapPrice_t + \varepsilon_t$$

where *IRShare* represents Tokyo-London transaction volume/(London intra + Tokyo intra transaction + Tokyo-London inter transaction volumes) for the London market analysis and London-New York transaction volume/(New York intra + London intra + LN-NY inter transaction volumes) for the New York market analysis. The *gapPrice* is the absolute price gap during the overlapping business hours between Tokyo and London, and those between London and New York, and that between London and New York. We use price changes between the London opting and Tokyo closing for the Tokyo-London overlapping hours, namely GMT 6-8 (5-7 in summer). For the analysis of London-New York overlapping hours, we use New York opening and London closing prices, namely GMT 13-15 (12-14 in summer). Coefficient, *b*, is expected to be positive.

The regression results are shown in Table 6. Results undoubtedly show the positive relationship between the price change and the inter-regional trading share during the overlapping hours. More disagreement on views of the exchange rate, which may come from different private information in two different regions will stimulate transactions between the two regions rather than trading within the region.

Table 6

## 7 Conclusion

In this paper, the intra-daily patterns were investigated from the rich data sets of EBS quotes, deals and relative trading shares. Some of the findings are well-known such as the high activities at the opening of the market, high correlations between quote entries and deals, and higher activities being associated with narrow spreads. However, some of the findings are somewhat surprising. The following observations are new in the literature.

First, there is no U-shape intraday activity pattern in the dollar/yen or euro/dollar market in New York market. The activities are high during the opening hours but not ending hours. Careful observations on the peak of activities, exploiting the difference between Tokyo and New York in adoption of summer (daylight saving) and winter time to conclude where the activities originate during the overlapping business hours. There is no surge in activities toward the end of the New York afternoon hours. Even on Fridays, there is no pick up in activities in the NY afternoon hours.

Second, intra-day patterns of activities and bid-ask spreads are quite stable over the time (yearly comparison). Namely, the peak of activities is observed in the opening hours (9am in Tokyo; 8am in Europe/7am London, and 8-10am New York), and the troughs are late afternoon hours of New York, with significant drops during the lunch hours in Tokyo and, to the lesser extent, in European lunch hours.

Third, the bid-ask spread is generally negatively correlated with the indicator of activities: Higher activities are associated with narrow spreads and low activities are associated with wide spreads. However, the first hour, or to be more specific the first half hour of the Tokyo market (GMT Hour 0) has a slightly wider spread than other hours of comparable activities.

Fourth, from observations of the figures, we found that a home-market bias in the foreign exchange market is significant. The yen is traded more by Tokyo financial institutions (Tokyo-Tokyo deals, Tokyo-London deals, in particular) and the euro is traded more by London financial institutions (London-London deals, London-New York deals, in particular). In total, about half of yen trades are attributable to the Tokyo financial institutions and more than half of euro trades are attributable to the London financial institutions.

Fifth, it is interesting to know that the overlapping business hours encourage inter-regional transactions and overall surges in activities. For both the yen and the euro, the London-New York deal share is the highest, and the Tokyo-New York deal share is the lowest. This may reflect the fact that participants from other regions may have different reactions to the same news, and resulting in the deal.

Sixth, a rigorous analysis of the opening hour effects of London and New York, and lunch hour effects of London, taking advantage of the one-hour shift between the regular and daylight saving times, we find that there are significant opening hour surge and lunch hour decline in activities (the number of deals and the number of price changes). However, there seems to be insignificant effects on the bid-ask spread from the London or New York openings or London lunch hour. These features are common between the yen and the euro trading.

Finally, a positive correlation between the price change and the inter-regional trading share was found for overlapping business hours between Tokyo and London, and also fo those between London and New York. When information, both private and public, available in the newly-opening market (e.g., London) is quite different from that had been known in the previously trading market (e.g., Tokyo), then inter-regional trading becomes more prevalent (relative to total volumes of transactions) in addition to the large change in prices during the overlapping business hours.

Although we have found several interesting facts in the newly available data, there are many tasks left for future research. First, changes in the exchange rate and an activity indicator may be correlated. If the deal is done on one side only, then the exchange rate may move toward that direction. The price impact of deals will be investigated in the future. Second, macroeconomic announcements are often planned during the hour that are before the market opening (say, 8:45 am). However, other markets are open in the case of foreign exchange markets. Additional activities on the day of announcements may be detected not in the market (say, NY) where it is announced but in other markets (say, London).

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Table 1-1: Data summary; Jan 1, 1999 – December 28, 2001

(Excluding Saturdays, Sundays, and national holidays in at least one of the three major markets)

（A） Quote and Deal data for the USD-JPY pair

| | | | |
|---|---|---|---|
| Total number of seconds | | | |
| | | | 59,234,400 |
| Quote | | | |
| | Number of Price changes | | 7,514,064 |
| | spread | mean | 0.020668 |
| | | median | 0.0191 |
| | | variance | 5.426400E-05 |
| | | skew | 1.63961 |
| | | kurtosis | 9.94646 |
| Deal | | | |
| | Number of deals | | |
| | | bid-side only | 2,746,195 |
| | | ask-side only | 2,618,326 |

（B） Quote and Deal data for Euro-USD pair

| | | | |
|---|---|---|---|
| Total number of seconds | | | |
| | | | 59,234,400 |
| Quote | | | |
| | Number of Price changes | | 7,250,465 |
| | spread | mean | 0.00014998 |
| | | median | 0.00010002 |
| | | variance | 1.03247D-08 |
| | | skew | 4.07975 |
| | | kurtosis | 42.61309 |
| Deal | | | |
| | Number of deals | | |
| | | bid-side only | 4,055,369 |
| | | ask-side only | 4,161,367 |

Table 1-2: Relative deal amount by region in the EBS Market.

(A)Relative volume for the USD-JPY pair

| | |
|---|---|
| Hourly relative volume by region | |
| Intra-market trading | |
| London | 16.75 |
| New York | 15.00 |
| Tokyo | 32.64 |
| Inter-market trading | |
| LN-NY | 14.86 |
| LN-TY | 13.47 |
| NY-TY | 6.00 |
| Relative trading share by market | |
| London | 30.91 |
| New York | 25.43 |
| Tokyo | 42.38 |

*Note:* percentage of the total daily volume for the USD-JPY pair

(B)Relative volume for the Euro-USD pair

| | |
|---|---|
| Hourly relative volume by region | |
| Intra-market trading | |
| London | 36.96 |
| New York | 18.54 |
| Tokyo | 7.78 |
| Inter-market trading | |
| LN-NY | 24.28 |
| LN-TY | 9.01 |
| NY-TY | 2.99 |
| Relative trading share by market | |
| London | 53.60 |
| New York | 32.18 |
| Tokyo | 13.79 |

*Note:* percentage of the total daily volume for the EUR-USD pair

Table 2: Intraday timeline: GMT Clock and corresponding Local time of the three major markets

Normal (Winter)

| GMT | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tokyo | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | +0 | +1 | +2 | +3 | +4 | +5 | +6 | +7 | +8 |
| London | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| NY | -19 | -20 | -21 | -22 | -23 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |

Daylight saving time (Summer)

| GMT | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tokyo | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | +0 | +1 | +2 | +3 | +4 | +5 | +6 | +7 | +8 |
| London | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | +0 |
| NY | -20 | -21 | -22 | -23 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |

March-April 1 week (Daylight saving time in London and Winter time in New York)

| GMT | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tokyo | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | +0 | +1 | +2 | +3 | +4 | +5 | +6 | +7 | +8 |
| London | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | +0 |
| NY | -19 | -20 | -21 | -22 | -23 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |

Table 4-1: Hour 0 Effect for USD-JPY trade

Panel A: Correlation between Number of Price change and Spread

| | Constant | s.e. | # of price change | s.e. | H0 Dummy | s.e. | NOB |
|---|---|---|---|---|---|---|---|
| whole | 0.0223 *** | 1.20E-04 | -3.23E-06 *** | 2.14E-07 | -4.99E-07 | 4.01E-07 | 16454 |
| 1999 | 0.0242 *** | 2.41E-04 | -4.30E-06 *** | 3.95E-07 | 5.87E-07 | 6.80E-07 | 5322 |
| 2000 | 0.0211 *** | 1.76E-04 | -3.67E-06 *** | 3.54E-07 | -9.99E-07 * | 6.61E-07 | 5590 |
| 2001 | 0.0227 *** | 2.03E-04 | -3.68E-06 *** | 3.57E-07 | -1.47E-06 ** | 7.26E-07 | 5542 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Panel B: Correlation between Number of Deals and Spread

| | Constant | s.e. | # of deals | | H0 Dummy | | NOB |
|---|---|---|---|---|---|---|---|
| whole | 0.0225 *** | 8.81E-05 | -4.91E-06 *** | 1.82E-07 | 5.39E-07 | 4.60E-07 | 16454 |
| 1999 | 0.0238 *** | 1.71E-04 | -4.48E-06 *** | 2.93E-07 | 1.20E-06 ** | 7.20E-07 | 5322 |
| 2000 | 0.0215 *** | 1.31E-04 | -6.46E-06 *** | 3.23E-07 | -2.74E-07 | 8.11E-07 | 5590 |
| 2001 | 0.0233 *** | 1.56E-04 | -6.90E-06 *** | 3.47E-07 | -6.03E-07 | 8.88E-07 | 5542 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Table 4-2 Hour 0 Effect for Euro-USD trade

Panel A: Correlation between Number of Price change and Spread

| | Constant | s.e. | # of price change | s.e. | H0 Dummy | s.e. | NOB |
|---|---|---|---|---|---|---|---|
| whole | 1.81E-04 *** | 1.56E-06 | -6.97E-08 *** | 3.02E-09 | -1.56E-08 * | 1.12E-08 | 16449 |
| 1999 | 1.94E-04 *** | 2.73E-06 | -9.58E-08 *** | 5.54E-09 | -2.01E-08 | 1.83E-08 | 5321 |
| 2000 | 1.80E-04 *** | 2.88E-06 | -5.97E-08 *** | 5.24E-09 | -4.63E-08 ** | 2.11E-08 | 5587 |
| 2001 | 1.71E-04 *** | 2.48E-06 | -6.02E-08 *** | 4.92E-09 | 2.31E-08 | 1.85E-08 | 5541 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Panel B: Correlation between Number of Deals and Spread

| | Constant | s.e. | # of deals | | H0 Dummy | | NOB |
|---|---|---|---|---|---|---|---|
| whole | 1.74E-04 *** | 1.16E-06 | -4.77E-08 *** | 1.68E-09 | -6.15E-08 *** | 1.75E-08 | 16449 |
| 1999 | 1.81E-04 *** | 2.02E-06 | -6.09E-08 *** | 3.20E-09 | -6.99E-08 ** | 2.86E-08 | 5321 |
| 2000 | 1.76E-04 *** | 2.15E-06 | -4.32E-08 *** | 2.91E-09 | -1.09E-07 *** | 3.38E-08 | 5587 |
| 2001 | 1.67E-04 *** | 1.86E-06 | -4.25E-08 *** | 2.67E-09 | -5.57E-09 | 2.87E-08 | 5541 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Table 4-3: Monday Opening effect for USD-JPY trade

Panel A: Correlation between the Number of Price changes and spread.

| | Constant | s.e. | # of price change | | MonH0 Dummy | | NOB |
|---|---|---|---|---|---|---|---|
| whole | 0.0223 *** | 1.19E-04 | -3.30E-06 *** | 2.11E-07 | 7.81E-07 | 9.15E-07 | 16454 |
| 1999 | 0.0242 *** | 2.40E-04 | -4.26E-06 *** | 3.87E-07 | 1.27E-06 | 1.47E-06 | 5322 |
| 2000 | 0.0211 *** | 1.75E-04 | -3.79E-06 *** | 3.49E-07 | 1.42E-06 | 1.52E-06 | 5590 |
| 2001 | 0.0227 *** | 2.03E-04 | -3.78E-06 *** | 3.54E-07 | -7.56E-07 | 1.79E-06 | 5542 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Panel B: Correlation between Number of Deals and spread

| | Constant | s.e. | # ofdeals | s.e. | MonH0 Dummy | s.e. | NOB |
|---|---|---|---|---|---|---|---|
| whole | 0.0225 *** | 8.81E-05 | -4.90E-06 *** | 1.79E-07 | 2.12E-06 ** | 1.03E-06 | 16454 |
| 1999 | 0.0238 *** | 1.71E-04 | -4.41E-06 *** | 2.88E-07 | 2.05E-06 * | 1.56E-06 | 5322 |
| 2000 | 0.0216 *** | 1.31E-04 | -6.53E-06 *** | 3.20E-07 | 3.17E-06 ** | 1.77E-06 | 5590 |
| 2001 | 0.0233 *** | 1.56E-04 | -6.94E-06 *** | 3.43E-07 | 7.51E-08 | 2.23E-06 | 5542 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Table 4-4: Monday Opening effect for Euro-USD trade

Panel A: Correlation between the Number of Price changes and spread.

| | Constant | s.e. | # of price change | | MonH0 Dummy | | NOB |
|---|---|---|---|---|---|---|---|
| whole | 1.81E-04 *** | 1.54E-06 | -6.95E-08 *** | 3.01E-09 | -2.35E-08 | 2.54E-08 | 16449 |
| 1999 | 1.93E-04 *** | 2.72E-06 | -9.56E-08 *** | 5.54E-09 | -3.91E-09 | 4.07E-08 | 5321 |
| 2000 | 1.79E-04 *** | 2.84E-06 | -5.90E-08 *** | 5.23E-09 | -5.61E-08 | 4.84E-08 | 5587 |
| 2001 | 1.72E-04 *** | 2.45E-06 | -6.05E-08 *** | 4.92E-09 | -1.41E-08 | 4.28E-08 | 5541 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Panel B: Correlation between Number of Deals and spread

| | Constant | s.e. | # ofdeals | s.e. | MonH0 Dummy | s.e. | NOB |
|---|---|---|---|---|---|---|---|
| whole | 1.74E-04 *** | 1.14E-06 | -4.72E-08 *** | 1.67E-09 | -7.31E-08 ** | 4.07E-08 | 16449 |
| 1999 | 1.81E-04 *** | 2.00E-06 | -6.04E-08 *** | 3.19E-09 | -4.55E-08 | 6.64E-08 | 5321 |
| 2000 | 1.74E-04 *** | 2.11E-06 | -4.23E-08 *** | 2.90E-09 | -1.26E-07 * | 7.97E-08 | 5587 |
| 2001 | 1.67E-04 *** | 1.83E-06 | -4.25E-08 *** | 2.65E-09 | -5.82E-08 | 6.58E-08 | 5541 |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Table 5-1: London and New York markets Effects for USD-JPY pair

| | Whole period | | | 1999 | | | 2000 | | | 2001 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coefficient | | s.e. | Coefficient | | s.e. | Coefficient | | s.e. | Coefficient | | s.e. |
| Number of price change | | | | | | | | | | | | |
| LNOPEN | 173.85 | *** | 11.91 | 223.19 | *** | 22.96 | 124.06 | *** | 17.02 | 178.05 | *** | 19.65 |
| LNOPEN2 | 175.34 | *** | 11.91 | 205.98 | *** | 22.96 | 129.56 | *** | 17.02 | 193.42 | *** | 19.65 |
| NYOPEN | 170.64 | *** | 12.01 | 238.40 | *** | 23.14 | 146.61 | *** | 17.16 | 128.22 | *** | 19.82 |
| NYOPEN2 | 182.36 | *** | 12.74 | 247.34 | *** | 24.51 | 171.80 | *** | 18.20 | 128.57 | *** | 21.07 |
| NYOPEN3 | 210.08 | *** | 12.01 | 239.25 | *** | 23.14 | 203.55 | *** | 17.16 | 187.57 | *** | 19.82 |
| LNLUNCH | -72.63 | *** | 11.23 | -76.74 | *** | 21.68 | -93.88 | *** | 16.04 | -47.43 | *** | 18.49 |
| Number of Deals | | | | | | | | | | | | |
| | Whole period | | | 1999 | | | 2000 | | | 2001 | | |
| LNOPEN | 243.81 | *** | 14.79 | 392.85 | *** | 32.86 | 154.17 | *** | 18.76 | 194.10 | *** | 20.83 |
| LNOPEN2 | 225.78 | *** | 14.79 | 330.81 | *** | 32.86 | 148.57 | *** | 18.76 | 205.12 | *** | 20.83 |
| NYOPEN | 205.45 | *** | 14.91 | 343.16 | *** | 33.10 | 167.49 | *** | 18.91 | 111.30 | *** | 21.01 |
| NYOPEN2 | 236.80 | *** | 15.82 | 407.08 | *** | 35.07 | 202.84 | *** | 20.07 | 106.94 | *** | 22.33 |
| NYOPEN3 | 257.34 | *** | 14.91 | 381.94 | *** | 33.10 | 236.49 | *** | 18.91 | 158.84 | *** | 21.01 |
| LNLUNCH | -94.04 | *** | 13.94 | -118.24 | *** | 31.02 | -105.15 | *** | 17.68 | -59.11 | *** | 19.60 |
| Spread | | | | | | | | | | | | |
| | Whole period | | | 1999 | | | 2000 | | | 2001 | | |
| LNOPEN | -0.0005 | | 0.0004 | -0.0015 | ** | 0.0008 | -0.0002 | | 0.0006 | 0.0002 | | 0.0007 |
| LNOPEN2 | -0.0005 | * | 0.0004 | -0.0014 | ** | 0.0008 | -0.0003 | | 0.0006 | 0.0002 | | 0.0007 |
| NYOPEN | -0.0006 | * | 0.0004 | -0.0010 | | 0.0008 | -0.0006 | | 0.0006 | -0.0002 | | 0.0007 |
| NYOPEN2 | -0.0013 | *** | 0.0004 | -0.0024 | *** | 0.0008 | -0.0010 | ** | 0.0006 | -0.0007 | | 0.0007 |
| NYOPEN3 | -0.0014 | *** | 0.0004 | -0.0026 | *** | 0.0008 | -0.0011 | ** | 0.0006 | -0.0005 | | 0.0007 |
| LNLUNCH | 0.0024 | *** | 0.0004 | 0.0025 | *** | 0.0007 | 0.0020 | *** | 0.0005 | 0.0026 | *** | 0.0006 |
| NOB | 16454 | | | 5322 | | | 5590 | | | 5542 | | |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Table 5-2: London and New York markets Effects for Euro-USD pair

| | Whole period | | | 1999 | | | 2000 | | | 2001 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Coefficient | | s.e. | Coefficient | | s.e. | Coefficient | | s.e. | Coefficient | | s.e. |
| Number of price change | | | | | | | | | | | | |
| LNOPEN | 132.45 | *** | 9.40 | 118.05 | *** | 15.82 | 88.91 | *** | 15.99 | 190.25 | *** | 16.12 |
| LNOPEN2 | 192.02 | *** | 9.40 | 172.76 | *** | 15.82 | 148.63 | *** | 15.99 | 254.28 | *** | 16.12 |
| NYOPEN | 159.64 | *** | 9.48 | 124.68 | *** | 15.94 | 144.48 | *** | 16.12 | 209.52 | *** | 16.25 |
| NYOPEN2 | 144.00 | *** | 10.06 | 93.41 | *** | 16.88 | 134.06 | *** | 17.10 | 204.33 | *** | 17.28 |
| NYOPEN3 | 162.54 | *** | 9.48 | 133.90 | *** | 15.94 | 149.54 | *** | 16.12 | 204.49 | *** | 16.25 |
| LNLUNCH | -86.65 | *** | 8.86 | -104.27 | *** | 14.93 | -121.94 | *** | 15.07 | -33.42 | ** | 15.16 |
| Number of Deals | | | | | | | | | | | | |
| | Whole period | | | 1999 | | | 2000 | | | 2001 | | |
| LNOPEN | 362.30 | *** | 14.24 | 316.61 | *** | 23.76 | 300.50 | *** | 24.38 | 467.76 | *** | 24.23 |
| LNOPEN2 | 310.31 | *** | 14.24 | 286.57 | *** | 23.76 | 245.09 | *** | 24.38 | 398.53 | *** | 24.23 |
| NYOPEN | 347.04 | *** | 14.35 | 294.98 | *** | 23.94 | 370.94 | *** | 24.58 | 371.55 | *** | 24.44 |
| NYOPEN2 | 336.77 | *** | 15.23 | 278.06 | *** | 25.36 | 366.85 | *** | 26.08 | 362.24 | *** | 25.98 |
| NYOPEN3 | 361.20 | *** | 14.35 | 304.40 | *** | 23.94 | 367.54 | *** | 24.58 | 408.96 | *** | 24.44 |
| LNLUNCH | -212.91 | *** | 13.42 | -244.44 | *** | 22.43 | -265.59 | *** | 22.98 | -129.55 | *** | 22.80 |
| Spread | | | | | | | | | | | | |
| | Whole period | | | 1999 | | | 2000 | | | 2001 | | |
| LNOPEN | -0.00001 | * | 0.00001 | -0.00002 | ** | 0.00001 | 0.000000 | | 0.00001 | -0.00001 | | 0.00001 |
| LNOPEN2 | -0.00001 | * | 0.00001 | -0.00002 | ** | 0.00001 | -0.000001 | | 0.00001 | -0.000003 | | 0.00001 |
| NYOPEN | -0.000004 | | 0.00001 | -0.00001 | | 0.00001 | -0.000005 | | 0.00001 | 0.000004 | | 0.00001 |
| NYOPEN2 | 0.000002 | | 0.00001 | -0.000002 | | 0.00001 | 0.000002 | | 0.00001 | 0.00001 | | 0.00001 |
| NYOPEN3 | -0.000005 | | 0.00001 | -0.000001 | | 0.00001 | -0.000003 | | 0.00001 | -0.00001 | | 0.00001 |
| LNLUNCH | 0.00001 | | 0.00001 | 0.00001 | | 0.00001 | 0.00001 | | 0.00001 | 0.000001 | | 0.00001 |
| NOB | 16449 | | | 5321 | | | 5587 | | | 5541 | | |

*Note:* ***, ** and * indicate significance at the 1,5, and 10%, respectively.

Table 6 Price gap on Inter-regional Trade

| | Tokyo-London Overlap | | | | London-New York Overlap | | | |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | | s.e. | (nob) | Coefficient | | s.e. | (nob) |
| 1999 winter | 0.7486 | *** | 0.0799 | 106 | 0.7302 | *** | 0.0649 | 106 |
| 1999 summer | 0.9983 | *** | 0.0835 | 150 | 0.9614 | *** | 0.0719 | 150 |
| 2000 winter | 1.3792 | *** | 0.1252 | 108 | 1.0168 | *** | 0.0846 | 107 |
| 2000 summer | 1.3477 | *** | 0.1071 | 151 | 0.9506 | *** | 0.0766 | 151 |
| 2001 winter | 1.0618 | *** | 0.0974 | 107 | 1.1457 | *** | 0.0857 | 106 |
| 2001 summer | 1.3723 | *** | 0.1061 | 152 | 0.7143 | *** | 0.0679 | 152 |

Figure 2-1: Intraday Activities (USD-JPY), Winter 1999-2001

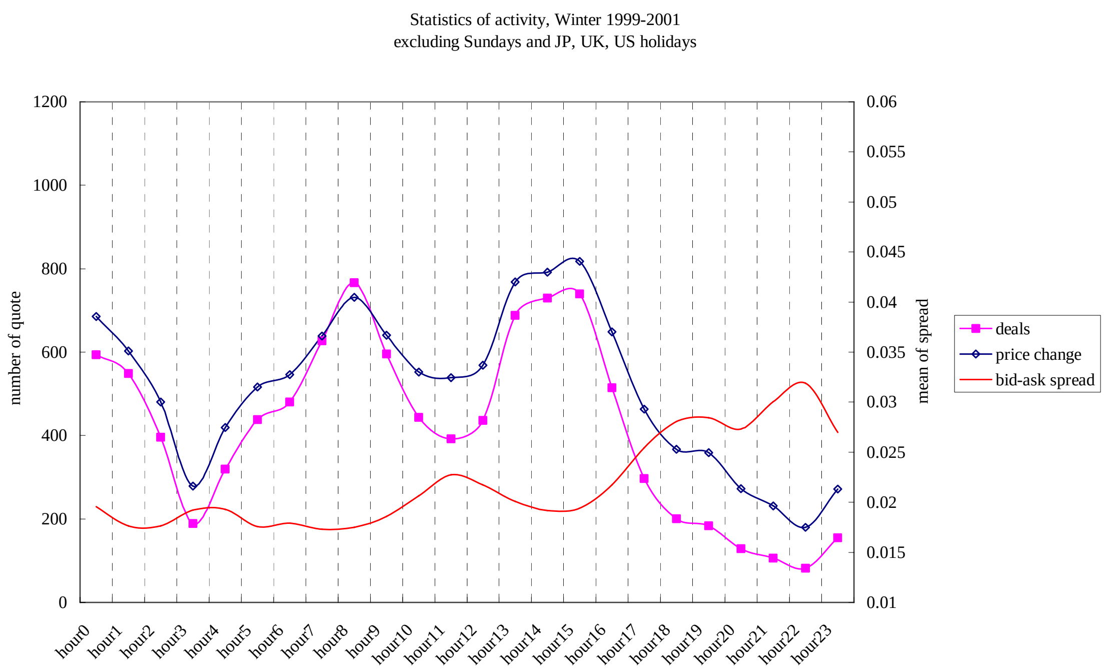


Figure 2-2: Intraday Activities (USD-JPY), Summer 1999-2001

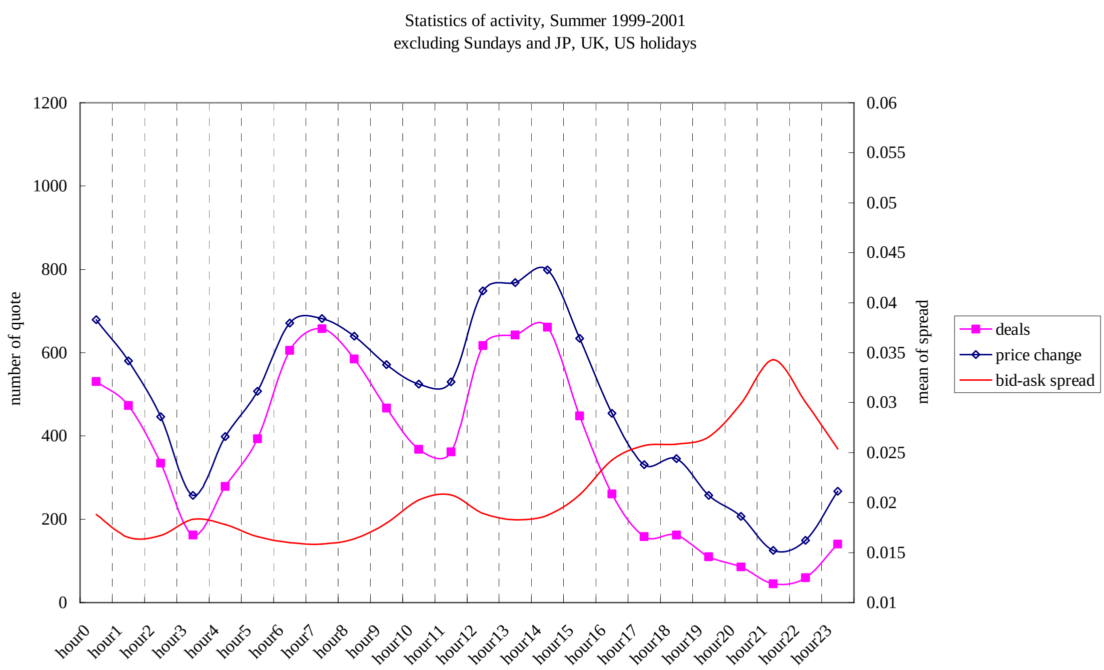

Figure 2-3: Intraday Activities (Euro-USD), Winter 1999-2001

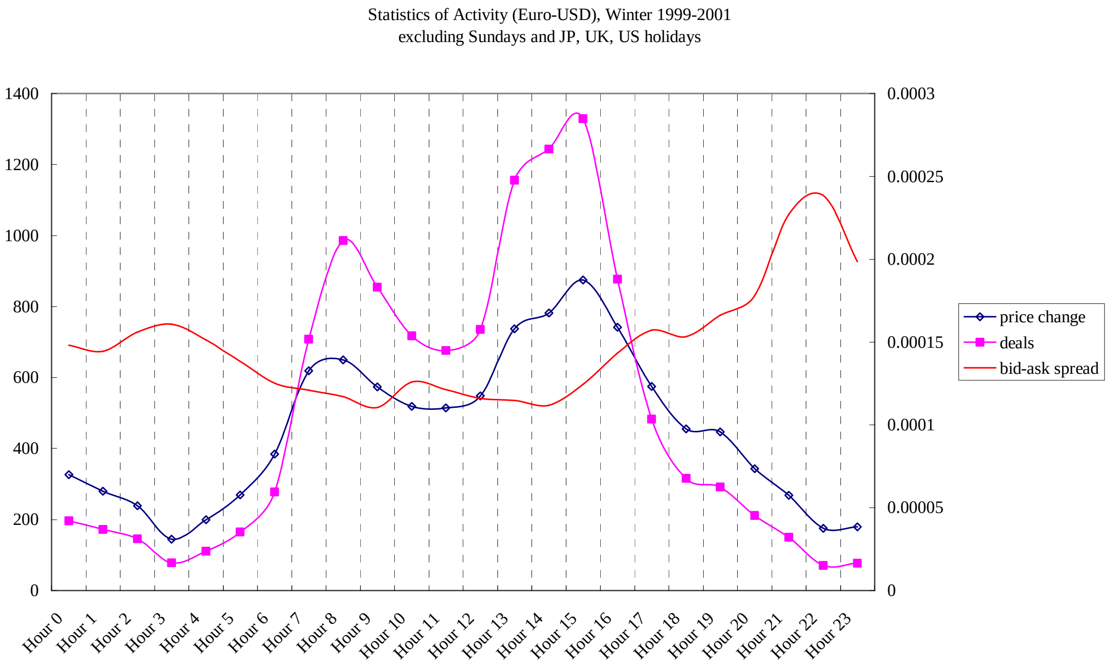


Figure 2-4: Intraday Activities (Euro-USD), Summer 1999-2001

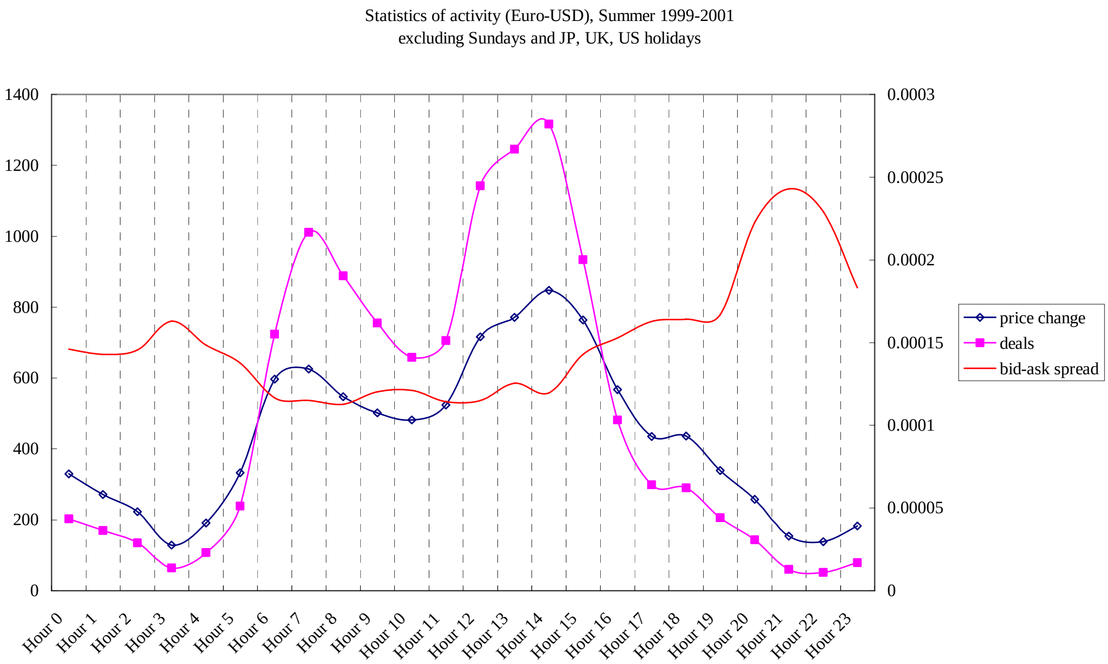

Figure 3-1: Relative volume (USD-JPY), Winter 1999-2001

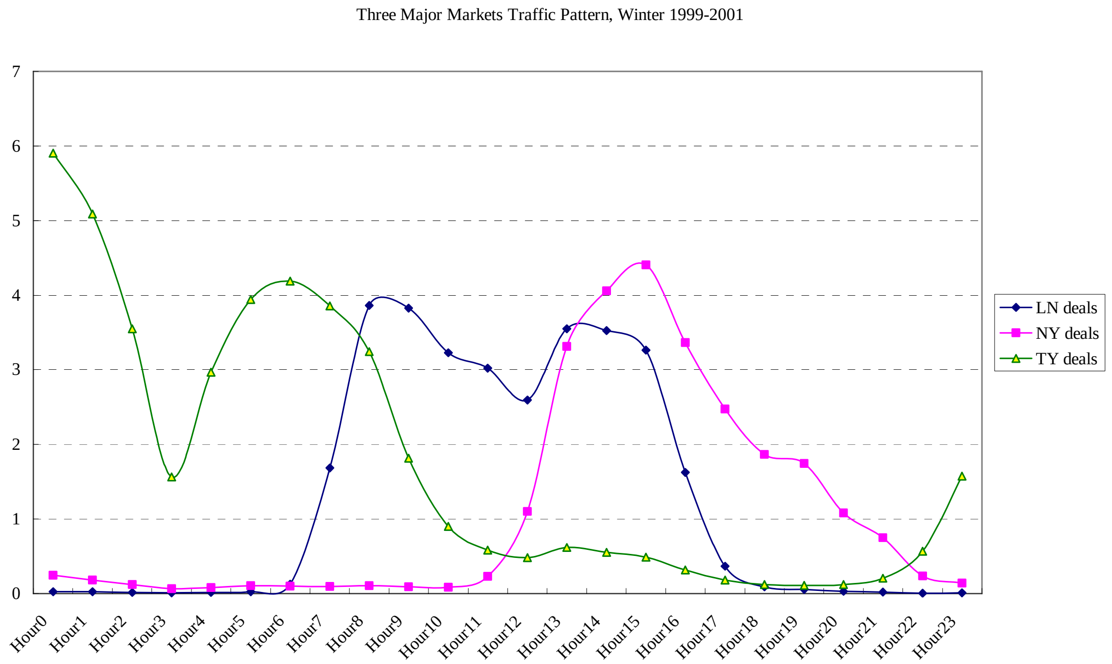


Figure 3-2: Relative volume (USD-JPY), Summer 1999-2001

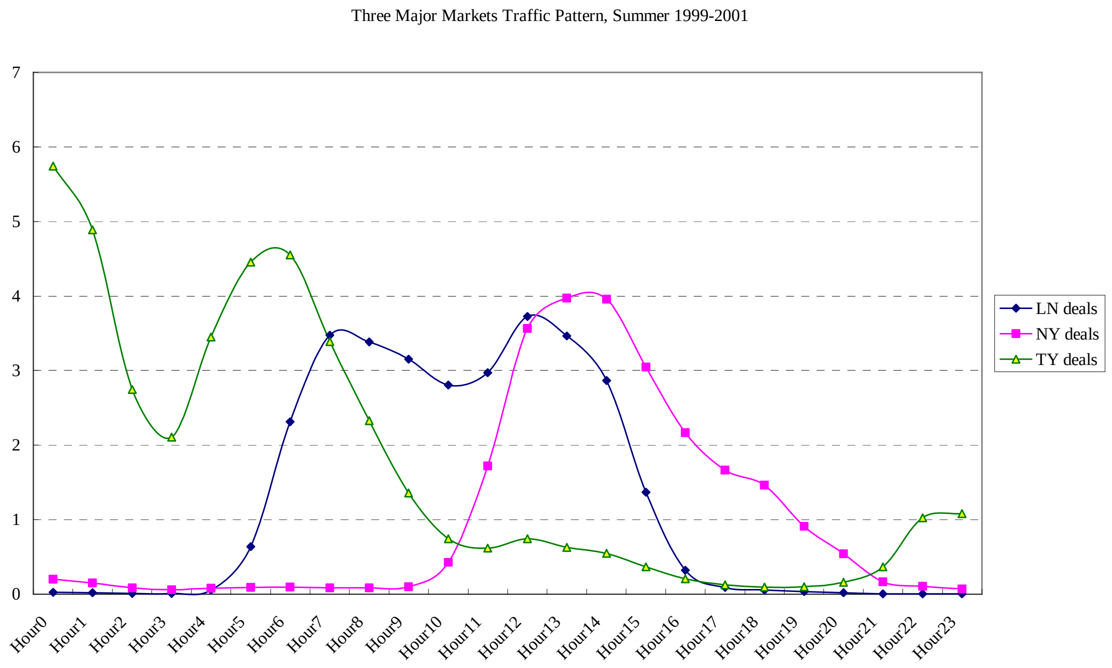

Figure 3-3: Relative volume (Euro-USD), winter 1999-2001

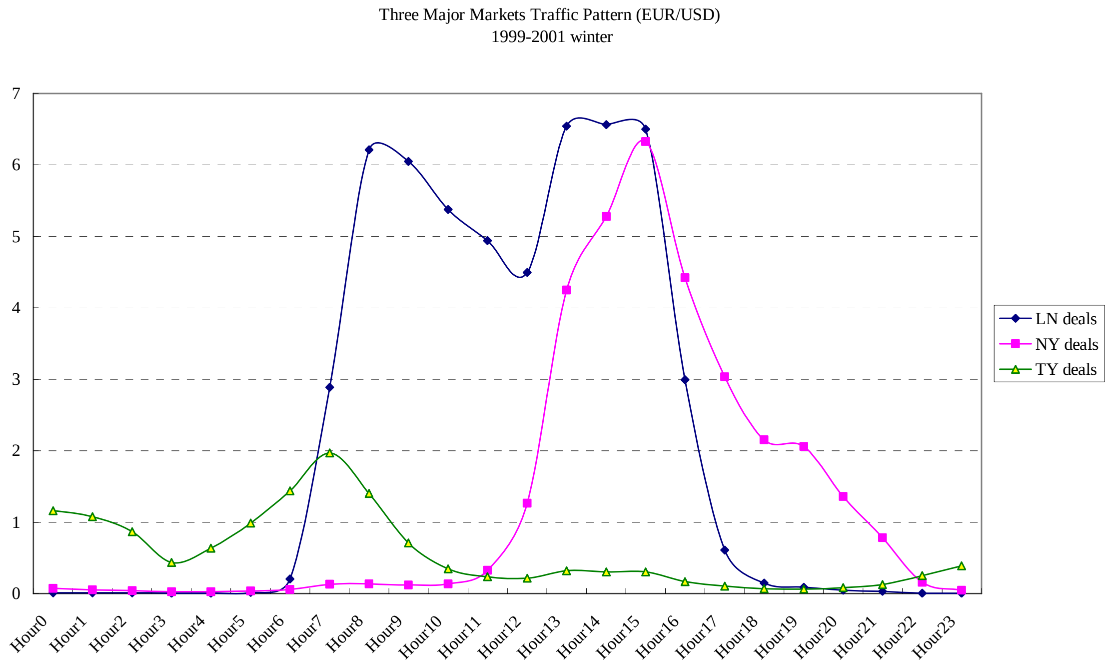


Figure 3-4: Relative volume(Euro-USD), summer 1999-2001

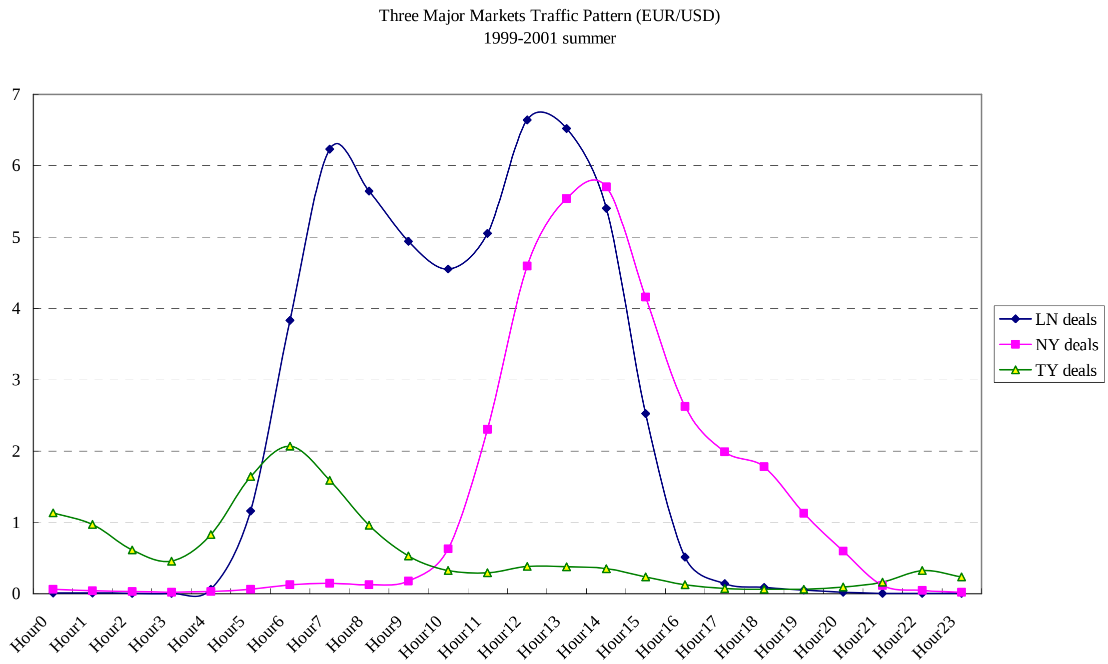

Figure 6-1,

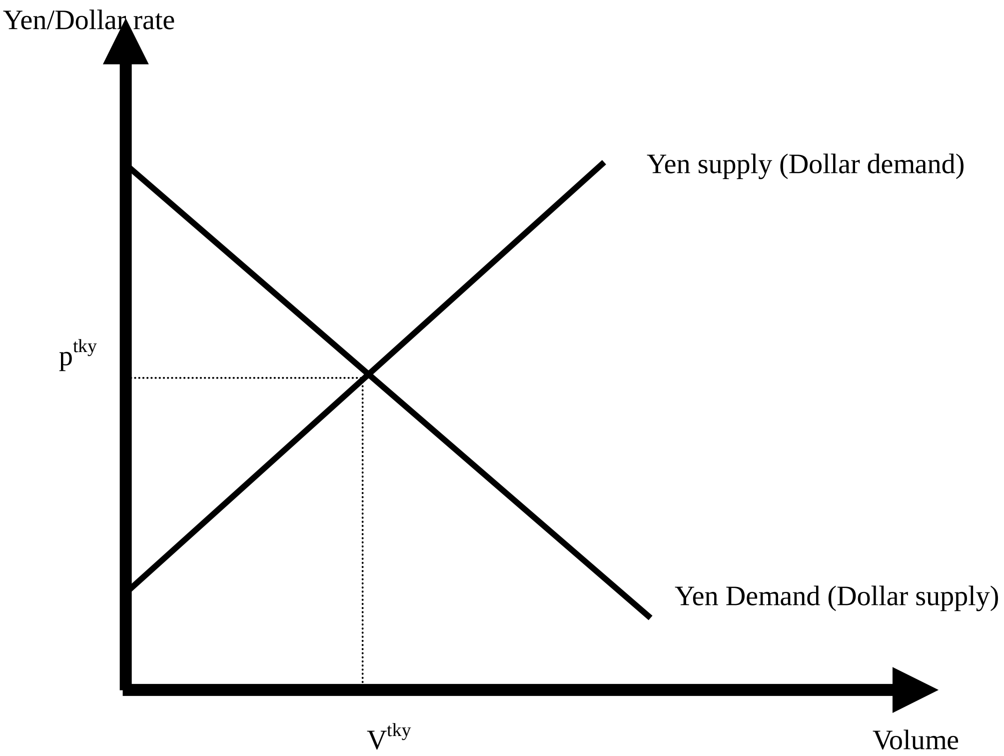


Figure 6.2

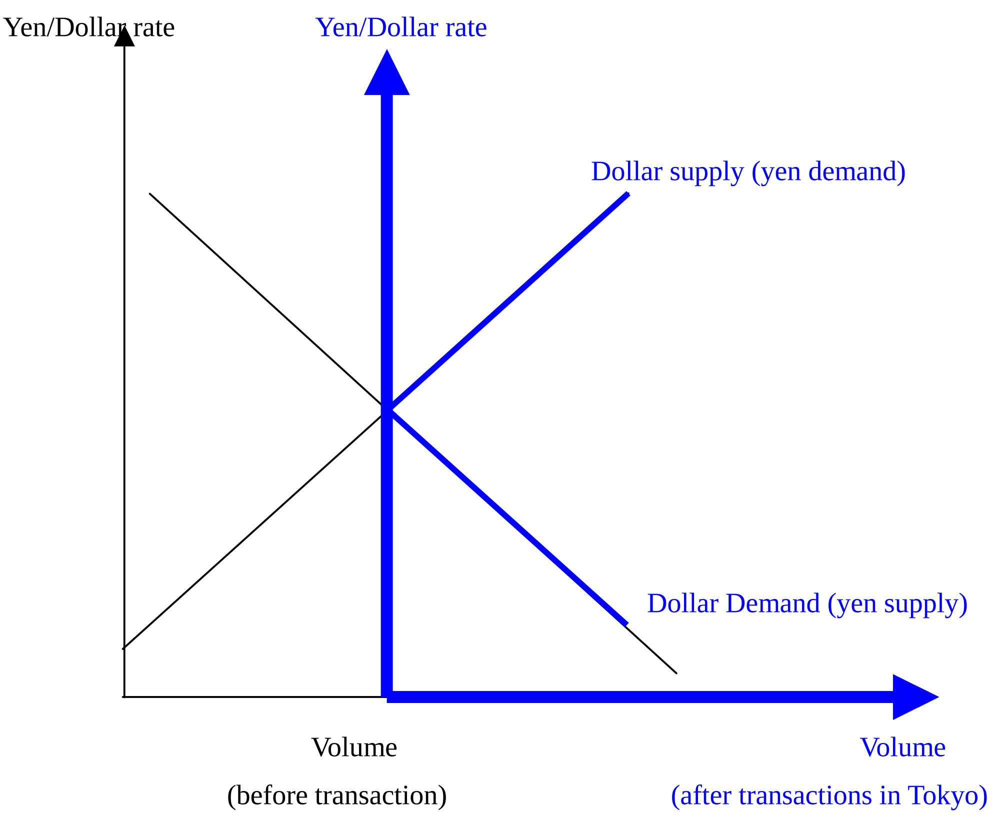

Figure 6.3

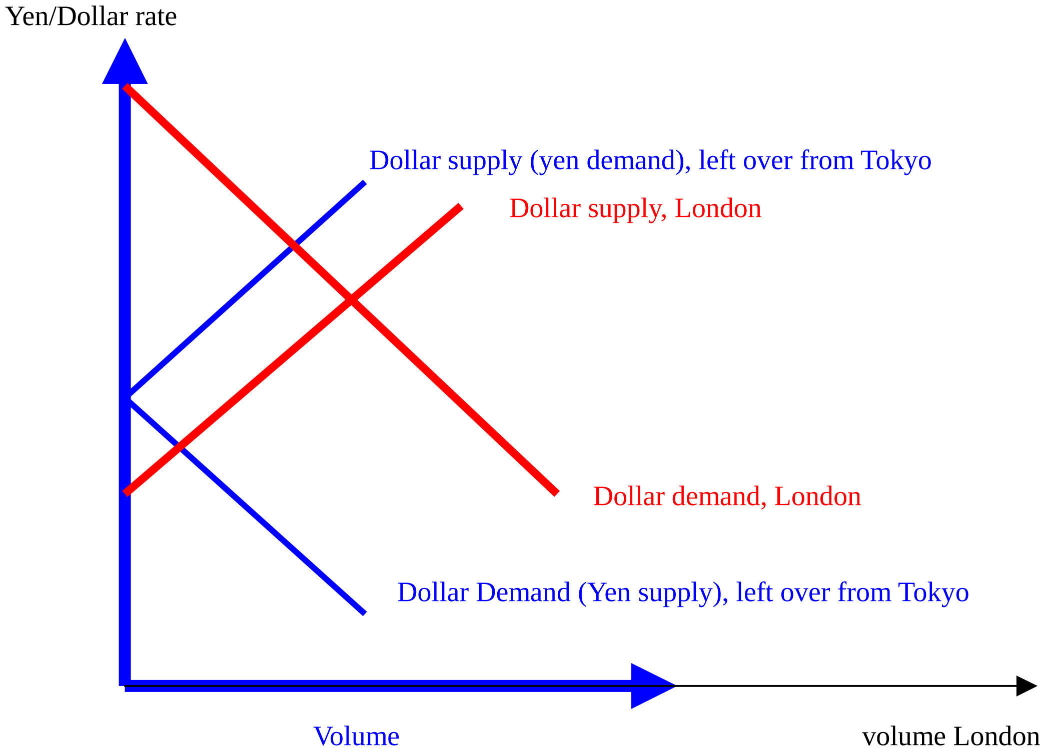


Figure 6.4