The Round-the-Clock Market for U.S. Treasury Securities

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The U.S. Treasury securities market is one of the most important financial markets in the world. Treasury bills, notes, and bonds are issued by the federal government in the primary market to finance its budget deficits and meet its short-term cash-management needs. In the secondary market, the Federal Reserve System conducts monetary policy through open market purchases and sales of Treasury securities. Because the securities are near-risk-free instruments, they also serve as a benchmark for pricing numerous other financial instruments. In addition, Treasury securities are used extensively for hedging, an application that improves the liquidity of other financial markets.

The Treasury market is also one of the world's largest and most liquid financial markets. Daily trading volume in the secondary market averages $125 billion.[1] Trading takes place overseas as well as in New York, resulting in a virtual round-the-clock market. Positions are bought and sold in seconds in an interdealer market, with trade sizes starting at $1 million for notes and bonds and $5 million for bills. Competition among dealers and interdealer brokers ensures narrow bid-ask spreads for most securities and minimal interdealer brokerage fees.

Despite the Treasury market's importance, size, and liquidity, there is little quantitative evidence on its intraday functioning. Intraday analysis of trading volume and the bid-ask spread is valuable, however, for ascertaining how market liquidity changes throughout the day. Such information is important to hedgers and other market participants who may need to trade at any moment and to investors who rely on a liquid Treasury market for the pricing of other securities or for tracking market sentiment. Intraday analysis of price volatility can also reveal when new information gets incorporated into prices and shed light on the determinants of Treasury prices. Finally, analysis of price behavior can be used to test the intraday efficiency of the Treasury market by determining, for example, whether overseas price changes reflect new information that is subsequently incorporated into prices in New York.

This article provides the first detailed intraday analysis of the round-the-clock market for U.S. Treasury securities. The analysis, covering the period from April 4 to August 19, 1994, uses comprehensive data on trading activity among the primary government securities dealers.[2] Trading volume, price volatility, and bid-ask spreads are

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examined for the three major trading locations—New York, London, and Tokyo—as well as for each half-hour interval of the global trading day. Price efficiency across trading locations is also tested by examining the relationship between price changes observed overseas and overnight price changes in New York.

The analysis reveals that trading volume and price volatility are highly concentrated in New York trading hours, with a daily peak between 8:30 a.m. and 9 a.m. and a smaller peak between 2:30 p.m. and 3 p.m. Bid-ask spreads are found to be wider overseas than in New York and wider in Tokyo than in London. Despite lower overseas liquidity, overseas price changes in U.S. Treasury securities emerge as unbiased predictors of overnight New York price changes.

THE STRUCTURE OF THE SECONDARY MARKET

Secondary trading in U.S. Treasury securities occurs primarily in an over-the-counter market rather than through an organized exchange.[3] Although 1,700 brokers and dealers trade in the secondary market, the 39 primary government securities dealers account for the majority of trading volume (Appendix A).[4] Primary dealers are firms with which the Federal Reserve Bank of New York interacts directly in the course of its open market operations. They include large diversified securities firms, money center banks, and specialized securities firms, and are foreign- as well as U.S.-owned. Over time, the number of primary dealers can change, as it did most recently with the addition of Dresdner Kleinwort Benson North America LLC.

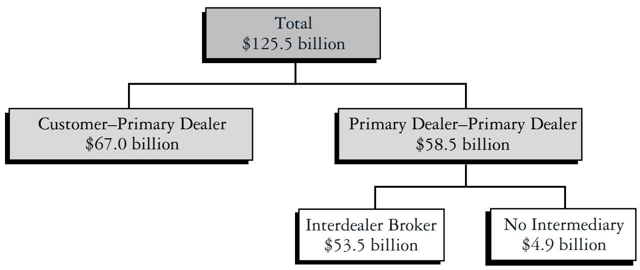
Among their responsibilities, primary dealers are expected to participate meaningfully at auction, make reasonably good markets in their trading relationships with the Federal Reserve Bank of New York's trading desk, and supply market information to the Fed. Formerly, primary dealers were also required to transact a certain level of trading volume with customers and thereby maintain a liquid secondary market for Treasury securities. Customers include nonprimary dealers, other financial institutions (such as banks, insurance companies, pension funds, and mutual funds), nonfinancial institutions, and individuals. Although trading with customers is no longer a requirement, primary dealers remain the predominant market makers in U.S. Treasury securities, buying and selling securities for their own account at their quoted bid and ask prices.

Primary dealers also trade among themselves, either directly or through interdealer brokers.[5] Interdealer brokers collect and post dealer quotes and execute trades between dealers, thereby facilitating information flows in the market while providing anonymity to the trading dealers. For the most part, interdealer brokers act only as agents. For their service, the brokers collect a fee from the trade initiator: typically $12.50 per $1 million on three-month bills (1/2 of a 100th of a point), $25.00 per $1 million on six-month and one-year bills (1/2 and 1/4 of a 100th of a point, respectively), and $39.06 per $1 million on notes and bonds (1/8 of a 32nd of a point).[6] The fees are negotiable, however, and can vary with volume.

The exchange of securities for funds typically occurs one business day after agreement on the trade. Settlement takes place either on the books of a depository institution or between depository institutions through the Federal Reserve's Fedwire securities transfer system. Clearance and settlement activity among primary dealers and other active market participants occurs primarily through the Government Securities Clearance Corporation (GSCC). The GSCC compares and nets member trades, thereby reducing the number of transactions through Fedwire and decreasing members' counterparty credit risk.

The level of trading activity among the various Treasury securities market participants is extremely high (see exhibit). Between April and August of 1994—the period examined in this article—trades involving primary dealers in the secondary market averaged about $125 billion per day.[7] More than half the volume involved primary dealer trades with customers, with the remainder involving trades between primary dealers. The vast majority of the $58.5 billion interdealer volume occurred through interdealer brokers. Activity data from these brokers form the basis of much of the analysis in this article (see box).

Daily Trading Volume of U.S. Treasury Securities
April to August 1994



Source: Author's calculations, based on data from the Board of Governors of the Federal Reserve System.

Notes: The exhibit shows the mean daily volume of secondary trading in the cash market as reported to the Federal Reserve by the primary dealers. Because the reporting data changed in July 1994, all figures are estimated based on full-year 1994 activity. The figures are also adjusted to eliminate double counting (trades between primary dealers are counted only once).

Trading Hours and Locations

Trading hours for U.S. Treasury securities have lengthened in line with the growth of the federal debt, the increase in foreign purchases of Treasuries, and the globalization of the financial services industry.[8] Trading now takes place twenty-two hours a day, five days a week (Chart 1).[9] The global trading day for U.S. Treasury securities begins at 8:30 a.m. local time in Tokyo, which is 7:30 p.m. New York daylight saving time (DST).[10] Trading continues until roughly 4 p.m. local time in Tokyo (3 a.m. New York), when trading passes to London, where it is 8 a.m.

Interdealer Broker Data

This article analyzes interdealer broker data obtained from GovPX, Inc., a joint venture of the primary dealers and several interdealer brokers set up under the guidance of the Public Securities Association (an industry trade group).[a] GovPX was formed in 1991 to increase public access to U.S. Treasury security prices (*Wall Street Journal* 1991).

GovPX consolidates and posts real-time quote and trade data from five of the six major interdealer brokers, which together account for about two-thirds of the interdealer broker market. Posted data include the best bids and offers, trade price and size, and aggregate volume traded for all Treasury bills, notes, and bonds. GovPX data are distributed electronically to the public through several on-line vendors such as Bloomberg, Knight-Ridder, and Reuters.

The data for this article include the quote and trade data for all "when-issued" and "on-the-run" securities in the cash market. When-issued securities are securities that have been announced for auction but not yet issued. On-the-run securities (also called active or current) are the most recently issued securities of a given maturity. Off-the-run (or inactive) securities, by contrast, are issued securities that are no longer active. Daily volume data obtained from GovPX reveal that 64 percent of interdealer trading is in on-the-run issues, 12 percent is in when-issued securities, and 24 percent is in off-the-run securities.

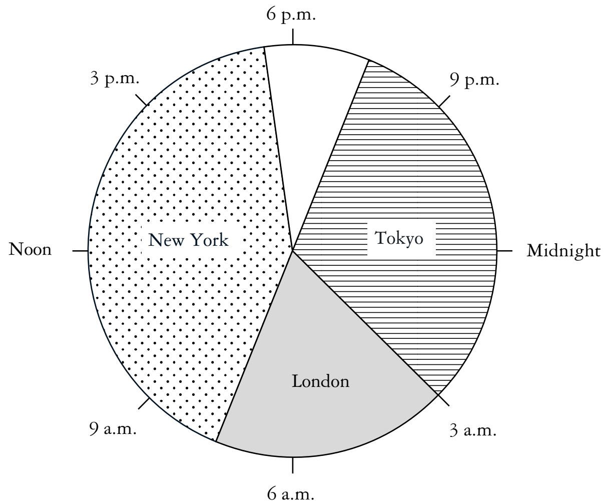
The period examined is April 4 to August 19, 1994. After holidays and missing data are excluded, ninety days from this twenty-week period are left for analysis.[b] An average of 2,702 trades a day were posted by GovPX in the sample period, along with 9,888 bid-ask spreads. For tractability purposes, the day is divided into half-hour periods. Trading locations are also assigned on the basis of the time of day a quote or trade was made (Chart 1). Appendix B discusses the data in more detail, including data cleaning and processing.

[a]The Public Securities Association has since changed its name to PSA, The Bond Market Trade Association.

[b]The market was closed in New York on three days, in Tokyo on four days, and in London on an additional two days during this period. One day was dropped because of missing data. End-of-day New York prices are used, when applicable, for the six overseas holidays to maintain as large a sample as possible.

Chart 1

TRADING TIMES FOR U.S. TREASURY SECURITIES



Notes: The chart shows the breakdown by location of interdealer trading over the global trading day. Crossover times are approximate because interdealer trading occurs over the counter and may be initiated from anywhere. All times are New York daylight saving time.

At about 12:30 p.m. local time in London, trading passes to New York, where it is 7:30 a.m. Trading continues in New York until 5:30 p.m.

Although it is convenient to think of trading occurring in three distinct geographic locations, a trade may originate anywhere. For example, business hours among the locations overlap somewhat: traders in London may continue to transact in their afternoon while morning activity picks up in New York. Traders may also transact from one location during another location's business hours. In fact, some primary dealers have traders working around the clock, but all from a single location (Stigum 1990, p. 471).

Regardless of location, the trading process for U.S. Treasuries is the same. The same securities are traded by the same dealers through the same interdealer brokers with the same brokerage fees. Trades agreed upon during overseas hours typically settle as New York trades do—one business day later in New York through the GSCC.[11]

TRADING ACTIVITY BY LOCATION

Although the U.S. Treasury securities market is an over-the-counter market with round-the-clock trading, more than 94 percent of that trading occurs in New York, on average, with less than 4 percent in London and less than 2 percent in Tokyo (Table 1).[12] While each location's share of daily volume varies across days, New York hours always comprise the vast majority (at least 87.5 percent) of daily trading.[13] This is not particularly surprising since Treasury securities are obligations of the U.S. government: most macroeconomic reports and policy changes of relevance to Treasury securities are announced during New York trading hours, and most owners of Treasury securities are U.S. institutions or individuals.[14]

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The share of U.S. Treasuries traded overseas, while small, can vary substantially. London reached its

Table 1

TRADING VOLUME OF U.S. TREASURY SECURITIES BY LOCATION

April 4 to August 19, 1994

	Tokyo	London	New York
Mean	1.84	3.50	94.66
Standard deviation	1.06	1.40	2.08
Minimum	0.14	0.55	87.53
Maximum	6.61	7.93	98.75

Source: Author's calculations, based on data from GovPX, Inc.

Note: The table reports the percentage distribution of daily interdealer trading volume by location for on-the-run and when-issued securities.

highest share of daily volume (7.9 percent) in the sample period on Friday, August 19, 1994. Tokyo reached its highest share (6.6 percent) on Friday, July 1, 1994. News reports indicate that dollar-yen movements drove overseas activity on both days. Overseas activity was also *relatively* high on July 1 because of a shortened New York session ahead of the July 4 weekend.

A more thorough examination of news stories on days when the overseas locations were particularly active or volatile suggests several reasons why U.S. Treasuries trade overseas:

- late afternoon New York activity spills over to the overseas trading locations (April 6);
- overnight activity in the foreign exchange market impacts the Treasury market (June 24);
- other overnight events occur—for example, comments are made by a government official during overseas hours (June 8);
- news is *released* during overnight hours—for instance, a U.S. newspaper article appears during overseas hours (June 21);
- overseas investors are active during overseas hours (August 17);
- central bank intervention occurs during overseas hours (May 10).

Overseas locations thus allow traders to adjust positions in response to overnight events and give foreign investors and institutions the opportunity to trade during their own business hours.

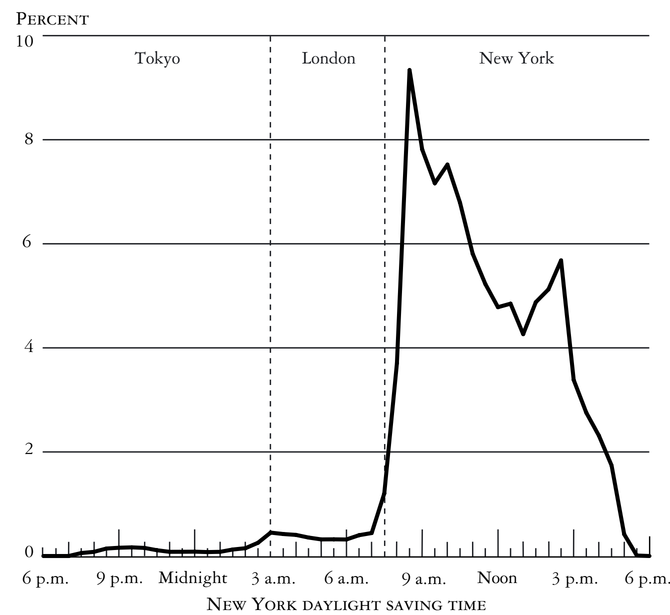
On a typical weekday, trading starts at 7:30 p.m. New York DST with relatively low volume throughout Tokyo hours (Chart 2). Volume picks up somewhat when London opens at 3 a.m. (New York DST) and remains fairly steady through London trading hours. Volume jumps higher in the first half hour of New York trading (7:30 a.m. to 8 a.m.), then spikes upward in the next half hour of trading. Volume reaches a daily peak between 8:30 a.m. and 9 a.m. Except for a small peak from 10 a.m. to 10:30 a.m., volume generally falls until the 1 p.m. to 1:30 p.m. interval. Volume rises again to a peak between 2:30 p.m. and 3 p.m., then quickly tapers off, with trading ending by 5:30 p.m. New York DST.

Overseas locations . . . allow traders to adjust positions in response to overnight events and give foreign investors and institutions the opportunity to trade during their own business hours.

The pattern of U.S. Treasuries trading between 8:30 a.m. and 3 p.m. parallels that of equity markets trading. Several studies of equity securities (such as Jain and Joh [1988] and McInish and Wood [1990]) have found

Chart 2

Trading Volume of U.S. Treasury Securities by Half Hour
April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Notes: The chart shows the mean half-hourly interdealer trading volume as a percentage of mean daily interdealer trading volume for on-the-run and when-issued securities. The times on the horizontal axis indicate the beginning of intervals (for example, 9 a.m. for 9 a.m. to 9:30 a.m.).

that daily volume peaks at the opening of trading, trails off during the day, then rises again at the close. Jain and Joh (1988) speculate that news since the prior close may drive morning volume, while afternoon volume may reflect the closing or hedging of open positions in preparation for the overnight hours.

In the U.S. Treasury securities market, the daily peak between 8:30 a.m. and 9 a.m. is at least partially explained by the important macroeconomic reports (including employment) released at 8:30 a.m. (Fleming and Remolona 1996). The opening of U.S. Treasury futures trading at 8:20 a.m. on the Chicago Board of Trade (CBT) is probably also a factor in this peak. The slight jump in volume between 10 a.m. and 10:30 a.m. may be a response to the 10 a.m. macroeconomic reports. The peak in volume between 2:30 p.m. and 3 p.m. coincides with the closing of U.S. Treasury futures trading at 3 p.m. There is little evidence that activity picks up during the Federal Reserve's customary intervention time (11:30 a.m. to 11:45 a.m.)[15] or during the announcement of Treasury auction results (typically 1:30 p.m. to 2 p.m.).

Trading Activity by Maturity

To this point, the volume statistics have been examined without regard to the particular issues making up the total volume. However, there is significant variation in trading activity by maturity for the most recently issued, or on-the-run, Treasury securities (Chart 3). The five-year note is the most actively traded security, accounting for more than one-fourth (26 percent) of on-the-run volume. The two- and ten-year notes are close behind, with shares of 21 percent and 17 percent, respectively, while the three-year note accounts for 8 percent.[16] The one-year bill accounts for 10 percent, the three-month bill for 7 percent, the six-month bill for 6 percent, and the occasionally issued cash-management bill for 1 percent.[17] The bellwether thirty-year bond accounts for less than 3 percent of total on-the-run volume.[18]

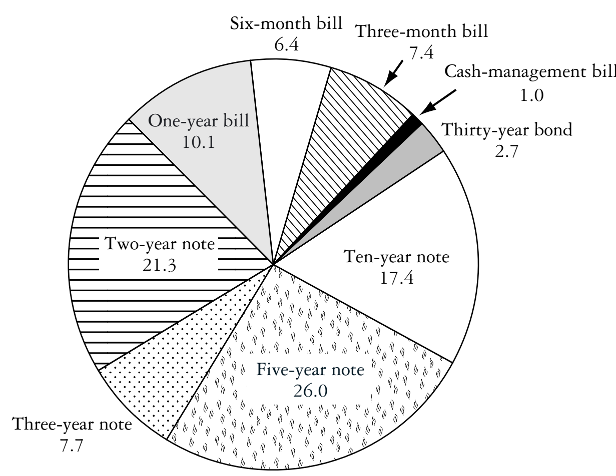
There is significant variation in trading activity by maturity for the most recently issued, or on-the-run, Treasury securities.

A breakdown of trading volume by maturity for each of the three locations reveals that the most significant difference across locations is the dearth of U.S. Treasury bill trading overseas.

The value of outstanding on-the-run securities by maturity cannot explain the level of trading by maturity. Auction sizes over the period examined were reasonably similar by maturity with three-month, six-month, five-year, ten-year, and thirty-year auctions running in the

Chart 3

Trading Volume of U.S. Treasury Securities by Maturity
April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Note: The chart shows the mean interdealer trading volume by maturity as a percentage of the mean total interdealer trading volume for on-the-run securities.

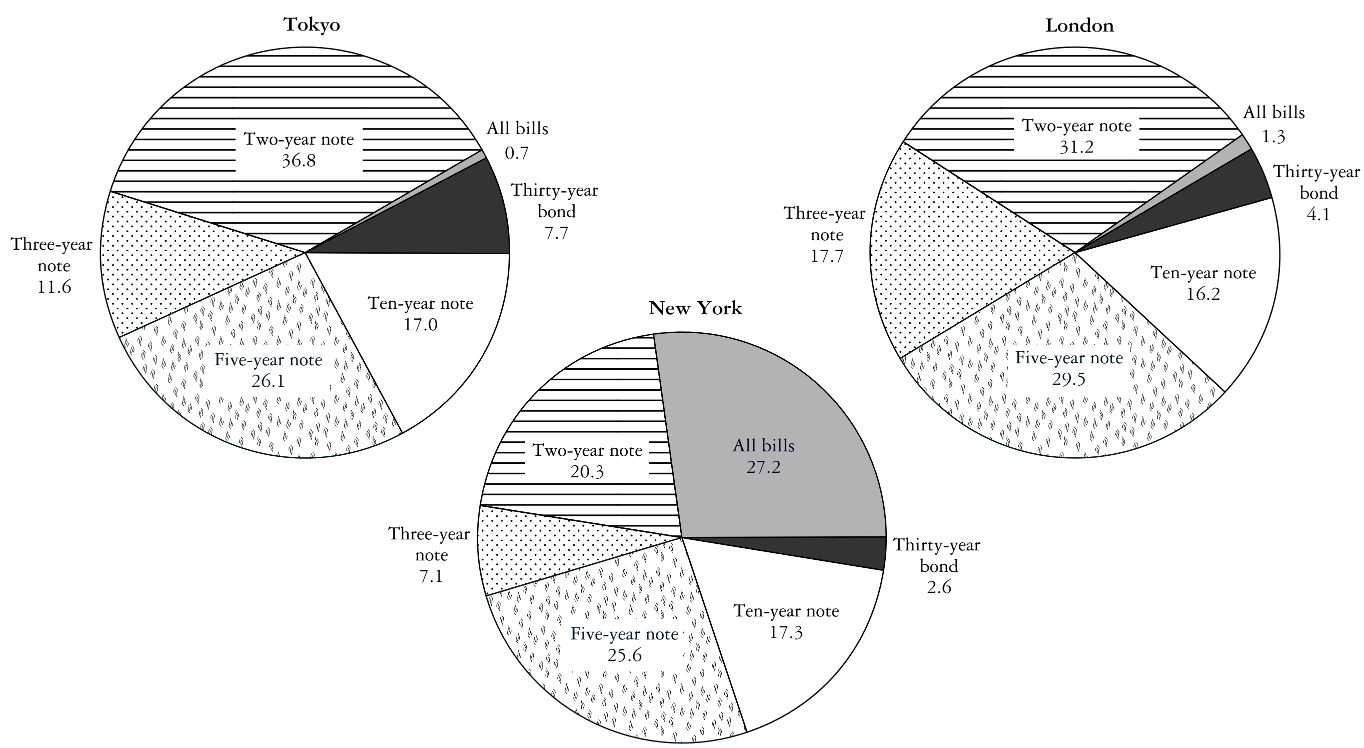
$11.0 billion to $12.5 billion range and one-, two-, and three-year auctions running in the $16.5 billion to $17.5 billion range. When the auctions that were reopenings of previously auctioned securities are taken into account, volume outstanding is actually higher for the relatively lightly traded three-month, six-month, and thirty-year securities.

A breakdown of trading volume by maturity for each of the three locations reveals that the most significant difference across locations is the dearth of U.S. Treasury bill trading overseas (Chart 4). Although Treasury bills (the one-year, six-month, three-month, and cash-management issues) represent 27 percent of trading in New York, they represent just 1 percent of trading in both London and Tokyo. On most days, in fact, not a single U.S. Treasury bill trade is brokered during the overseas hours. The distribution of overseas trading in Treasury notes is reasonably similar to that of New York, although the two-year note is the most frequently traded overseas (as opposed to the five-year note in New York) and heavier relative volume is evident in the three-year note. The thirty-year bond is traded more intensively overseas relative to total volume—particularly in Tokyo, where it represents nearly 8 percent of total volume.

A distributional breakdown of trading in each maturity by location (Table 2) confirms that bill volume is extremely low overseas. London trades less than 0.4 percent of the total daily volume for each bill (on average) and Tokyo trades less than 0.2 percent. In contrast, London trades 3 to 6 percent of daily volume for the two-, five-, ten-, and thirty-year securities, and more than 9 percent for the three-year note. Tokyo trades 2 to 4 percent of daily

Chart 4

Trading Volume of U.S. Treasury Securities by Location and Maturity
April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Note: The chart shows the mean interdealer trading volume by maturity as a percentage of the mean total interdealer trading volume in each location for on-the-run securities.

volume for each of the notes, and more than 6 percent for the thirty-year bond. Although volumes vary substantially across trading locations, a plot of daily volume by half hour (not shown) would reveal a very similar intraday pattern for each of the notes and bonds. Like bill trading, when-issued trading is low overseas and particularly so in Tokyo. Because of the limited overseas trading in bills and when-issued securities, the remainder of the analysis will treat on-the-run notes and bonds exclusively.

Price Volatility

Analyzing intraday price volatility leads to an improved understanding of the determinants of Treasury prices. As noted by French and Roll (1986), price volatility arises not only from public and private information that bears on prices but also from errors in pricing. The authors show, however, that pricing errors are only a small component of equity security volatility. This article contends that pricing errors are probably an even smaller component of Treasury security volatility because of the market's greater liquidity.

The vast majority of price discovery is found to occur during New York hours, with relatively little price discovery in Tokyo or London.

Table 2
TRADING VOLUME OF U.S. TREASURY SECURITIES BY MATURITY AND LOCATION
April 4 to August 19, 1994

Security Type	Tokyo	London	New York
Cash-management bill			
Mean	0.00	0.00	100.00
Standard deviation	0.00	0.00	0.00
Three-month bill			
Mean	0.15	0.03	99.82
Standard deviation	1.06	0.27	1.11
Six-month bill			
Mean	0.03	0.40	99.57
Standard deviation	0.25	1.69	1.70
One-year bill			
Mean	0.01	0.23	99.76
Standard deviation	0.12	1.00	1.01
Two-year note			
Mean	3.87	5.85	90.27
Standard deviation	3.60	3.60	5.85
Three-year note			
Mean	3.07	9.23	87.71
Standard deviation	2.67	6.33	7.27
Five-year note			
Mean	2.13	4.48	93.40
Standard deviation	1.41	1.87	2.70
Ten-year note			
Mean	2.07	3.64	94.29
Standard deviation	1.48	2.09	2.99
Thirty-year bond			
Mean	6.37	5.95	87.68
Standard deviation	5.99	4.72	8.81
When-issued bills			
Mean	0.02	0.28	99.70
Standard deviation	0.16	2.51	2.52
When-issued notes and bonds			
Mean	0.92	1.80	97.28
Standard deviation	1.29	2.16	2.75

Source: Author's calculations, based on data from GovPX, Inc.

Note: The table reports the percentage distribution of daily interdealer trading volume by location and security type for on-the-run and when-issued securities.

The examination of price volatility is therefore largely an examination of price movements caused by the arrival of information. The process by which Treasury prices adjust to incorporate new information is referred to in this article as *price discovery.*

Price volatility is examined across days, trading locations, and half-hour intervals of the day. Daily price volatility is calculated as the absolute value of the difference between the New York closing bid-ask midpoint and the previous day's New York closing bid-ask midpoint.[19] Price volatility for each trading location is calculated as the absolute value of the difference between that location's closing bid-ask midpoint and the closing bid-ask midpoint for the previous trading location in the round-the-clock market. Half-hour price volatility is calculated as the absolute value of the difference between the last bid-ask midpoint in that half hour and the last bid-ask midpoint in the previous half hour.[20] Volatility is not calculated for two different securities of similar maturity (there is a missing observation when the on-the-run security changes after an auction).

The vast majority of price discovery is found to occur during New York hours, with relatively little price discovery in Tokyo or London (Table 3). For example, the five-year note's expected price movement during Tokyo hours is 6/100ths of a point, during London hours 6/100ths of a point, and during New York hours 27/100ths of a point. By contrast, the daily expected price movement is 28/100ths of a point. For other securities as well, volatility is similar for Tokyo and London but much higher for New York.

Like the findings for trading volume, these results are not too surprising. Treasury securities are obligations of the U.S. government, and most macroeconomic reports and policy changes of relevance to the securities are announced during New York trading hours. Studies of the foreign exchange market have also found price volatility to be generally greater during New York trading hours, albeit to a lesser extent than found here (Ito and Roley 1987; Baillie and Bollerslev 1990).

An examination of price volatility by half-hour interval (Chart 5) reveals that volatility is fairly steady from the global trading day's opening in Tokyo (7:30 p.m. New York DST) through morning trading hours in London (7 a.m. New York). Volatility picks up in early afternoon London trading right before New York opens (7 a.m. to 7:30 a.m. New York). It then increases in the first hour of New York trading (7:30 a.m. to 8:30 a.m.) and spikes higher to reach its daily peak between 8:30 a.m. and 9 a.m. A general decline is observed until the 12:30 p.m. to 1 p.m. period, although there is a spike in the 10 a.m. to 10:30 a.m. period. Volatility then picks up again, reaches a peak between 2:30 p.m. and 3 p.m., and falls off quickly after 3 p.m. to levels comparable to those seen in the overseas hours. The intraday volatility pattern is similar across maturities.

In their study of intraday price volatility in the CBT's Treasury bond futures market, Ederington and Lee (1993) find that volatility peaks between 8:30 a.m. and 8:35 a.m. and is relatively level the rest of the trading day (the trading day runs from 8:20 a.m. to 3 p.m.). The authors observe, however, that price volatility shows no increase between 8:30 a.m. and 8:35 a.m. on days when no 8:30 a.m. macroeconomic announcements are made. These

Table 3

Price Volatility of U.S. Treasury Securities

April 4 to August 19, 1994

Security Type	Daily	Tokyo	London	New York
Two-year note				
Mean	10.68	2.91	2.12	9.94
Standard deviation	9.91	2.61	2.00	9.39
Three-year note				
Mean	16.60	3.91	3.38	15.61
Standard deviation	13.64	3.78	3.45	12.99
Five-year note				
Mean	28.08	6.10	5.69	26.63
Standard deviation	23.43	5.55	5.93	22.19
Ten-year note				
Mean	43.40	8.00	8.73	43.10
Standard deviation	37.22	8.30	8.66	35.93
Thirty-year bond				
Mean	58.28	11.35	10.32	56.53
Standard deviation	50.45	11.33	11.93	48.62

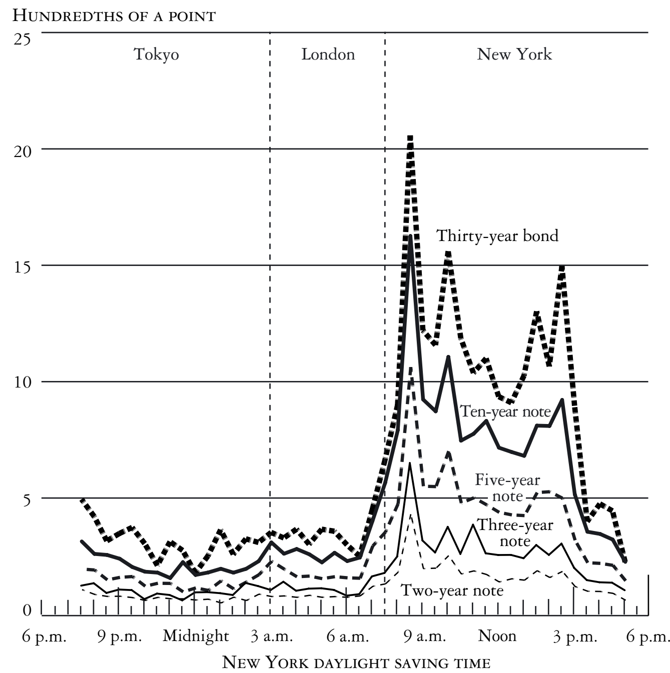
Source: Author's calculations, based on data from GovPX, Inc.

Notes: The table reports price volatility for on-the-run notes and bonds. Values are in hundredths of a point. Daily price volatility is calculated as the absolute value of the difference between the New York closing bid-ask midpoint and the previous day's New York closing bid-ask midpoint. Price volatility for each trading location is calculated as the absolute value of the difference between that location's closing bid-ask midpoint and the closing bid-ask midpoint for the previous trading location in the round-the-clock market.

Chart 5

Price Volatility of U.S. Treasury Securities by Half Hour

April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Notes: The chart shows the mean half-hourly price volatility for on-the-run notes and bonds. Volatility is calculated as the absolute value of the difference between the last bid-ask midpoint in that half hour and the last bid-ask midpoint in the previous half hour. For the 7:30 p.m. to 8 p.m. interval, the previous interval is considered 5 p.m. to 5:30 p.m. The times on the horizontal axis indicate the beginning of intervals (for example, 9 a.m. for 9 a.m. to 9:30 a.m.).

findings give strong support to the hypothesis that the 8:30 a.m. to 9 a.m. volatility in the cash market is driven by these announcements.[21]

The intraday pattern of price volatility has also been studied for equity and foreign exchange markets. Equity market studies (such as Wood, McInish, and Ord [1985] and Harris [1986]) find volatility peaking at the markets' opening, falling through the day, and rising somewhat at the end of trading. Again, we see a similar pattern for U.S. Treasury securities if we limit our examination to the 8:30 a.m. to 3 p.m. period. Outside of this period, price volatility is relatively low.

By contrast, the intraday volatility pattern in the foreign exchange market is markedly different. Although price volatility does peak in the morning in New York, the second most notable peak is seen in the morning in Europe and no volatility peak occurs in the New York afternoon (Baillie and Bollerslev 1990; Andersen and Bollerslev forthcoming). Although there is no official closing time for the U.S. Treasury securities market, the market behaves in some ways as if there were one, apparently because of the fixed trading hours of Treasury futures and the predominance of U.S. news and investors in determining prices.

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The similarities in the Treasury market between intraday price volatility (Chart 5) and intraday volumes (Chart 2) are striking. Both peak between 8:30 a.m. and 9 a.m., a period encompassing the 8:30 a.m. macroeconomic announcements and following, by just ten minutes, the opening of CBT futures trading. Both peak again between 2:30 p.m. and 3 p.m., the last half hour of CBT futures trading. Both show small peaks in the 10 a.m. to 10:30 a.m. period, when less significant macroeconomic announcements are made. Volatility seems to jump slightly in periods of Fed intervention (then 11:30 a.m. to 11:45 a.m.) and when auction announcements are made (typically 1:30 p.m. to 2 p.m.), but these movements are secondary.

The relationship between trading volume and price changes has also been studied extensively in other financial markets.[22] These studies consistently find trading volume and price volatility positively correlated for a variety of trading intervals. Most models attribute this relationship to information differences or differences of opinion among traders. New information or opinions become incorporated in prices through trading, leading to the positive volume-volatility relationship.

The volume-volatility relationship for U.S. Treasury securities is depicted in Chart 6. The five-year note's trading volume is plotted against price volatility (as calculated in Chart 5) for every half-hour interval in the sample period.[23] The upward slope of the regression lines demonstrates a positive relationship between volume and price volatility. A positive relationship is also indicated by the positive correlation coefficients (.57 for all trading locations combined, .24 for Tokyo, .22 for London, and .51 for New York), all of which are significant at the .01 level. The same positive correlation between trading volume and price volatility documented in other financial markets holds for the U.S. Treasury market.

BID-ASK SPREADS

U.S. Treasury investors who may need to trade at any moment or who rely on the market for pricing other instruments or gauging market sentiment are concerned with market liquidity. The bid-ask spread, which measures a major cost of transacting in a security, is an important indicator of market liquidity. The spread is defined as the difference between the highest price a prospective buyer is willing to pay for a given security (the bid) and the lowest price a prospective seller is willing to accept (the ask, or the offer). In looking across days, trading locations, and half-hour intervals, this article calculates spreads as the mean difference between the bid and the offer price for all bid-ask quotes posted.[24]

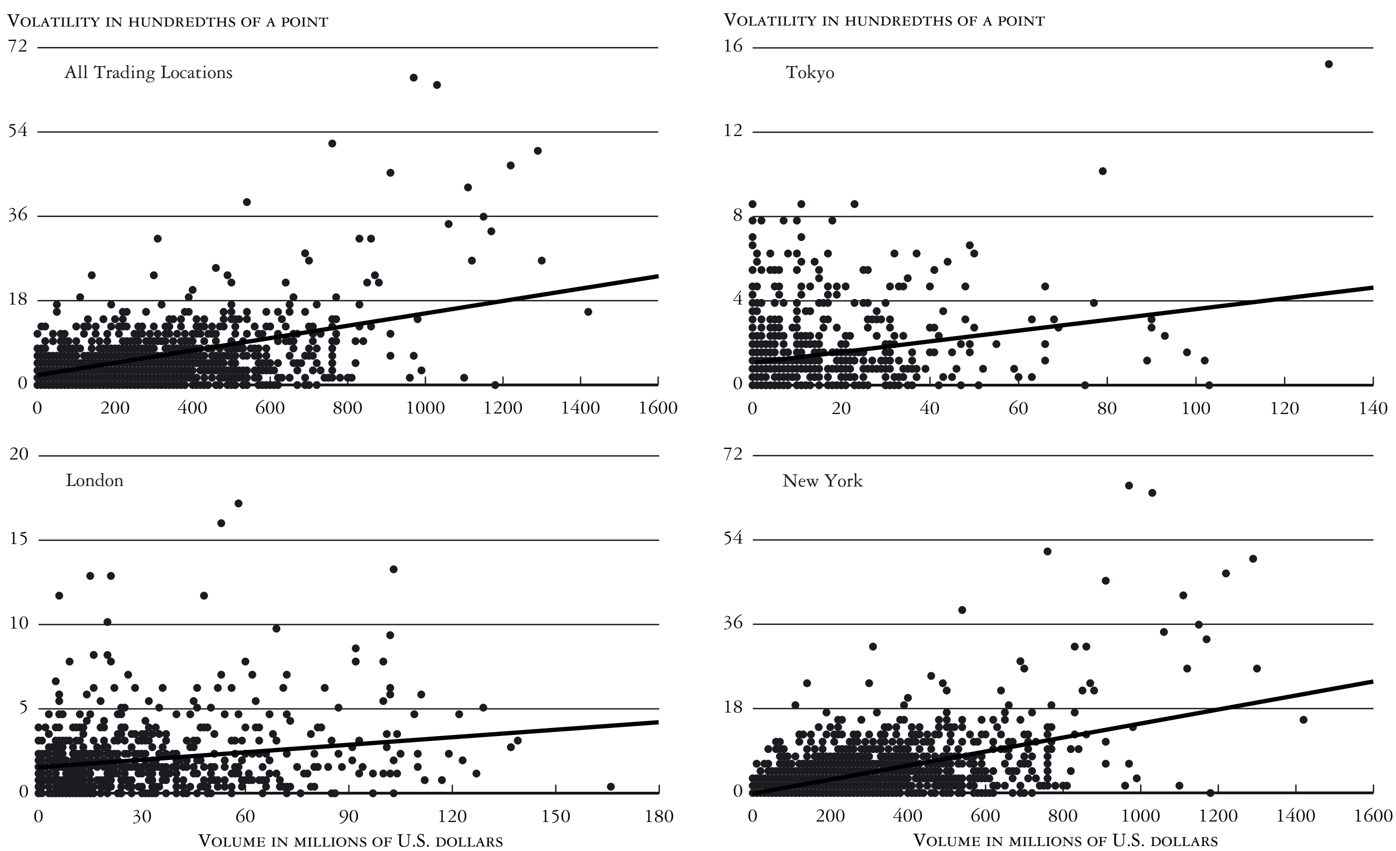
Four components of the bid-ask spread have been identified in the academic literature: asymmetric information, inventory carrying, market power, and order processing.[25] Asymmetric information compensates the market maker for exposure to better informed traders; inventory carrying accounts for the market maker's risk in holding a security; market power is that part of the spread attributable to imperfect competition among market makers; order processing allows for the market maker's direct costs of executing a trade.

Treasury market bid-ask spreads are extremely narrow and increase with maturity (Table 4). The daily spread averages 0.8/100ths of a point for the two-year security, 1.7/100ths for the three-year, 1.5/100ths for the five-year, 2.5/100ths for the ten-year, and 6.3/100ths for the thirty-year.[26] The increase in spread with maturity is not surprising given the positive relationship between price volatility and maturity (Table 3).[27] The higher spread on more volatile securities compensates the market

Treasury market bid-ask spreads are extremely narrow and increase with maturity.

Chart 6

Correlation of Trading Volume and Price Volatility for Five-Year U.S. Treasury Note
April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Note: The chart plots half-hourly price volatility against GovPX trading volume for the on-the-run U.S. Treasury note for all trading locations and by location.

maker for increased asymmetric information and inventory-carrying costs. The exception to this pattern—the five-year note, which has a lower spread than the three-year note—is likely attributable to the greater volume transacted in the five-year note (Chart 3). Higher volume in a security leads to economies of scale in order processing and is probably associated with greater market maker competition.

Bid-ask spreads in the U.S. Treasury market are comparable to those in the foreign exchange market but significantly lower than those in the equity markets. Bessembinder (1994) finds interbank bid-ask spreads of 0.064 percent for dollar-yen transactions and 0.062 percent for dollar-pound transactions—roughly the size of the spread on a thirty-year Treasury bond. Mean equity market spreads are found to vary from 1.4 to 3.1 percent (Amihud and Mendelson 1986; Stoll 1989; Laux 1993; Affleck-Graves, Hegde, and Miller 1994), a range roughly 50 to 200 times greater than that for on-the-run U.S. Treasury securities. The substantially lower bid-ask spreads in the Treasury market probably reflect lower asymmetric information costs, lower order-processing costs, and lower market-power costs. Market making for U.S. Treasuries is extremely competitive, with a high number of trades, large trade sizes, and limited private information.

New York spreads are lower than overseas spreads for every U.S. Treasury note, and London spreads are narrower than those in Tokyo. For example, the five-year note's spread is 1.5/100ths of a point in New York, 2.0/100ths in London, and 2.5/100ths in Tokyo. The New York differences from Tokyo are statistically significant (at the .01 level) for every note, and the New York differences from London are statistically significant (at the .01 level) for the two-, five-, and ten-year notes. The London-Tokyo differences are statistically significant for the two- and three-year notes (at the .01 level) and to a lesser extent for the five-year note (at the .05 level).

Bid-ask spreads in the U.S. Treasury market are comparable to those in the foreign exchange market but significantly lower than those in the equity markets.

Table 4
BID-ASK SPREADS ON U.S. TREASURY SECURITIES
April 4 to August 19, 1994

Security Type	All Locations	Tokyo	London	New York
Two-year note				
Mean	0.83	1.37	1.12**	0.78 ** ##
Standard deviation	0.14	0.58	0.38	0.15
Three-year note				
Mean	1.68	2.47	1.79**	1.65**
Standard deviation	0.30	1.06	0.77	0.31
Five-year note				
Mean	1.53	2.48	2.04 *	1.47 ** ##
Standard deviation	0.23	1.90	0.59	0.24
Ten-year note				
Mean	2.50	3.83	3.73	2.39 ** ##
Standard deviation	0.36	1.21	1.13	0.38
Thirty-year bond				
Mean	6.30	5.93	6.27	6.36
Standard deviation	1.11	2.12	2.86	1.15

Source: Author's calculations, based on data from GovPX, Inc.

Notes: The table reports interdealer bid-ask spreads for on-the-run notes and bonds. Values are in hundredths of a point. Spreads are calculated daily as the mean difference between the bid and the offer for all bid-ask quotes posted during that location's (or during all locations') trading hours.

* Significantly different from Tokyo at the .05 level based on two-sided t-test.

** Significantly different from Tokyo at the .01 level based on two-sided t-test

\# Significantly different from London at the .05 level based on two-sided t-test.

Significantly different from London at the .01 level based on two-sided t-test.

Spreads are similar across trading locations for the thirty-year bond. The mean spread is 6.4/100ths of a point in New York, 6.3/100ths in London, and 5.9/100ths in Tokyo. However, two cautions regarding the spreads are in order: First, spreads are often not posted during the overseas hours, particularly in Tokyo.[28] Second, the spreads give no indication of the associated quantities bid or offered, which may be lower in the overseas locations (but are not part of this study's data set).[29] Cautions notwithstanding, the higher relative volume of the thirty-year bond in Tokyo might be expected to result in smaller spread differences. Another factor may be the CBT's evening and overnight hours in the futures market—a market dominated by the thirty-year bond.

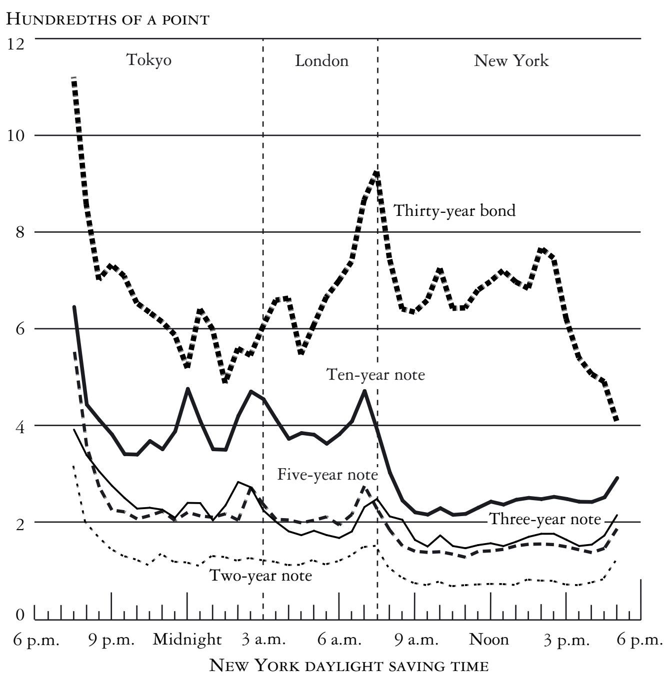
Examining bid-ask spreads by half-hour intervals, this article finds that the general pattern exhibited by the three-, five-, and ten-year notes (and to a lesser extent the two-year note) is of a triple "u" shape (Chart 7). The bid-ask spread begins at its daily high with the start of trading in Tokyo (7:30 p.m. New York DST). The spread drops quickly, levels out, and rises toward the end of trading in Tokyo (2 a.m. to 3 a.m. New York). The spread declines from this early morning peak as London trading gets under way, then rises again to a peak when trading passes to New York (7 a.m. to 8 a.m.). The spread then falls again, remains roughly level throughout the late morning and early afternoon, and rises in the late afternoon as trading drops off (4:30 p.m. to 5:30 p.m.).

This pattern is quite different from that found in the foreign exchange market, but similar in some ways to that in the equity markets. Bollerslev and Domowitz (1993) find that the deutsche mark–dollar spread peaks during the Far Eastern lunch break and reaches a low during morning trading in Europe. U.S. equity market studies (such as McInish and Wood [1992] and Brock and Kleidon [1992]) have found that bid-ask spreads are highest at the markets' opening, fall through the day, and rise again at the end of trading. U.S. Treasury notes follow the same pattern in New York, but also seem to replicate it overseas. The result is the triple-u-shaped pattern of Chart 7.

Chart 7

Bid-Ask Spreads on U.S. Treasury Securities by Half Hour

April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Notes: The chart shows the mean half-hourly interdealer bid-ask spread for on-the-run notes and bonds. Spreads are calculated daily as the mean difference between the bid and the offer for all bid-ask quotes posted during that half hour. The times on the horizontal axis indicate the beginning of intervals (for example, 9 a.m. for 9 a.m. to 9:30 a.m.).

The pattern for the thirty-year bond is somewhat different. Like the note spreads, the thirty-year bond

Examining bid-ask spreads by half-hour intervals, this article finds that the general pattern exhibited by the three-, five-, and ten-year notes (and to a lesser extent the two-year note) is of a triple "u" shape.

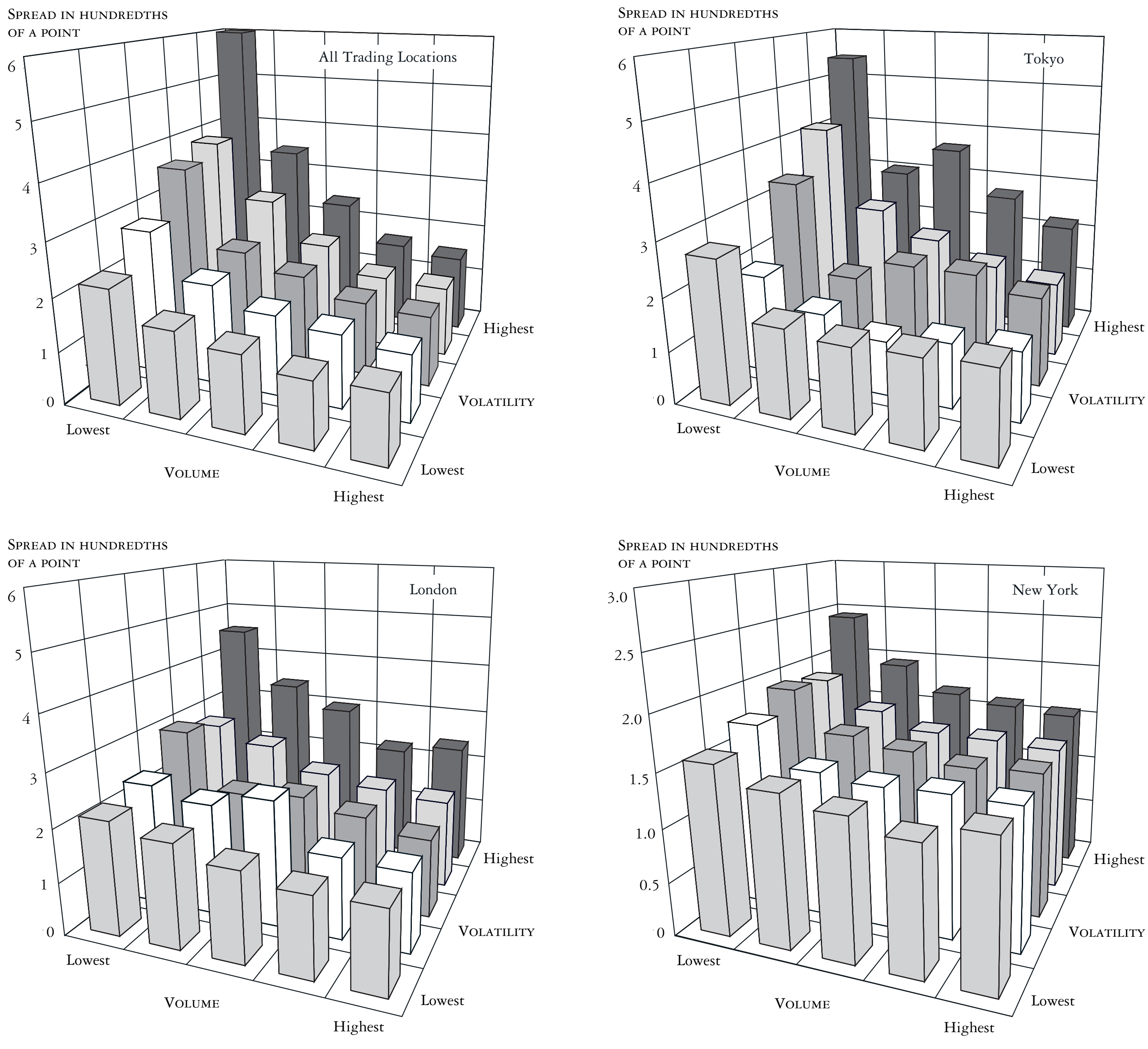
spread peaks at the opening in Tokyo and also peaks in the morning, when New York opens. Unlike the note spreads, however, the bond spread does not peak at the Tokyo close. More striking is the afternoon behavior of the bond spread in New York: it peaks between 1:30 p.m. and 2 p.m., then declines during the rest of the afternoon. The CBT futures market's 3 p.m. closing may help explain this pattern. Note, too, that the thirty-year bond is the only security examined for which a substantial number of observations are missing in the late afternoon of New York.[30]

Numerous studies have related bid-ask spreads to trading activity and price volatility for a variety of financial markets.[31] These studies generally find a negative relationship between volume and bid-ask spreads and a positive relationship between price volatility and bid-ask spreads. The volume-spread relationship probably reflects decreasing order-processing costs, decreasing inventory-carrying costs, and increasing market maker competition as volume increases. The volatility-spread relationship likely reflects increasing inventory-carrying costs and increasing asymmetric information costs as volatility increases.

This relationship for the U.S. Treasury securities market is illustrated in Chart 8. Half-hour price volatility and trading volume are grouped into quintiles as defined for the relevant trading location. The plots show the mean of the mean half-hourly bid-ask spread for every volume-volatility quintile combination for the five-year note. The

Chart 8

RELATIONSHIP OF BID-ASK SPREAD TO TRADING VOLUME AND PRICE VOLATILITY FOR FIVE-YEAR U.S. TREASURY NOTE
April 4 to August 19, 1994



Source: Author's calculations, based on data from GovPX, Inc.

Notes: The chart plots the mean half-hourly mean bid-ask spread against the half-hour trading volume quintile and price volatility quintile for the on-the-run U.S. Treasury note for all trading locations and by location. Volume and volatility quintiles are defined separately for each panel.

chart reveals that higher price volatility is associated with higher bid-ask spreads, and higher trading volume is associated with lower bid-ask spreads. These simple relationships are confirmed by highly significant correlation coefficients.[32]

Price Efficiency Regressions

With low overseas trading volume, low overseas price discovery, and high overseas bid-ask spreads, it is reasonable to ask whether the overseas trading locations are efficient. That is, are the price changes observed overseas a response to new information that later becomes incorporated in prices in New York? Or does the relative illiquidity of the overseas markets make price changes there an unreliable guide to the path of future prices? Those who have studied the U.S. Treasury market report that large trades are not easily transacted overseas without significant price concessions (Madigan and Stehm 1994; Stigum 1990). Furthermore, work by Neumark, Tinsley, and Tosini (1991) uncovers evidence that overseas price changes of U.S. equity securities are not efficient.[33] They argue that higher overseas transaction costs are a barrier to the transmission of small (but not large) price signals.

However, overseas price efficiency might be expected for several reasons. While volume is relatively low overseas, a typical day still sees interdealer volume of more than $450 million during Tokyo hours and nearly $900 million

Table 5
Overnight Price Response of U.S. Treasury Securities to Tokyo Price Movements
April 4 to August 19, 1994

	Two-Year Note	Three-Year Note	Five-Year Note	Ten-Year Note	Thirty-Year Bond
Intercept	0.00	0.00	0.00	0.00	0.00
(Standard error)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\beta}$	0.97	0.89	0.85	0.89	0.94
(Standard error)	(0.14)	(0.10)	(0.10)	(0.11)	(0.05)
Adjusted R-squared	0.50	0.39	0.36	0.30	0.58
Durbin-Watson statistic	1.61	2.00	1.76	1.70	1.90
Number of observations	86	82	85	87	83

Source: Author's calculations, based on data from GovPX, Inc.

Notes: The table reports regression estimates of New York overnight price response to price movements during Tokyo hours for on-the-run notes and bonds. Reported standard errors are heteroskedasticity-consistent.

Table 6
Overnight Price Response of U.S. Treasury Securities to London Price Movements
April 4 to August 19, 1994

	Two-Year Note	Three-Year Note	Five-Year Note	Ten-Year Note	Thirty-Year Bond
Intercept	0.00	0.00	0.00	0.00	0.00
(Standard error)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\beta}$	0.98	0.95	1.05	1.10	1.04
(Standard error)	(0.07)	(0.06)	(0.07)	(0.08)	(0.05)
Adjusted R-squared	0.78	0.71	0.80	0.78	0.84
Durbin-Watson statistic	1.87	1.69	1.95	1.37	1.64
Number of observations	85	87	87	88	84

Source: Author's calculations, based on data from GovPX, Inc.

Notes: The table reports regression estimates of New York overnight price response to price movements during London hours for on-the-run notes and bonds. Reported standard errors are heteroskedasticity-consistent.

during London hours.[34] In addition, the same market participants are transacting overseas and in New York. Furthermore, while spreads may be relatively high overseas, they are still low in an absolute sense, and brokerage fees are the same overseas as in New York. Overseas departures from price efficiency would seem to be easily exploited with trades that could be reversed for a profit just a few hours later.

This article follows the Neumark, Tinsley, and Tosini (1991) methodology. If overseas trading locations are efficient, overseas prices should reflect the evolving value of Treasury securities as news arrives during the overnight hours. If high-frequency price movements of U.S. Treasury securities can be characterized as a martingale process,[35] overseas price movements should provide an unbiased prediction of overnight price changes in New York. The regression of the overnight New York price change on the Tokyo price change,

$$(1) \qquad (NY_t^o - NY_{t-1}^c)/NY_{t-1}^c = \alpha + \beta^*(TK_t^c - NY_{t-1}^c)/NY_{t-1}^c + \varepsilon_t \ ,$$

and the regression of the overnight New York price change on the London price change,

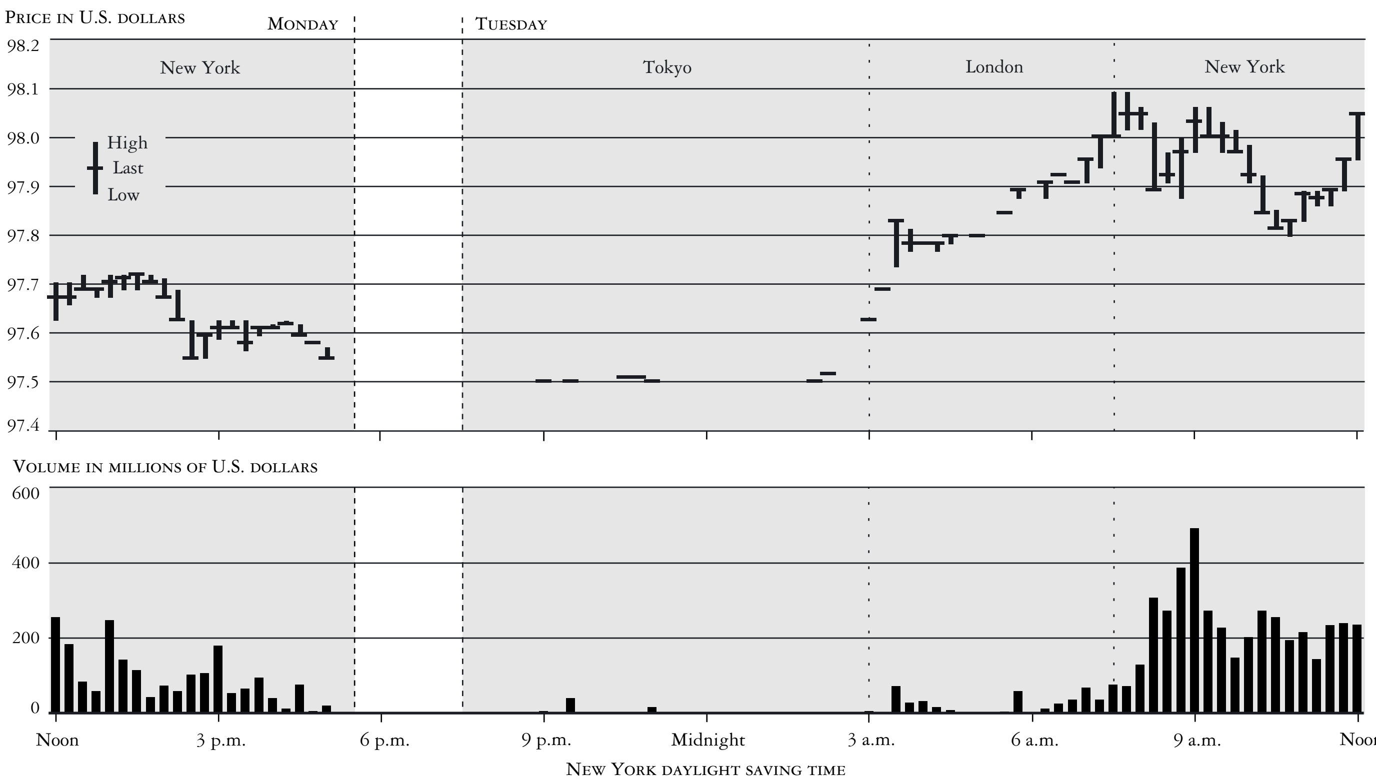
$$(2) \qquad (NY_t^o - NY_{t-1}^c)/NY_{t-1}^c = \alpha + \beta^*(LN_t^c - NY_{t-1}^c)/NY_{t-1}^c + \varepsilon_t \ ,$$

should have slope coefficients (β) equal to 1.0.

The regressions exclude crossover times in order to get "clean" prices that are more easily attributable to a particular location. Sample times are 5:30 p.m. for the

Chart 9

LONDON PRICE CHANGE AS A PREDICTOR OF OVERNIGHT PRICE CHANGE IN NEW YORK
MAY 9 (NOON) TO MAY 10 (NOON) 1994



Source: Author's calculations, based on data from GovPX, Inc.

Note: The chart shows the interdealer price path and the associated GovPX trading volume for the on-the-run five-year U.S. Treasury note by quarter hour.

New York close, 2:30 a.m. (3:30 p.m. Tokyo time) for the Tokyo close, 7 a.m. (noon London time) for the London close, and 8 a.m. for the New York opening. Observations are included only when all prices refer to the same security (there is a missing observation when the on-the-run security changes).

The Tokyo price movement regressions reveal that the slope coefficient is insignificantly different from 1.0 in all five maturities (Table 5). There is, therefore, insufficient evidence to reject the null hypothesis that Tokyo price changes are unbiased predictors of overnight price changes in New York. Furthermore, the slope coefficient is significantly different from zero (at the .01 level) in all five maturities. U.S. Treasury security price movements in Tokyo thus reflect new information that is subsequently incorporated in New York prices.

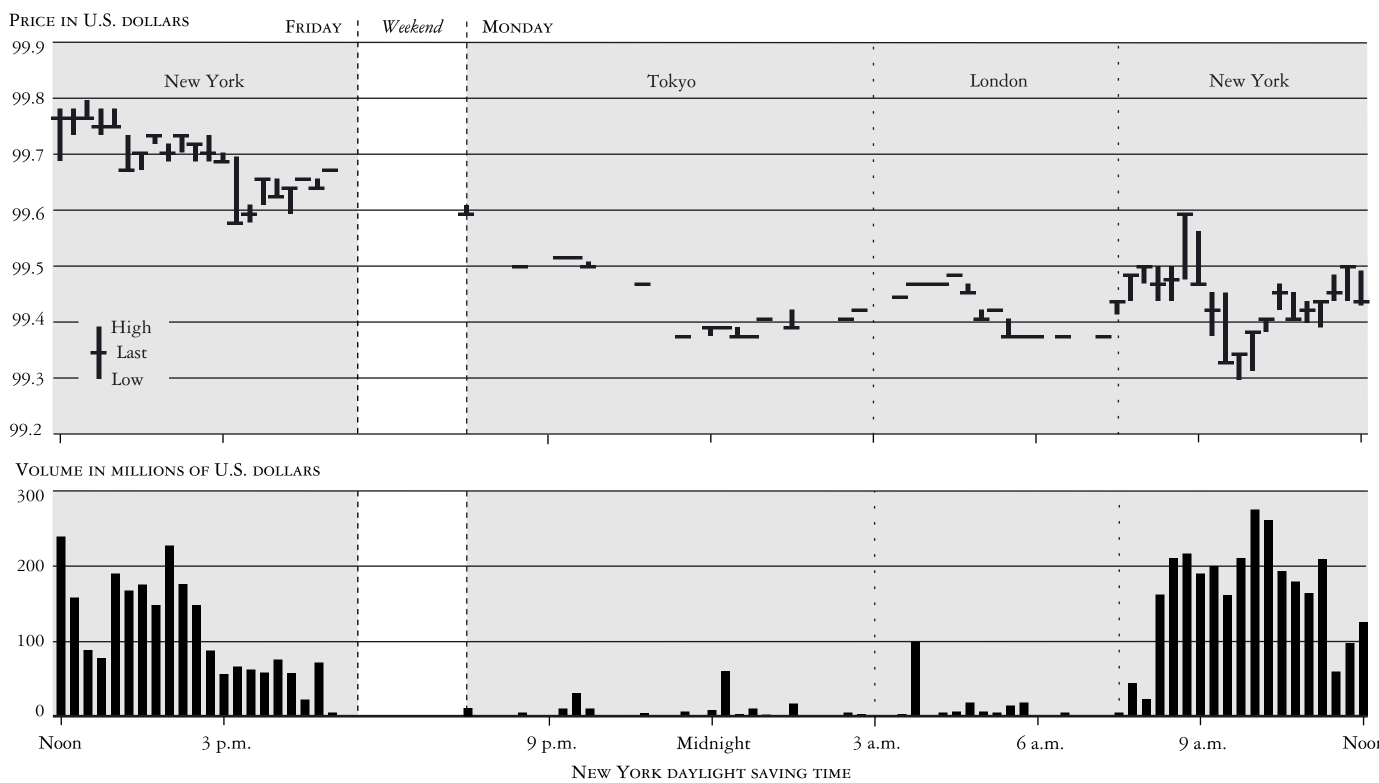
Unsurprisingly, given the Tokyo results, the slope coefficient for the London price movement regressions is also insignificantly different from 1.0 in all five maturities (Table 6). There is insufficient evidence to reject the null hypothesis that London price changes are unbiased predictors of overnight price changes in New York. In addition, the slope coefficient is significantly different from zero (at the .01 level) in all five maturities. U.S. Treasury security price movements in London (from the New York close) therefore reflect new information that is later incorporated in New York prices.

Price Efficiency Case Studies

Two case studies now illustrate how large overseas price changes in U.S. Treasury securities may be accurate indicators of overnight New York price changes. The first study

Chart 10

Tokyo Price Change as a Predictor of Overnight Price Change in New York
June 24 (Noon) to June 27 (Noon), 1994



Source: Author's calculations, based on data from GovPX, Inc.

Note: The chart shows the interdealer price path and the associated GovPX trading volume for the on-the-run five-year U.S. Treasury note by quarter hour.

examines the largest price change observed in London hours during the sample period—Tuesday, May 10, 1994, when news reports suggested that European central banks and Middle Eastern investors were purchasing U.S. Treasury securities during London trading hours.

The global trading day opened quietly on May 10 with little activity in Tokyo (Chart 9). The five-year note then rallied in London, jumping 48/100ths of a point from the last Tokyo price to the last London price. The price change was thus eight times the magnitude of the expected price change during London hours (Table 3) and nearly twice as large as the typical daily change. The London price change was maintained when New York opened at 7:30 a.m. While there was some price slippage later in the morning, it is clear that the bulk of the London price movement was not reversed when New York opened.

The second study examines the largest price change observed in Tokyo hours during the sample period—June 27, 1994. Japanese Prime Minister Tsutomu Hata resigned on Saturday, June 25. On Monday, June 27, the dollar declined in the foreign exchange market to a new post–World War II low of 99.50 yen. News stories indicated that U.S. Treasury securities were sold by dealers and overseas investors on fears that the Fed would boost interest rates to halt the dollar's fall.

The five-year note opened on June 27 down slightly from the June 24 close (Chart 10). The price made two further downward jumps: in the 8:30 p.m. to 8:45 p.m. and the 11:30 p.m. to 11:45 p.m. (New York time) intervals. The note finished in Tokyo down 25/100ths of a point, a drop that was four times the magnitude of the expected price change during Tokyo hours and about as large as a typical daily change. It fell a few more hundredths in late morning London before New York opened. While the price rose slightly in early New York trading, most of the Tokyo price movement was maintained.

Conclusion

Although the secondary market for U.S. Treasury securities operates around the clock, it behaves more like U.S. equity markets, with limited trading hours, than like the round-the-clock foreign exchange market. Trading volume and price volatility are highly concentrated during New York trading hours, with a daily peak between 8:30 a.m. and 9 a.m. and a smaller peak between 2:30 p.m. and 3 p.m. During these hours, the u-shaped patterns of trading volume, price volatility, and the bid-ask spread are similar to patterns found in the equity markets (but not in the foreign exchange market). The preponderance of relevant news during New York trading hours and the fixed hours of the CBT's futures market seem to be the most likely determinants of these intraday patterns.

Trading volume outside of New York hours is relatively low, with less than 2 percent of round-the-clock volume attributable to Tokyo hours and less than 4 percent attributable to London hours. Although prices have at times moved significantly during the overseas hours, price volatility tends to be significantly lower overseas than in New York. Bid-ask spreads are higher overseas than in New York and higher in Tokyo than in London. The spreads exhibit a triple u pattern across the global trading day corresponding to the start and stop of trading in the three trading locations.

Despite the relatively low trading volume, low price discovery, and high bid-ask spreads during the overseas hours, overseas price changes of U.S. Treasury securities can effectively predict overnight price changes in New York. Lower liquidity notwithstanding, the overseas trading locations provide important information on the path of U.S. Treasury security prices.

Appendix A: Primary Government Securities Dealers

The primary government securities dealers as of June 6, 1997, were as follows:

BA Securities, Inc.
Bear, Stearns & Co., Inc
BT Securities Corporation
BZW Securities Inc.
Chase Securities Inc.
CIBC Wood Gundy Securities Corp.
Citicorp Securities, Inc.
Credit Suisse First Boston Corporation
Daiwa Securities America Inc.
Dean Witter Reynolds Inc.
Deutsche Morgan Grenfell/C.J. Lawrence Inc.
Dillon, Read & Co. Inc.
Donaldson, Lufkin & Jenrette Securities Corporation
Dresdner Kleinwort Benson North America LLC.
Eastbridge Capital Inc.
First Chicago Capital Markets, Inc.
Fuji Securities Inc.
Goldman, Sachs & Co.
Greenwich Capital Markets, Inc.
HSBC Securities, Inc.
Aubrey G. Lanston & Co., Inc.
Lehman Brothers Inc.
Merrill Lynch Government Securities Inc.
J.P. Morgan Securities, Inc.
Morgan Stanley & Co. Incorporated
NationsBanc Capital Markets, Inc.
Nesbitt Burns Securities Inc.
The Nikko Securities Co. International, Inc.
Nomura Securities International, Inc.
Paine Webber Incorporated
Paribas Corporation
Prudential Securities Incorporated
Salomon Brothers Inc.
Sanwa Securities (USA) Co., L.P.
SBC Warburg Inc.
Smith Barney Inc.
UBS Securities LLC
Yamaichi International (America), Inc.
Zions First National Bank

Source: Federal Reserve Bank of New York (1997).

Appendix B: Data Description

GovPX, Inc., supplies real-time market information through on-line vendors by sending out a digital ticker feed, daily backup copies of which are used in this study. The data contained in the feed provide a precise history of the trading information sent to GovPX subscribers. Any posting errors made by the interdealer brokers that are not filtered out by GovPX are included in the backup files. Additionally, since the purpose of the digital feed is to refresh vendors' screens, the data must be processed before they can be effectively analyzed.

When a trade occurs, two pieces of information are typically transmitted by GovPX. First, during the "workup stage," when traders are jumping into a transaction, GovPX posts the news that a bid is being "hit" or that an offer is being lifted (a "take"); it also posts price and volume information. Seconds later, the total volume of the trade(s) is posted. Transactions occurring through the same interdealer broker at the same price and virtually the same time are thus counted as a single transaction. Occasionally, there are several lines of data per transaction, but sometimes there is only a single line.

For this analysis, the volume data are processed to ensure that each trade is counted only once. The aggregate daily volume provided with each trade is helpful in this regard. Aggregate daily volume data provided separately from the ticker feed are also useful in ensuring data accuracy. The study identifies 243,222 unique transactions over the ninety-day sample period, or an average of 2,702 per day.

Prices in U.S. Treasury notes and bonds are quoted in 32nds and can be refined to 256ths. Transaction prices, as well as bids and offers, are converted to decimal form for this analysis. Pricing errors are also screened from the data set using a two-step procedure. First, large trade-to-trade price movements that revert a short time later and are clearly erroneous are screened out. Second, prices that are more than ten standard deviations from the daily price mean or daily bid-ask midpoint mean are screened out. Just over one price per day is dropped, leaving an average of 2,701 prices per day.

A multistep procedure is used to screen quotes from the data set:

- Bids are first screened for large quote-to-quote movements that revert a short time later. This first screen drops an average of 4 quotes per day.
- As offers in the data set are quoted off of the bids, large positive spreads are indistinguishable from small negative ones. Spreads calculated to be greater than 0.9 (but less than 1.0) are likely to be negative spreads that existed only momentarily when quotes arrived from two different brokers. These quotes (an average of 115 per day) are dropped.
- One-sided quotes (a bid *or* an offer, but not both) are occasionally posted by dealers. This study makes no use of these bids (an average of 366 per day) or offers (an average of 287 per day).
- Finally, spreads with bid-ask midpoints more than ten standard deviations from the daily bid-ask midpoint mean or daily price mean are dropped, as are spreads more than ten standard deviations from the daily spread mean. This process screens out an average of 9 quotes per day.

As spreads posted by the interdealer brokers do not include the brokerage fee charged to the transaction initiator, zero spreads are common and can persist for lengthy periods. Quotes calculated to be zero are therefore kept in the data set. The data set retains 889,936 quotes from the sample period, or an average of 9,888 per day.

Once the data are cleaned, they are summarized by half-hour period using the digital feed's minute-by-minute time stamp. The final data set contains market information on each security for each half hour of the sample period, including volume, last price, and mean bid-ask spread. Because information on market participants and trading location is not available, the trading location is assigned according to the time the information is posted (Chart 1).

ENDNOTES

The author thanks GovPX, Inc., for its data. Mitch Haviv, Jean Helwege, Frank Keane, Jim Mahoney, Amy Molach, Stavros Peristiani, Anthony Rodrigues, and Jeff Stehm provided helpful comments, as did Federal Reserve Bank of New York workshop and seminar participants. The research assistance of Ray Kottler and Irene Pedraza is gratefully acknowledged.

1. In contrast, trading volume on the New York Stock Exchange averages only about $9.7 billion per day (New York Stock Exchange 1995).

2. Initially, data for the period March 1–August 31, 1994, were obtained from the data provider, GovPX, Inc. However, the period was shortened to April 4–August 19 to eliminate differences in the data format and to ensure that daylight saving time did not go into effect during the sample period.

3. Although Treasuries *are* listed on the New York Stock Exchange, trading volume of all debt issues there (corporate bonds as well as U.S. government securities) averaged just $28.6 million per day in 1994 (New York Stock Exchange 1995). Odd-lot trading of Treasuries takes place on the American Stock Exchange, with an average volume of just $14 million per day in 1994 (American Stock Exchange 1996).

4. See U.S. Department of the Treasury et al. (1992). More information on the structure of the secondary market can be found in this source and in Bollenbacher (1988), Madigan and Stehm (1994), Stigum (1990), and U.S. General Accounting Office (1986).

5. The major interdealer brokers are Cantor Fitzgerald Inc., Garban Ltd., Hilliard Farber & Co. Inc., Liberty Brokerage Inc., RMJ Securities Corp., and Tullett and Tokyo Securities Inc.

6. These are the fees reported by Stigum (1990). Communication with market participants suggests that these fees are very similar today.

7. It is estimated that primary dealers also trade $18.3 billion per day in U.S. Treasury futures, $6.1 billion in forwards, and $7.8 billion in options. Primary dealers' outstanding financing transactions (repurchase agreements, loaned securities, and collateralized loans) averaged $850 billion to $875 billion over this period.

8. The debt stood at $4,645.8 billion on June 30, 1994, $3,051.0 billion of which existed in the form of marketable securities; foreign investors accounted for 20.5 percent ($633.2 billion) of the $3,088.2 billion held by private investors (Board of Governors of the Federal Reserve System 1995).

9. Trading increases to twenty-three hours per day when New York switches to eastern standard time. There is no trading on weekends. Other sources on overseas activity in U.S. Treasury securities include Madigan and Stehm (1994) and Stigum (1990).

10. All of the intraday data examined in this study fall within a period when New York and London times are daylight saving time. Japan has not adopted daylight saving time.

11. Financing transactions involving U.S. Treasury securities are also conducted in New York, regardless of the trading time for or location of the associated cash trade.

12. As explained in the data description sections (see box and Appendix B), trading locations are assigned according to the time of day a trade was made. For example, a trade at 7:45 a.m. is considered to be a New York trade even though it may have originated in London (or elsewhere). This convention may bias the summary statistics for the individual trading locations. The similarity of this article's findings to earlier estimates reported by Stigum (1990)—93 percent for New York, 4 to 5 percent for London, 1 to 2 percent for Tokyo—suggests that the distribution of trading activity by location has been relatively stable in recent years.

13. Similarly, Barclay, Litzenberger, and Warner (1990) find negligible trading volume in Tokyo for U.S. stocks listed on the Tokyo Stock Exchange.

14. As noted earlier, foreign investors accounted for 20.5 percent of the U.S. Treasury securities held by private investors on June 30, 1994; this amount increased to 30.3 percent as of September 30, 1996 (Board of Governors of the Federal Reserve System 1995 and 1997).

15. In January 1997, the customary intervention time was moved forward one hour to around 10:30 a.m.

16. Madigan and Stehm (1994) believe that the high level of intermediate note activity is driven by hedging activity for swap transactions and underwritings.

17. Cash-management bills are very short-term bills (maturing in, say, fourteen days) issued on an unscheduled basis to meet immediate cash flow needs.

18. Because data from one of the six interdealer brokers are not available for the analysis, the figures may present a biased picture of the interdealer market. In particular, the excluded broker is regarded as being stronger in the longer term issues than the other interdealer brokers.

19. Although volatility results based on actual trade prices are similar, use of the bid-ask midpoint results in many fewer missing observations

Note 19 continued
in the overseas half-hour intervals. In addition, although volatility is calculated in terms of nominal price changes, percentage price change numbers look very similar. This similarity occurs because Treasury notes and bonds are issued at a price close to 100 and the on-the-run securities examined in this study are recently issued securities, by definition.

20. For the 7:30 p.m. to 8 p.m. interval, the previous interval is considered to be 5 p.m. to 5:30 p.m.

21. More recent findings for the cash market also support this hypothesis (Fleming and Remolona 1996, 1997).

22. Karpoff (1987) reviews the literature. Recent studies in this area include Bessembinder and Seguin (1993) and Jones, Kaul, and Lipson (1994).

23. The five-year note is chosen for this and subsequent analyses because it is the security that is most actively traded between the primary dealers. Results are similar for other securities.

24. Although spreads are calculated as the nominal difference between the bid and the ask prices, percentage bid-ask spreads look very similar. Treasury notes and bonds are issued at a price close to 100 and the on-the-run securities examined in this study are recently issued securities, by definition. None of the spread calculations incorporates interdealer broker fees.

25. McInish and Wood (1992) review the components of the bid-ask spread and cite much of the relevant literature.

26. As noted earlier, data from one of the six interdealer brokers are not included in the analysis. The daily spread averages may therefore be somewhat inaccurate—particularly in the longer term issues, in which the excluded broker is considered to be more active than the other interdealer brokers.

27. The relationship between spread and maturity for U.S. Treasury securities has also been documented in Tanner and Kochin (1971), Garbade and Silber (1976), and Garbade and Rosey (1977).

28. No bid-ask quote for the thirty-year bond is recorded for 40 percent of the Tokyo half-hour periods in the sample.

29. Average trade sizes for notes and bonds are similar in the three trading locations (although slightly *lower* in New York), however, suggesting that bid and offer quantities are similar.

30. For example, the 4:30 p.m. to 5 p.m. mean bid-ask spread is based on eighty-eight days of data for the two-, three-, five-, and ten-year notes, but only seventy-five days of data for the thirty-year bond.

31. Equity market studies include Demsetz (1968), Tinic (1972), Tinic and West (1972), Benston and Hagerman (1974), and Branch and Freed (1977). Foreign exchange market studies include Bollerslev and Domowitz (1993), Bollerslev and Melvin (1994), and Bessembinder (1994). Treasury market studies include Garbade and Silber (1976) and Garbade and Rosey (1977). Both Treasury market studies use daily data and do not have volume figures.

32. The spread-volume correlation coefficients are -.26 (all locations), -.22 (Tokyo), -.24 (London), and -.14 (New York), all significant at the .01 level. The spread-volatility coefficients are .00 (all locations), .27 (Tokyo), .32 (London), and .18 (New York), all significant at the .01 level with the exception of the "all locations" coefficient. The insignificant coefficient for "all locations" results from low spreads in New York in spite of high price volatility.

33. The authors regress overnight price changes in New York on overseas price changes from the New York close. They find that overseas price changes are generally biased predictors of overnight New York price changes, but that they were unbiased immediately after the October 1987 stock market crash.

34. Mean trading volumes of $470 million (Tokyo) and $893 million (London) for on-the-run and when-issued securities were calculated using data from GovPX, which covers roughly two-thirds of the interdealer broker market.

35. When each successive price observation depends only on the previous one plus a random disturbance term, the price series is said to follow a *random walk*. Generally speaking, a martingale process is a random walk that allows price volatility to vary over time. A martingale is therefore a process in which past prices have no information beyond that contained in the current price that is helpful in forecasting future prices.

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