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# Price discovery in the round-the-clock U.S. Treasury market

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ABSTRACT

We evaluate the efficacy of price discovery in the round-the-clock U.S. Treasury market. Using a comprehensive intraday database, we explore informational role of trades over the 24-hour day. We find that information asymmetry is generally highest in the preopen period and lowest in the postclose period. Information asymmetry in the overnight period is comparable to that in the regular trading period. However, on days with macroeconomic announcements, information asymmetry peaks shortly after the news release at 8:30. Moreover, information asymmetry is higher on Monday morning and higher immediately before than after the open of U.S. Treasury futures trading. Although volume is low after hours and trading cost is relatively high, overnight trading generates significant price discovery. Results suggest that overnight trading activity is an important part of the Treasury price discovery process.



## 1. Introduction

Price discovery—the efficient and timely incorporation of new information into security price—is arguably the most important function of securities markets. Modern technology has dramatically changed the trading mechanisms of secondary markets. It is now relatively easy to trade securities in the U.S. markets after hours. However, trading after hours continues to be dominated by professional

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traders, and trading volume is low. This raises a concern about the efficacy of price discovery in the after-hours market.

The dramatic change in the way securities markets operate has drawn financial researchers' attention to trading outside exchange trading hours.[1] In an important paper, Barclay and Hendershott (2003) investigate the effects of trading after hours on the magnitude and timing of price discovery in the equity market. They find that the price discovery process is considerably different in the after-hours market. Although prices are more efficient and more information is revealed per hour during the regular trading period, after-hours trading generates significant price discovery and individual trades contain more information after hours than during the day on a per trade basis.

While studies on the after-hours markets have generated important insights on the amount and timing of price discovery over the trading day, empirical investigations are complicated by the large shifts in the trading process at the open and close of the regular daytime market. As a consequence, it is not clear whether the significant change in the price discovery pattern after hours is due to the change in trading mechanisms associated with different platforms, or the fundamental variation in the informational role of trades over the day.

The market for U.S. Treasury securities provides an excellent forum to isolate the effect of the change in the trading process. Trading in the Treasury market takes place round the clock in the U.S. and from overseas and the trading mechanism is virtually the same wherever a trade takes place. For instance, U.S. Treasuries are traded by the same dealers and interdealer brokers using the same settlement procedure around the world. In addition, these securities are relatively homogeneous in terms of risk and return characteristics. These unique features make the Treasury market an ideal forum to study how heterogeneous traders impound new information into prices at different trading time and markets under the same trading mechanism. Thus, a finding of significant differences in price discovery between market segments (e.g., domestic vs. overseas) using intraday data of Treasury securities trading cannot be attributed to variations in the trading mechanism or securities characteristics.

In this paper we examine the informational role of trades in the U.S. Treasury market during and outside the regular domestic trading hours. We are particularly interested in the effects of trading after hours on the amount and timing of price discovery over the 24-hour day. We analyze informed trading activity and their effects on prices and trading cost components of U.S. Treasury securities across trading periods.[2] Besides looking into the information effect on price, we estimate components of trading costs and volatility over the day using a large sample of intraday data spanned over a long time horizon.

In addition to uncovering the relationship between pricing efficiency and trading after hours, an understanding of the price discovery process of the Treasury market is in itself important for academic researchers as well as practitioners. From an investment perspective, it is of interest to understand how Treasury security price is determined. More importantly, Treasury price movement affects the performance of every facet of financial markets since riskfree rates of different maturities are benchmarks for pricing other financial assets. Understanding Treasury security price changes is thus an integral part of any unified theory of asset pricing.

Our study on price discovery of the U.S. Treasury market is related to several recent papers. Huang et al. (2002) examine intraday trading patterns, information content of trades, macroeconomic announcement effects, adverse information component of bid–ask spreads, and volatility–volume relations using the interdealer Treasury market data. They find that trading frequency reflects information-based trading activity while trade size has no information content, and that information asymmetry increases around macroeconomic announcements. Green (2004) examines the impact of trading on government bond prices after the release of macroeconomic news. His study documents a significant increase in the informational role of trading following macroeconomic announcements,

[1] See, for example, Biais et al. (1999), Cao et al. (2000), and Barclay and Hendershott (2003, 2004).

[2] While the issue of information-based trading in the equity markets has been examined extensively, much less effort has been devoted to the fixed income markets. Studies on the equity markets include, among others, Barclay et al. (1990), Easley and O'Hara (1992), McInish and Wood (1990, 1992), Hasbrouck (1993, 1995), Chan et al. (1995a, 1995b), Kim and Verrecchia (1994, 1997), Krinsky and Lee (1996), Easley et al. (1996), Greene and Watts (1996), Madhavan et al. (1997), Biais et al. (1999), Koski and Michaely (2000), Cao et al. (2000), Huang (2002), Barclay and Hendershott (2003) and Li and Wu (2006).

and shows that the relation between trading and price impacts is intimately associated with both the surprise component of the announcement and the precision of public information. Brandt and Kavajecz (2004) study the price discovery process of the Treasury market from a different perspective. They find that order flow imbalance explains a significant portion of day-to-day variations in the Treasury yield curve, even on days without macroeconomic announcements. The effect of order flow on yields is permanent and is largely due to private information rather than liquidity or inventory control. Their findings suggest that the government bond order flow reveals the fundamental information about riskless rates. Pasquariello and Vega (2007) show that unanticipated order flow explains a bigger portion of bond yield changes when the dispersion of beliefs across informed traders is high and public announcements are noisy. Li et al. (2009) examine the effects of information and liquidity risks on the pricing of Treasury securities and find that both risk factors are priced.

Our paper differs from these studies by focusing on the informational role of trading after hours in the U.S. Treasury market. This emphasis allows us to address the following questions. Is there greater information asymmetry in after-hours trading and how does it affect Treasury pricing? What are the relative amounts of public and private information incorporated into Treasury prices and what are their impacts on trading cost and volatility over the 24-hour day? How does the overnight trading in foreign markets affect price discovery in the daytime U.S. Treasury market? These are questions of fundamental importance from the investment and public policy perspectives.

Because our study deals with trading overseas, it is naturally related to studies on price discovery and trading activity in multiple trading venues. Barclay et al. (1990) examine information efficiency across markets and find that the listing of U.S. stocks in Tokyo substantially increases the number of trading hours but has little impact on volume and information efficiency. Craig et al. (1995) examine whether information across international markets is rationally incorporated into stock prices. They find that Nikkei index-based futures traded in the U.S. provide complete information about contemporaneous overnight Nikkei returns in Japan. Werner and Kleidon (1996) analyze intraday patterns for UK and U.S. trading of British cross-listed stocks and find that order flow for cross-listed securities is segmented. Tse (1999) finds that the London market reveals less information about Japanese government bond (JGB) futures than the Tokyo market. Lehmann (2002) examines the measurement issues of price discovery across markets. Unlike these studies, we focus on the informational role of Treasury security trading in the domestic market as well as from overseas.[3]

Our study generates several interesting results. First, we find that the informational role of trades varies considerably over the 24-hour day. Information asymmetry is greater, and impacts of trading on prices are much stronger in the preopen period than any other trading periods of the day. There is more informed trading and price discovery in the early morning and less informed trading and price discovery toward the end of the day in the U.S. Treasury market. Notably, the degree of information asymmetry in the overnight period is comparable to that in the regular daytime trading period. Although overnight trading volume is low and trading cost relatively high, price errors are small and trades generate significant price discovery. Second, consistent with the intraday trading pattern, informed trading cost is higher in the preopen whereas liquidity cost is higher in the postclose. The magnitude of informed trading cost in the overnight period is comparable to that during the regular daytime trading period. Third, price volatility in the Treasury market is predominantly driven by public information shocks though private information also plays a significant role. Although volatility is low, the public information component of volatility (in percentage) is high during the overnight trading period, suggesting that overseas price changes are primarily driven by information, not irrational trading noise. Fourth, the intraday asymmetric information pattern is strongly affected by both public information release and private information of customer order flows. Information asymmetry peaks in the preopen period on days with no macroeconomic announcements whereas it peaks after the news

[3] Chen et al. (2006) examine the effects of trades and time duration between trades on returns and bid–ask spreads of Treasury securities over the trading day. Their study employs a time-series technique within the VAR framework to study the temporal behavior of Treasury returns. Unlike their study, we employ a structural model which provides richer economic insight. This structural model allows us to explore the informational role of trading in the Treasury market over the 24-hour day and to perform a complete analysis on adverse selection, liquidity provision, and components of trading costs and return volatility in terms of the underlying economic parameters.

release at 8:30 on days with macroeconomic announcements. On average, information asymmetry is higher in preopen period on Monday than other weekdays, reflecting more public information to be processed by analysts on Monday morning after the market has been closed for the preceding two days. In addition, information asymmetry is higher immediately before than after the open of the futures market, suggesting that private information of client order flow is another important source of information asymmetry in the preopen period. Finally, overnight trading is an important part of the Treasury price discovery process. Although price changes are noisier in the early part of the overnight trading period, pricing efficiency improves as trading progresses and overseas price changes provide an unbiased prediction of New York overnight price changes.

Our paper makes several unique contributions to the literature. First of all, our study provides the first comprehensive empirical analysis of the efficacy of price discovery in the U.S. Treasury market over the 24-hour day. Our analysis of the informational role of after-hours trades contrasts with the studies by Green (2004) and Brandt and Kavajecz (2004), which investigate price discovery in the daytime Treasury market. Fleming (1997) documents intraday patterns of trading volume, bid–ask spreads and price volatility in the Treasury market across main trading centers. By contrast, we focus on price discovery and the sources of information asymmetry in the round-the-clock U.S. Treasury market. Along this line, we provide important evidence for the information content of trades, trading cost components, the relative contribution of public and private information components to price discovery, and noisiness of prices and efficiency of price discovery across the trading day.

Our paper also represents the first extension of Barclay and Hendershott's (2003) study to the Treasury market. This extension generates important new insights into the price discovery process and several new findings unique to the Treasury market.[4] First, we find that higher information asymmetry in the preopen Treasury market is not driven by differences in the trading mechanism. Like our study, Barclay and Hendershott (2003) document evidence that information asymmetry is higher and trades contain more information in the preopen period than in the postclose and daytime periods. They find that most trades before the market opens are executed anonymously on the electronic communication networks while trades after the close are facilitated primarily by market makers. This difference in the trading mechanism affects the trading activity of informed and uninformed traders and the pattern of information asymmetry after hours.[5] Unlike their study, we find that higher information asymmetry in the preopen period exists even in a market with a uniform trading mechanism over the trading day. Second, we find that overnight trading contributes significantly to price discovery in the Treasury market and that information content of overnight trades is comparable to that of daytime trades. This contrasts sharply with Barclay and Hendershott's finding that the overnight period has little contribution to price discovery in the equity market.[6] Third, public information is the dominant factor contributing to price discovery in the Treasury market over the 24-hour day. Contrary to the equity market, a much larger portion of total price discovery is attributable to the public information component in the overnight and preopen periods in the Treasury market. Finally, we find that heterogeneity in public information interpretations and private information of client order flow are two fundamental sources of information asymmetry in the preopen period. This evidence differs from the previous finding that price discovery in the preopen of the equity market is dictated by private information for a firm's cash flow. Results suggest that the information content of after-hours Treasury trades is quite different from that of equity trades. Moreover, because of the importance of public information effects in the Treasury market, scheduled macroeconomic news release and the

[4] Some of the disparities between the equity and Treasury markets are attributable to the relatively inefficient price discovery overnight due to low trading volume. Barclay and Hendershott (2003) find significant but inefficient price discovery after hours (primarily in the preopen period). In their paper there are very few trades in the overnight period (see their Table 1, p. 1047). By contrast, there are much more overnight trades and volume in the U.S. Treasury market, which makes price discovery overnight more important in this market. This may explain the disparities between Barclay and Hendershott's findings and ours for the overnight period. Other disparities are mainly due to unique trading mechanisms and securities in the U.S. Treasury market.

[5] Barclay and Hendershott (2003) referred to the findings of French and Roll (1986) and Barclay et al. (1990) that price discovery is closely linked with the trading process.

[6] See Barclay and Hendershott (2003, p. 1056).

market close over the weekend significantly affect the relative distribution of price discovery across the trading day.

The remainder of this paper is organized as follows. Section 2 provides an overview of the characteristics of the U.S. Treasury market. Section 3 describes the method for measuring information asymmetry in the U.S. Treasury market over the 24-hour day. Section 4 discusses data and empirical methodology, and Section 5 presents empirical results. We separate spread and volatility into components associated with informational and microstructural factors and compare them across trading periods. To further identify the sources of information asymmetry, we examine the effects of macroeconomic announcements, the open of the futures market, and the close of the Treasury market over the weekend. Following this, we evaluate pricing efficiency and contribution of overseas trading to price discovery in the U.S. Treasury market. Finally, Section 6 summarizes major findings and concludes the paper.

## 2. Price discovery and trading in U.S. Treasury securities

The market for U.S. Treasury securities is by many measures the largest and most active debt market in the world. The amount of marketable U.S. Treasury debt outstanding has reached $4.52 trillion[7] and trading volume is close to $700 billion daily.[8] Trading takes place in the U.S. as well as overseas (e.g., Tokyo and London), resulting in a virtual round-the-clock market. Competition among dealers and interdealer brokers narrows bid–ask spreads for Treasury securities, minimizes brokerage fees, and facilitates information flow. Low transaction cost, high volume, and ease of trading make the U.S. Treasury market one of the most liquid markets in the world.

The Treasury market differs from the equity market in various aspects and this can have significant implications for the relationship between trading and price discovery. First of all, the organizational structure and trading mechanism of these two markets are not the same. Unlike stocks which are typically traded through a centralized exchange, Treasury securities are traded in a somewhat fragmented over-the-counter (OTC) market. Fragmentation of order flow may have an impact on the price discovery process. In addition, unlike equity trading, Treasury securities are traded in a 24-hour market.

The nature of securities traded in these markets is also fundamentally different. The cash flow of equity is uncertain but the payoff of Treasury securities is known. This difference in the nature of cash flow affects the relative importance of different information variables in security pricing. While equity prices are affected by private information which is predominantly the advanced knowledge about a firm's cash flow, Treasury securities prices are primarily driven by macroeconomic announcements which affect the future discount factor.

Because of these unique features, information asymmetry in the Treasury market derives mainly from two sources (see Green, 2004; Brandt and Kavajecz, 2004). One is the heterogeneous interpretation of public information. Even though traders observe the same set of public information, they differ in their abilities to analyze it. For example, large investment banks may have more skilled analysts, or possess more sophisticated models, to analyze public information than small individual investors. This can create a significant information disparity among traders. The other source of information asymmetry comes from private information on order flows.[9] In the OTC market, dealers post their own quotes and observe a portion of order flows, which often contain important information for forecasting short-term price movements. In this capacity, dealers become aware of future intentions of their clients and thus possess private information for expected future order flows and price movements.

[7] See Treasury Bulletin, March 2008, pp. 24–25.

[8] See weekly release of average primary dealer transactions of U.S. government securities for the week ended by August 29, 2007 by the New York Fed.

[9] Many features of the Treasury market structure are shared by currency markets. Not surprisingly, studies in currency markets also support a broader view of information asymmetry (see, for example, Lyons, 1995; Peiers, 1997; Ito et al., 1998; Evans and Lyons, 2002; Evans, 2002; and Cao et al., 2006). Cao et al. (2006) argue that while private information about nominal cash flows is generally absent in FX markets, private information about discount factors does exist. They find that inventory information in FX markets predicts future prices by forecasting future discount factors. The permanent effect of the inventory information typically ranges between 15 and 30 percent of that of the public information.

It is not clear how these distinct organizational and informational structures may affect price discovery in the after-hours Treasury market. For instance, the Treasury market is a round-the-clock trading system and traders can trade at a reasonably low transaction cost at any location during the overnight period. There is no compelling reason for informed traders to wait until next morning to execute their orders in the New York market. Quite contrarily, it may be to the informed trader's best interest to trade before the New York open to exploit their information advantage. Thus, the informed trading intensity (in proportion to trading volume) may not be low during the overnight period. Also, traders motivated by public information can trade at any time when information is released during overnight trading hours. The usual pattern of high volatility observed at the open of the equity market, typically attributed to overnight information accumulation, may become less acute for the U.S. Treasury market. On the other hand, Treasury securities are debts of the U.S. government. The value of these securities is strongly affected by U.S. macroeconomic news which is announced typically during New York trading hours. Also, trading volume is high and the market is much more liquid during the New York daytime trading period. Informed traders prefer to trade in a more liquid market. Thus, more information is likely to be revealed and prices are expected to be more efficient during the regular daytime trading hours. It would be interesting to see how these factors interact and impact price discovery during and outside the regular daytime trading period.

## 3. Methodology

Market microstructural theory characterizes traders into two groups: informed and liquidity (uninformed) traders. Informed traders trade to profit from their private information whereas liquidity traders trade to rebalance their portfolios or adjust their inventories. The participation rates of informed and liquidity traders in the security trading often vary over the day. Standard microstructural models predict that information asymmetry and uncertainty over fundamentals decline monotonically over the day as market participants continue to learn from the trading process. Accordingly, information asymmetry is expected to be higher at the beginning and lower toward the end of the day.

Trading activity is also driven by public information, which is often regularly released. Previous studies have shown that trading activity during the daytime is clustered and price is more volatile surrounding the time of news announcements. If there is no trading overnight as is typically the case in the equity market, information accumulates during the night and price tends to be more volatile at the opening of the daytime market. Trading after hours is however quite different from trading during the day. The volume is much lower and trading costs are much higher after hours than during the day. The participants in the after-hours market are dominated by professional traders with a strong incentive to trade in spite of low market volume and relatively high trading costs.

Barclay and Hendershott (2003) provide empirical evidence for price discovery in the after-hours equity market. They find that before and after regular trading hours, volume is thin and different types of traders participate in different trading periods of the day. Informed traders are more likely to trade in the preopen than in the postclose period to exploit their information advantage before the regular daytime trading starts. As a result, the bid–ask spread tends to be wider in the preopen period to reflect the higher intensity of informed trading and at the same time, higher transaction cost deters liquidity traders in this period. On the other hand, the lower probability of informed trading in the postclose period encourages more liquidity traders to participate in the market and to engage in direct negotiations.

It is unclear whether these findings for the equity market may hold for the Treasury market due to various factors cited earlier. In this paper we examine the trading data after hours and during the day in an attempt to provide concrete evidence on the temporal pattern of information-based versus liquidity-motivated trading in the Treasury market. This objective is accomplished by analyzing the components of price changes associated with private and public information and other microstructural factors.

To estimate different components of Treasury price movements, we employ the model of Madhavan, Richardson, and Roomans (1997) (MRR), which provides a generalized framework for measuring the effects of public information, private information, liquidity, and rounding errors on security price changes. The order flow of Treasury securities conveys valuable information about bond yields. The

MRR model relies on order flows to track price movements associated with public and private information arrivals. A distinct advantage of the model is its ability to jointly estimate the components of bid–ask spread, variance, and autocorrelation of price changes in relation to asymmetric information and liquidity provision, and to reveal the channels through which Treasury price evolves throughout the 24-hour day.

The MRR model is built on the theoretical framework of Glosten and Milgrom (1985). Central to this framework is the notion that information arrivals cause revisions in beliefs. In this model, the revision in beliefs is linked to the innovations in order flows and public information shocks. In addition, the model accounts for stochastic rounding errors induced by price discreteness, market frictions or time-varying returns. In the following, we briefly describe the model and its usage for uncovering the price discovery process in the Treasury market.

Let $\Delta p_t$ be the transaction price change from time $t-1$ to $t$. $\theta$ measures the degree of information asymmetry or the permanent effect of order flow innovations on prices, whereas $\phi$ captures the transitory effect on prices. $\varepsilon_t$ is the revision in beliefs due to new public information, and $\xi_t$ is the effect of price rounding errors. Both $\varepsilon_t$ and $\xi_t$ are independent and identically distributed, with mean zero and variances $\sigma_p^2$ and $\sigma_e^2$, respectively. The indicator variable for trade initiation $x_t$ has a value equal to $+1$ if a trade is buyer initiated, and $-1$ if it is seller initiated. The variance of $x_t$ is normalized to one. Order flow may be serially correlated and $\rho$ represents the first-order autocorrelation of the order flow. Given this setting, MRR show that price changes can be characterized by the following dynamic process:

$$\Delta p_t = (\phi + \theta)x_t - (\phi + \rho\theta)x_{t-1} + \mu_t, \tag{1}$$

where $\mu_t = \varepsilon_t + \xi_t - \xi_{t-1}$, $\theta$ measures the degree of information asymmetry, and $\phi$ measures the compensation for liquidity provision. When order flow is autocorrelated, only the innovation reveals information. The autocorrelation parameter $\rho$ permits the calculation of the expectation and innovation of order flow.

The model can be used to estimate the components of bid–ask spread and variance associated with information asymmetry and liquidity provision. It can be shown that the model-implied bid–ask spread (ISPR) is a sum of the two components: costs of informed trading (INFO) and liquidity (CL).[10] Specifically,

$$ISPR = INFO + CL = 2\theta + 2\phi. \tag{2}$$

In addition, the model-implied variance of price changes (IVAR) can be written as

$$\mathrm{var}[\Delta p_t] = \sigma_p^2 + 2\sigma_e^2 + \left[\left(1-\rho^2\right) * \theta^2 + 2(1-\rho)\phi^2 + 2\theta\phi\left(1-\rho^2\right)\right], \tag{3}$$

where variance of price changes contains components associated with public information shocks $\sigma_p^2$, rounding errors $\sigma_e^2$, and an interactive term (including all terms inside the brackets).[11] The third variance component includes three terms. The first term, $(1-\rho^2) * \theta^2$, is associated with information asymmetry; the second, $2(1-\rho)\phi^2$, is associated with liquidity provision; and the third, $2\theta\phi(1-\rho^2)$, contains the interaction between information asymmetry and liquidity provision. The value of each term is inversely related to the autocorrelation of order flow $\rho$. Furthermore, the model-implied first-order autocorrelation of price changes (IAC) can be derived from model parameters.[12] In empirical investigation, we first estimate model parameters and then based on these estimates, calculate the

[10] See Madhavan et al. (1997).

[11] Rounding errors could be due to either transaction cost or high trading frequency. High transaction cost reduces the number of trades and pricing efficiency, and so it increases errors. High trade frequency increases pricing efficiency but increases total rounding errors associated with bid–ask bounce or price discreteness. Thus, there is a trade-off effect on rounding errors associated with trade frequency.

[12] The implied autocorrelation of transaction price changes (see Madhavan et al., 1997) is

$$IAC = \frac{\mathrm{cov}(\Delta p_t, \Delta p_{t-1})}{\mathrm{var}[\Delta p_t]} = \frac{-\sigma_e^2 + \rho[(\theta+\phi)^2 + (\theta\rho+\phi)^2] - (\theta\rho+\phi)(\theta+\phi)(1+\rho^2)}{\sigma_p^2 + 2\sigma_e^2 + [(1-\rho^2)\theta^2 + 2(1-\rho)\phi^2 + 2\theta\phi(1-\rho^2)]}.$$

model-implied components of bid–ask spread, variance, and autocorrelation of price changes over the day.

## 4. Data and empirical methodology

### 4.1. Data

Trades and quotes of U.S. Treasury bonds are obtained from a dataset provided by GovPX, Inc.[13] The GovPX dataset contains detailed individual security information such as CUSIP, coupon, maturity date, and an indicator of whether the security is trading when issued, on-the-run, or off-the-run. The quote data include the best bid and ask prices, associated yields, the time of each bid and offer, and the respective bid and ask size (depths). The transaction data include the time of trade, size, side (buy or sell), price, yield, and cumulative volume. An important feature of this database is that trade side (or initiator) is clearly indicated.

We focus on the most recently issued, or on-the-run, five-year Treasury note, which is the most frequently traded issue in the GovPX database. However, the coverage of GovPX declines substantially after 1999 due to the growth of trading through electronic platforms that do not report to GovPX (see Barclay et al., 2006). This has considerably reduced the number of trade and quote records in the GovPX database. Incomplete data can cause bias in empirical estimation and we hence restrict our sample to the period from January 1992 to December 1999.

Fleming (1997) examines the patterns of intraday trading activity and bid–ask spreads in the U.S. Treasury market using interdealer broker data over the period from April 4 to August 19, 1994. Although our study covers a much longer time span, we find similar intradaily patterns for trading volume, bid–ask spreads and price volatility. The global trading of Treasury securities takes place round the clock, five days a week. Trading volume is concentrated in New York trading hours. On average, 91% of trading occurs in New York, 5% in London and 3% in Tokyo.[14] In a typical day, trading in New York picks up quickly at 7:30, and reaches the peak around 9:00. Trading generally declines after 10:00 with a rebound before the futures market closes at 15:00. After the closing of the futures market, trading in New York declines sharply and eventually subsides at 17:30. Tokyo hours begin at 18:30 New York standard time (or 19:30 New York daylight saving time), while London trading begins at 3:00 in the morning.[15] Trading hours in different locations may overlap, and traders may trade from one location during another location's business hours. Thus, a trade at anytime can originate anywhere. As shown later, the trading pattern in the Treasury market between 8:30 and 15:00 resembles that in the equity market between 9:30 and 16:00. We hence refer to the period from 8:30 to 15:00 as the regular daytime trading period, 7:30 to 8:30 as the preopen period, 15:00 to 17:30 as the postclose period, and 17:30 to 7:30 the next morning as the overnight period. Although technically there is no specific opening and closing time in the OTC market, we designate 8:30 as the time of daytime market open and 15:00 as market close for convenience.

While the quality of GovPX data is quite good, there are data errors. We filter out transaction prices and quotes which are way out of the normal range and data with extreme price changes.[16] In calcu-

[13] GovPX, Inc. was set up under the guidance of the Public Securities Association as a joint venture by the primary dealers and several interdealer brokers in 1991 to increase public access to U.S. Treasury security prices. GovPX consolidates and posts real-time quotes and trades from five of the six major interdealer brokers (Liberty, Tullett & Tokyo, Garban, ICAP, and Hilliard and Farber) in our sample period.

[14] This is based on the trading volume in our sample period from 1992 to 1999.

[15] New York and London adopt daylight saving time (DST) but Tokyo does not.

[16] We employ a 0.5% filter rule to remove extreme price changes from transaction to transaction. This is done by identifying and removing the data at the 0.25 percentile of both tails of the transaction price change distribution. This filter rule also helps us identify handle errors quite effectively. When there is a handle error, typically there is a sharp price change, which suddenly reverts subsequently (marked by a subsequent large price change with an opposite sign). These sharp price changes can be easily identified by our filtering procedure. Whenever a reverting pattern occurs in a short window, we will carefully check transactions surrounding these large price changes to ensure that persistent handle errors are all cleaned up. This eliminates handle errors that persist for more than a tick. We also checked the robustness of our results to our filtering procedure by using a smaller filter (e.g., 0.1%). We found that our results are not sensitive to the filter size. Thus, our results are quite

lating returns, we delete trade-to-trade price change across 6 p.m. New York time whenever there is an auction to avoid comparing the new on-the-run security price to the old on-the-run price.[17]

### 4.2. Empirical methodology

We employ the generalized method of moments (GMM) to jointly estimate the parameters $\rho$, $\phi$, $\theta$, $\sigma_p^2$, and $\sigma_e^2$ for different trading periods. The Newey–West procedure is used to obtain consistent standard errors by accounting for autocorrelation and conditional heteroskedasticity in price changes. Dummy variables, $I_1, I_2, \ldots, I_n$, where $n$ is the number of intraday periods, are included to capture the trade impacts over the day. The following moment conditions exactly identify the model parameters $(\rho_1, \phi_1, \theta_1, \sigma_{p1}^2, \sigma_{e1}^2; \rho_2, \phi_2, \theta_2, \sigma_{p2}^2, \sigma_{e2}^2; \ldots; \rho_n, \phi_n, \theta_n, \sigma_{pn}^2, \sigma_{en}^2)$ and the constant term $(\alpha)$ for different trading periods:

$$E\begin{bmatrix} [x_t - (\rho_1 I_1 + \rho_2 I_2 + \cdots + \rho_n I_n)x_{t-1}]x_{t-1} \\ \mu_t - \alpha \\ (\mu_t - \alpha)x_t \\ (\mu_t - \alpha)x_{t-1} \\ (\mu_t - \alpha)^2 - (\sigma_{p1}^2 I_1 + 2\sigma_{e1}^2 I_1 + \sigma_{p2}^2 I_2 + 2\sigma_{e2}^2 I_2 + \cdots + \sigma_{pn}^2 I_n + 2\sigma_{en}^2 I_n) \\ (\mu_t - \alpha)(\mu_{t-1} - \alpha) + (\sigma_{e1}^2 I_1 + \sigma_{e2}^2 I_2 + \cdots + \sigma_{en}^2 I_n) \end{bmatrix} = 0, \tag{4}$$

where $\mu_t = \Delta p_t - [(\phi_1 + \theta_1)I_1 + (\phi_2 + \theta_2)I_2 + \cdots + (\phi_n + \theta_n)I_n]x_t + [(\phi_1 + \rho_1\theta_1)I_1 + (\phi_2 + \rho_2\theta_2)I_2 + \cdots + (\phi_n + \rho_n\theta_n)I_n]x_{t-1}$. An advantage of the GovPX dataset is that trade side (or buy and sell indicator) is clearly indicated so that there is no need to use the traditional method to estimate $x_t$ as in most equity market studies. This is a distinct advantage because the model depends crucially on the accuracy of trade side information.

Besides fitting transaction data to the above structural model, we employ a nonparametric approach similar to the one used by Koski and Michaely (2000) and Green (2004) to perform robustness checks on the efficacy of the structural model. This nonparametric approach relies only on the sequence of transaction returns to estimate the impact of trading on prices and so it is robust to model specification. This model-free approach provides additional evidence on the variation in the informational role of trading over the 24-hour day.

## 5. Empirical results

Fig. 1 displays the round-the-clock trading patterns by half-hour interval for the five-year on-the-run Treasury note over the period from 1992 to 1999. Panels A and B show that both the number of trades and volume reach the peak at the 8:30–9:00 interval. The trading pattern between 8:30 and 15:00 in the Treasury market parallels that between 9:30 and 16:00 in the equity market. The peak between 8:30 and 9:00 can be attributed to regular macroeconomic news announcements at 8:30 and also to the open of U.S. Treasury futures trading at 8:20 on the Chicago Board of Trade (see Ederington and Lee, 1993). The increase in volume between 10:00 and 10:30 coincides with regular news reports at 10:00. Volume declines thereafter until 13:00 and rises again to a smaller peak at the closing of the U.S. Treasury bond futures trading at 15:00. The increase in trading volume after 13:00

robust to our data screening procedure. Note that our filter rule does not apply to the data points surrounding macroeconomic announcements where large price movements are possible. When calculating the effective spread, we use data records with zero and positive bid–ask spreads. We exclude records with no quotes, one-sided quotes, quotes with negative bid–ask spreads and with bid–ask spreads more than 25 hundredths of one percent of price.

[17] When an on-the-run security becomes off the run after a new on-the-run security is issued, one should be careful not to compare the price of the old on-the-run to that of the new one because it may cause large price changes and bias the result. We thank an anonymous referee for pointing out this problem.

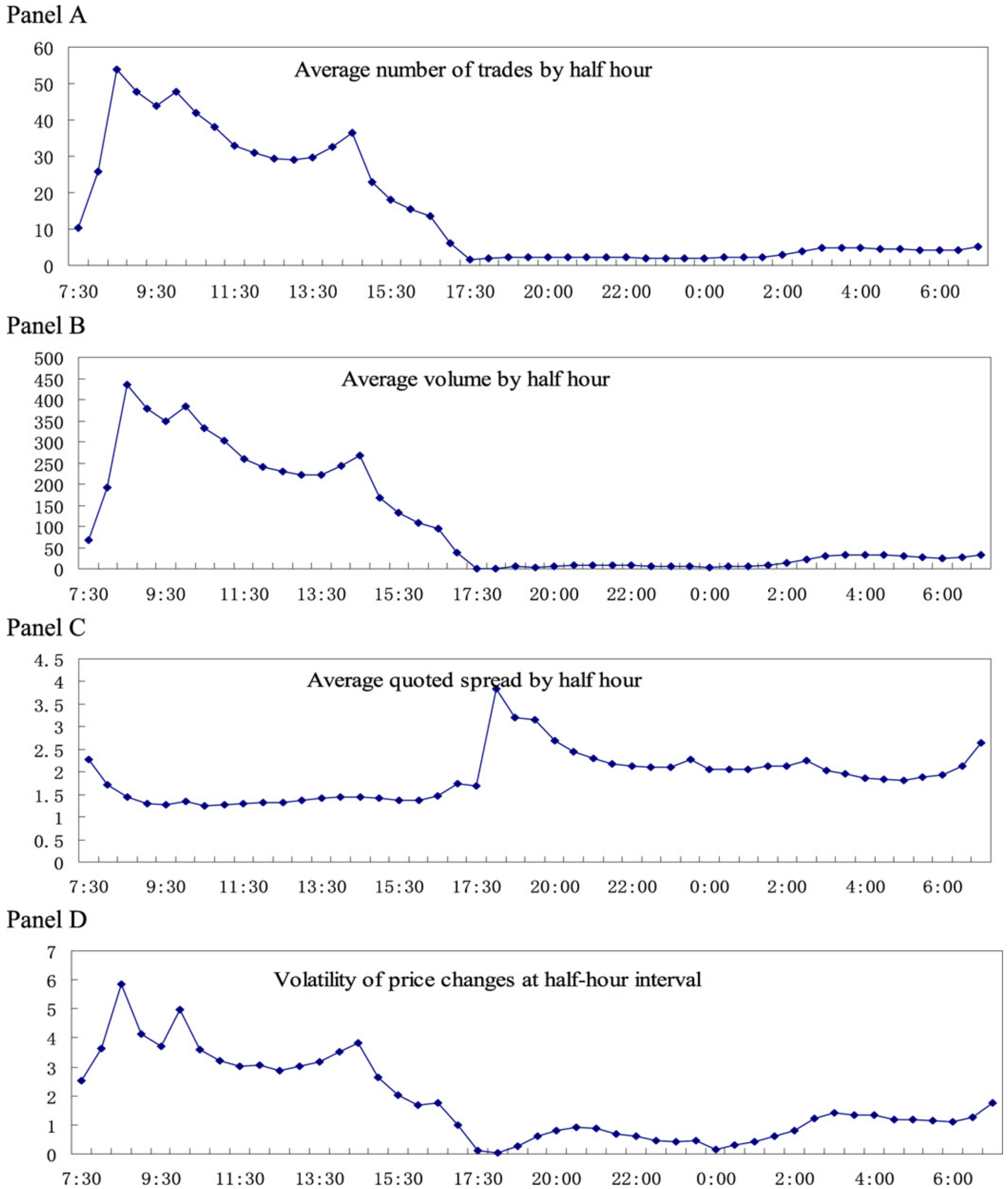


**Fig. 1.** Round-the-clock patterns by half hour. This figure shows the round-the-clock patterns of trading activity, spreads and volatility by half hour for the five-year on-the-run Treasury note over the period 1/1/1992–12/31/1999. Average number of trades, volume (in million dollars), quoted bid–ask spreads and absolute price changes are plotted from Panels A to D at half-hour intervals. Both spreads and price changes are expressed in hundredths of a percent of price.

may reflect the impacts of regular releases of Treasury auction results and FOMC announcements.[18] Volume and the number of transactions drop quickly after the closing of the futures market.

[18] Treasury auction results were released mostly around 14:00 (see also Nyborg and Sundaresan, 1996) during our sample period although they are now released just after 13:00. The time of FOMC announcements and minute releases varies somewhat over our sample period. FOMC announcements are typically made around 14:15 and minutes are released around 14:00.

**Table 1**
Summary statistics of Treasury data.

| | Preopen | Daytime trading | Postclose | Overnight | All |
|---|---|---|---|---|---|
| Price | 99.9444 | 99.9366 | 99.9500 | 99.9595 | 99.9406 |
| Trade size ($ million) | 7.3214 | 7.9190 | 7.4905 | 7.5337 | 7.8119 |
| Number of trades per day | 38 | 503 | 78 | 58 | 665 |
| Volume per day ($ million) | 279 | 3995 | 586 | 447 | 5218 |
| *SPR* | 1.7389 | 1.3415 | 1.3863 | 1.9382 | 1.4324 |
| *ESPR* | 1.0083 | 0.9103 | 0.8701 | 1.0928 | 0.9354 |
| *SD* | 0.9835 | 0.8164 | 0.7475 | 1.2223 | 0.8585 |
| *AC* | 0.0251* | −0.0017* | −0.0322* | 0.0183* | 0.0009 |

*Notes*. This table reports summary statistics for the five-year on-the-run Treasury note over the period of 1/1/1992 to 12/31/1999. The preopen period is from 7:30 to 8:30. The daytime trading period is from 8:30 to 15:00. The postclose period is from 15:00 to 17:30. The overnight period is from 17:30 to 7:30. Reported are means of bond trading and characteristic variables in four intraday trading periods for the entire sample. SPR is the quoted bid–ask spread and ESPR is the effective spread in hundredths of a percent of price. SD is the standard deviation of trade-by-trade price changes in hundredths of a percent of price. AC is the first-order autocorrelation of transaction price changes.

* Significance at the 5% level.

Panel C shows that the average quoted spread after hours is higher than that in the daytime trading period, and daytime spreads in New York and overnight spreads in Tokyo and London both exhibit a u-shaped pattern. Panel D shows that volatility, measured by mean absolute returns at half-hour intervals, is higher in the daytime than overnight. It peaks at the 8:30–9:00 interval and then declines over the daytime trading period with a rebound near the close of the futures market.[19] The downward trend through most of the daytime trading period is consistent with the argument that information uncertainty declines over the day as market participants learn from the trading process (see Easley and O'Hara, 1992; Madhavan, 1992; Bloomfield, 1996). Similar to trading volume, volatility drops substantially after the closing of U.S. Treasury bond futures trading.[20]

Table 1 reports summary statistics of price, trades, spreads, volatility (standard deviation) and autocorrelation for different trading periods of the day over the entire sample period. On-the-run five-year Treasury notes are typically traded around par. In the regular daytime trading period, trade size averages 7.92 million dollars per transaction, trading frequency is 503 transactions, and volume is 3995 million dollars per day. Average quoted bid–ask spread is 1.34 (in hundredths of a percent of price) and average effective spread is 0.91. Standard deviation of trade-by-trade price changes is 0.82 (in hundredths of a percent of price), and price changes are only weakly autocorrelated.

Comparing trading statistics across four periods, we observe the following patterns. First of all, volume concentrates in the regular daytime trading period.[21] On average, 76 percent of trading volume occurs in the daytime, 11 percent in the postclose, 8 percent in the overnight, and 5 percent in the preopen period. While overseas trading activity is low relative to New York, the average dollar trading volume is still sizable (447 million). Trade size is comparable across trading periods. Bid–ask spreads are higher in the overnight and preopen periods than in other trading periods. Standard deviation (SD) of price changes is also higher in the preopen period than in the regular trading and postclose periods. Interestingly, standard deviation of price changes is high overnight.[22] This contrasts with the low intraday volatility overnight in Panel D of Fig. 1. The discrepancy is primarily due to different methods used to measure volatility. The volatility in Panel D of Fig. 1 is measured by mean absolute price changes at each half-hour interval, whereas the standard deviation (SD) in Table 1 is calculated

[19] Volatility is the absolute price difference between the last price in that half hour and the last price in the preceding half hour.

[20] Fleming (1997) reports similar results for volume, spreads and volatility based on a much shorter sample.

[21] Brandt and Kavajecz (2004) and Brandt et al. (2007) find that order imbalance contains important information for yields. We also calculated order imbalances in volume and number of trades and found that both are higher during the daytime period. By contrast, overnight order imbalance is about half size of the daytime order imbalance. In principle, order imbalances can be associated with either asymmetric or inventory information (see Chordia et al., 2002).

[22] A similar phenomenon is found in foreign exchange markets, though it is not as strong (see Baillie and Bollerslev, 1990). In foreign exchange markets, price volatility is also high overseas but not as high as in New York trading period.

**Table 2**
Model parameter estimates.

| | Preopen | Daytime trading | | | | Postclose | Overnight | Wald test statistics |
|---|---|---|---|---|---|---|---|---|
| | 7:30–8:30 | 8:30–10:00 | 10:00–12:00 | 12:00–14:00 | 14:00-15:00 | 15:00–17:30 | 17:30–7:30 | |
| $\theta$ | 0.6400 | 0.6130 | 0.5526 | 0.5284 | 0.5789 | 0.4369 | 0.5624 | 1377.50* |
| (S.E.) | (0.0073) | (0.0035) | (0.0029) | (0.0032) | (0.0046) | (0.0040) | (0.0069) | |
| $\phi$ | −0.2706 | −0.2541 | −0.2385 | −0.2251 | −0.2448 | −0.1885 | −0.3176 | 454.41* |
| (S.E.) | (0.0066) | (0.0032) | (0.0026) | (0.0029) | (0.0041) | (0.0034) | (0.0061) | |
| $\sigma_p^2$ | 0.7398 | 0.5583 | 0.4213 | 0.3832 | 0.4580 | 0.3903 | 1.3257 | 1433.20* |
| (S.E.) | (0.0213) | (0.0092) | (0.0065) | (0.0064) | (0.0110) | (0.0083) | (0.0284) | |
| $\sigma_e^2$ | 0.0461 | 0.0551 | 0.0525 | 0.0545 | 0.0578 | 0.0525 | 0.0356 | 12.51* |
| (S.E.) | (0.0056) | (0.0023) | (0.0016) | (0.0017) | (0.0028) | (0.0022) | (0.0068) | |
| $\rho$ | 0.4412 | 0.4919 | 0.4864 | 0.4727 | 0.4651 | 0.4179 | 0.3594 | 1904.60* |
| (S.E.) | (0.0037) | (0.0018) | (0.0017) | (0.0020) | (0.0027) | (0.0026) | (0.0031) | |

*Notes*. This table reports parameter estimates for the five-year on-the-run Treasury note over the period 1/1/1992–12/31/1999. Parameters $\theta$, $\phi$, $\sigma_p^2$, $\sigma_e^2$, and $\rho$ are estimated from the moment conditions in (4) for each of the seven time intervals (7:30–8:30, 8:30–10:00, 10:00–12:00, 12:00–14:00, 14:00–15:00, 15:00–17:30, and 17:30–7:30). $\theta$ is the information asymmetry parameter, $\phi$ measures the compensation for liquidity provision, $\sigma_p^2$ and $\sigma_e^2$ are the variance components associated with public information shocks and rounding errors, respectively and $\rho$ measures the autocorrelation of the order flow. We report the Wald test statistic on the hypothesis that parameters at different time intervals are equal.

* Significance at least at the 5% level.

from all trades over the entire overnight period. Finally, serial correlation of price changes is modest and is only slightly higher (in absolute terms) in the postclose period.

### *5.1. Informational role of trading*

We obtain GMM estimates of model parameters from the moment conditions in (4). The daytime trading period is further divided into four intervals to reveal more details on the information assimilation process. Table 2 reports parameter estimates for each period. Model parameters are estimated with great precision: standard errors are low and all parameter estimates are highly significant. The estimates of the intensity of informed trading ($\theta$), cost for supplying liquidity ($\phi$), and autocorrelation in order flow ($\rho$) in the preopen period (7:30–8:30) are all comparable to Green's (2004) estimates for the interval 8:00–8:30 before macroeconomic news releases. Wald tests (see the last column) show that parameter estimates are significantly different across periods.

The asymmetric information parameter ($\theta$) has the highest value (0.64) in the preopen period. It then declines over the daytime trading period with a rebound before the close of Treasury bond futures trading.[23] The high information asymmetry in the preopen period is consistent with the prediction that informed traders are more likely to trade before the market opens to exploit their information advantage. The decline in $\theta$ during the regular daytime period supports the contention that market makers learn about the fundamental value of the security over the course of daytime trading. The value of $\theta$ is lowest (0.4369) in the postclose period, similar to the finding of Barclay and Hendershott (2003) for the equity market that information asymmetry is low after the market closes. Compared with the postclose period, $\theta$ in the overnight period is relatively high (0.5624). The informational role of trading in the overnight market is actually comparable to that of trading during most of the daytime period. This finding contrasts with Barclay and Hendershott's (2003) finding that the overnight period has almost no contribution to price discovery.

The cost for supplying liquidity ($\phi$) increases modestly throughout the day, with a slight reverse before the close of the futures market. The $\phi$ value is highest in the postclose period. While $\phi$ tends to be positive in the equity market, its value is negative in the interdealer Treasury market, consistent with Green's (2004) finding. The negative $\phi$ suggests that dealers consume liquidity instead

[23] Green (2004, p. 1213) reports $\theta = 0.654$, $\phi = -0.246$, and $\rho = 0.492$. Our estimates are in line with his estimates.

of providing it.[24] Green argues that dealers may pay for liquidity in the interdealer market if they are sufficiently compensated for providing liquidity in the retail market by trading at more favorable prices with their customers. In a market with heterogeneous beliefs, dealers' ability to sell to the most optimistic dealer and buy from the most pessimistic dealer effectively lowers transaction cost. It appears that in the interdealer market the compensation for assuming asymmetric information risk is partially offset by the price paid for consuming liquidity.

The temporal variation of $\theta$ and $\phi$ estimates points to a larger permanent (information) effect and a smaller temporary (liquidity) effect of order flow on trading price in the preopen period, but a reverse in the postclose period. This implies a high proportion of informed traders at the beginning of the day but a high proportion of liquidity traders in the postclose period.

The variance component due to public news shocks ($\sigma_p^2$) declines over the day. Highest $\sigma_p^2$ occur in the overnight period and it is second highest in the preopen period. This finding is somewhat surprising because the public information component of volatility is not higher in the period of 8:30–10:00 despite that news announcements often occur between 8:30 and 10:00. One possible reason for the high $\sigma_p^2$ value overnight is the length of this period (14 hours). The overnight period covers Tokyo and London trading hours during which public news relevant to U.S. Treasury prices may be released.[25] If information arrives at a constant rate, the public information component of variance overnight will be greater than the sum of the remaining trading period of the day. Although information is unlikely to arrive at a constant rate over the 24-hour day, in general the public information component of variance would tend to be higher when the trading period is longer.

The high $\sigma_p^2(0.7398)$ in the preopen period is attributable to heterogeneity in traders' expectations or news interpretation. An important determinant of $\sigma_p^2$ is heterogeneous interpretation of public news events (see Madhavan et al., 1997). The high $\sigma_p^2$ value in the preopen period can be caused by heterogeneous interpretation for the news accumulated overnight. Trading volume and the number of traders are much higher in the preopen period than in the overnight period. Market participants in the preopen period tend to be sophisticated professional traders with strong incentives to trade. Information disparity would heighten as more sophisticated traders with divergent skills participate in a trading venue to process the information accumulated overnight. This interpretation for the high $\sigma_p^2$ value in the preopen period is consistent with price discovery under information heterogeneity. In this interpretation, the variance of public information shocks in the preopen period reflects the disagreement among a greater number of traders about the implications of public news accumulated during the overnight period.

The variance component associated with rounding errors ($\sigma_e^2$) is small, which is largely due to the Treasury market's high liquidity and low transaction cost. This variance component is relatively flat across the daytime trading periods. This pattern contrasts the finding for the equity market where price variation attributed to rounding errors is typically lowest at the market open and increases steadily over the day with the magnitude of dealers' transaction cost $\phi$.[26] Rounding errors are quite low in the overnight period possibly due to low trading frequency. Results show that public information shocks are the dominant source of intraday variations in Treasury market volatility over the course of the day.

The autocorrelation in order flow ($\rho$) exhibits a narrow range from 0.36 to 0.49. Order flow autocorrelation tends to be higher during the daytime trading. The estimate of the autocorrelation coefficient is higher than that for the equity market, indicating that order flow is more serially correlated in the Treasury market. This suggests that past order flows contain rich information for predicting the future order flow.

In summary, information asymmetry in the U.S. Treasury market is highest in the preopen period and declines over most of the day to reach the lowest level in the postclose period. Informed trading tends to concentrate in the preopen period, whereas liquidity trading dominates in the postclose pe-

[24] For example, the estimate of −0.27 in the preopen period implies that the price paid for consuming liquidity is about 0.27.
[25] Public news released in foreign markets may affect U.S. Treasury bond price just as public news released in the U.S. markets may affect foreign government bond price (see Frino and Hill, 2000).
[26] See Madhavan et al. (1997).

**Table 3**
Components of bid–ask spread, variance, and autocorrelation.

| | Preopen | Daytime | | | | Postclose | Overnight |
|---|---|---|---|---|---|---|---|
| | 7:30–8:30 | 8:30–10:00 | 10:00–12:00 | 12:00–14:00 | 14:00–15:00 | 15:00–17:30 | 17:30–7:30 |
| *Panel A. Bid–ask spreads* | | | | | | | |
| Observed spread | | | | | | | |
| *SPR* | 1.7389 | 1.3242 | 1.2641 | 1.3171 | 1.3874 | 1.3863 | 1.9382 |
| *ESPR* | 1.0083 | 0.9392 | 0.8845 | 0.8787 | 0.9210 | 0.8701 | 1.0928 |
| Model-implied spread | | | | | | | |
| *INFO* | 1.2800 | 1.2259 | 1.1052 | 1.0568 | 1.1578 | 0.8738 | 1.1249 |
| *CL* | −0.5413 | −0.5082 | −0.4769 | −0.4502 | −0.4896 | −0.3771 | −0.6353 |
| *ISPR* | 0.7388 | 0.7177 | 0.6283 | 0.6066 | 0.6682 | 0.4968 | 0.4896 |

| Variance component | Preopen | Daytime trading | | | | Postclose | Overnight |
|---|---|---|---|---|---|---|---|
| | 7:30–8:30 | 8:30–10:00 | 10:00–12:00 | 12:00–14:00 | 14:00–15:00 | 15:00–17:30 | 17:30–7:30 |
| *Panel B. The components of the volatility of transaction price changes* | | | | | | | |
| Public information | 76.68% | 71.32% | 68.32% | 66.34% | 67.52% | 69.92% | 88.95% |
| Rounding errors | 9.56% | 14.08% | 17.03% | 18.85% | 17.05% | 18.80% | 4.77% |
| Asymmetric information | 34.19% | 36.38% | 37.80% | 37.54% | 38.72% | 28.23% | 18.48% |
| Transaction cost | 8.48% | 8.38% | 9.47% | 9.25% | 9.45% | 7.41% | 8.67% |
| Interactive effect | −28.92% | −30.17% | −32.62% | −31.98% | −32.75% | −24.36% | −20.88% |

| | Preopen | Daytime trading | | | | Postclose | Overnight |
|---|---|---|---|---|---|---|---|
| | 7:30–8:30 | 8:30–10:00 | 10:00–12:00 | 12:00–14:00 | 14:00–15:00 | 15:00–17:30 | 17:30–7:30 |
| *Panel C. Autocorrelation* | | | | | | | |
| *AC* | 0.0244 | 0.0081 | −0.0043 | −0.0125 | −0.0056 | −0.0314 | 0.0191 |
| *IAC* | 0.0093 | −0.0150 | −0.0257 | −0.0343 | −0.0230 | −0.0447 | 0.0152 |

*Notes*. This table reports the bid–ask spread components, variance components, and autocorrelation for the five-year on-the-run Treasury note over the period 1/1/1992–12/31/1999. These components are calculated based on the parameter estimates in Table 2. In Panel A, variables include the observed bid–ask spread (*SPR*), the effective bid–ask spread (*ESPR*), the implied bid–ask spread (*ISPR*), the informed trading cost component of spread (*INFO*), and the cost component for supplying liquidity (*CL*). The implied spread and the spread components are calculated based on the parameter estimates in Table 2. In Panel B, variance components due to public information shocks, rounding errors, asymmetric information, transaction cost and interaction are expressed in percentage of total variance. The interactive effect component is the variance due to the interaction between information and transaction cost. Each variance component is divided by the total variance to indicate the proportion of variance contributed by each component. In Panel C, *AC* is the first-order autocorrelation of observed price changes. *IAC* is the model-implied first-order autocorrelation of price changes. We calculate *IAC* by using the following formula

$$IAC = \frac{-\sigma_e^2 + \rho[(\theta+\phi)^2 + (\theta\rho+\phi)^2] - (\theta\rho+\phi)(\theta+\phi)(1+\rho^2)}{\sigma_p^2 + 2\sigma_e^2 + [(1-\rho^2)\theta^2 + 2(1-\rho)\phi^2 + 2\theta\phi(1-\rho^2)]},$$

where parameter estimates for $\theta$, $\phi$, $\sigma_p^2$, $\sigma_e^2$, and $\rho$ are obtained from Table 2.

riod. These results are consistent with Barclay and Hendershott's (2003) finding for the equity market. The variance component associated with public information is also higher in the preopen than in the postclose period. The public information component of variance is highest in the overnight period. Despite thin volume and high trading cost, the degree of information asymmetry in the overnight market is comparable to that in the daytime. This result differs considerably from Barclay and Hendershott's (2003) finding for the equity market and reflects the unique feature of the U.S. Treasury trading system.

### 5.2. *Informational effects on bid–ask spreads, variance, and autocorrelation*

Table 3 shows the components of bid–ask spread, volatility and autocorrelation over the day. Panel A compares the model implied spreads with the observed spreads across periods. The model-implied bid–ask spreads (ISPR) are systematically smaller than the quoted and effective spreads, which is attributable to negative compensation for liquidity provision in the interdealer market.[27] One possible reason is that dealers use the interdealer market as a source of liquidity, while they provide liquidity to retail investors. Because dealers are not required to submit quotes in the interdealer market, the cost of liquidity is lower. The cost of liquidity provision is highest in the postclose and lowest in the overnight period, suggesting that dealers consume more liquidity in the overnight trading. By contrast, the information cost component of spreads is highest in the preopen and lowest in the postclose whereas the information cost component of spreads in the overnight period is comparable to that in the daytime period.

Panel B of Table 3 reports variance components in percentage for different trading periods. Results show that the public information component of variance in percentage terms is higher in the overnight and preopen periods. The rounding error component in percentage is relatively high during regular trading hours. The high rounding error during regular trading hours may be due to the asynchronous reporting problem with the GovPX feed. The GovPX dataset reports consolidated trading information from several different brokers. Two or more trades might be occurring simultaneously at two or more different brokers, and a trade that started after another trade might be completed and get reported before the first. The high frequency of trading during the regular trading hours could exacerbate this trade time reporting problem and cause noise.[28]

An interesting finding is that the variance component associated with the public information shock is much stronger than any other components.[29] This is in line with the previous finding that macroeconomic shocks have a dominating effect on Treasury price movement (see Fleming and Remolona, 1997, 1999; Balduzzi et al., 2001; Green, 2004). The proportion of the public information component to total return volatility in the preopen and overnight periods is much higher than that reported for the equity market (see Barclay and Hendershott, 2003). Results suggest that a large portion of price discovery after hours is attributable to public information in the Treasury market.

Panel C reports the serial correlation of price changes over the day. Price changes are correlated due to the temporary effects of the cost of liquidity provision, bid and ask bounce, and rounding errors. Results show that serial correlation is quite modest. The model-implied first-order autocorrelation (IAC) is correspondent with the autocorrelation of observed price changes (AC) in terms of both magnitude and sign for most subperiods. Thus, the structural MRR model appears to capture the sources of serial correlation in transaction returns rather well.

### *5.3. Robustness checks*

The preceding results were estimated from a structural model conditional on a specification for the transaction price process and the belief revision process. To see if this may cause a specification bias, we next employ the nonparametric approach of Koski and Michaely (2000) to infer the informational role of trading directly from its price impact. This nonparametric approach relies solely on sequential transaction returns to measure the impact of trades on prices and so the result is independent of model specification. To examine the price impact of each trade, we calculate the mean cumulative transaction returns prior to and following the trade of interest. Following Green (2004), we calculate cumulative returns based on transaction prices for purchases and sales of three size groups: less than 4 million, greater than 8 million and between 4 and 8 million. To assess the price impact of trades in key trading periods, we calculate the cumulative returns for the preopen, open (8:30 to 10:00),

[27] See also Green (2004).

[28] The trade time report can also be biased by the workup process. An order may be hit (or taken) earlier but because of the workup process, the transaction time is posted only after all trading interest is exhausted at the initially-agreed price on at least one side of trading. We examined the sensitivity of our estimation to this problem using the adjustment procedure suggested by Boni and Leach (2004, pp. 179–184) and found this is not a serious concern.

[29] Note that the magnitude of asymmetric information, $(1-\rho^2)*\theta^2$, is high in the preopen (0.33) and overnight (0.28) periods, compared with those of the four daytime intervals (ranging from 0.21 to 0.29) and the postclose period (0.16). However, the implied variance of transaction price changes is also high in both preopen and overnight periods. This brings down the asymmetric information component of variance in percentage terms for these two periods.

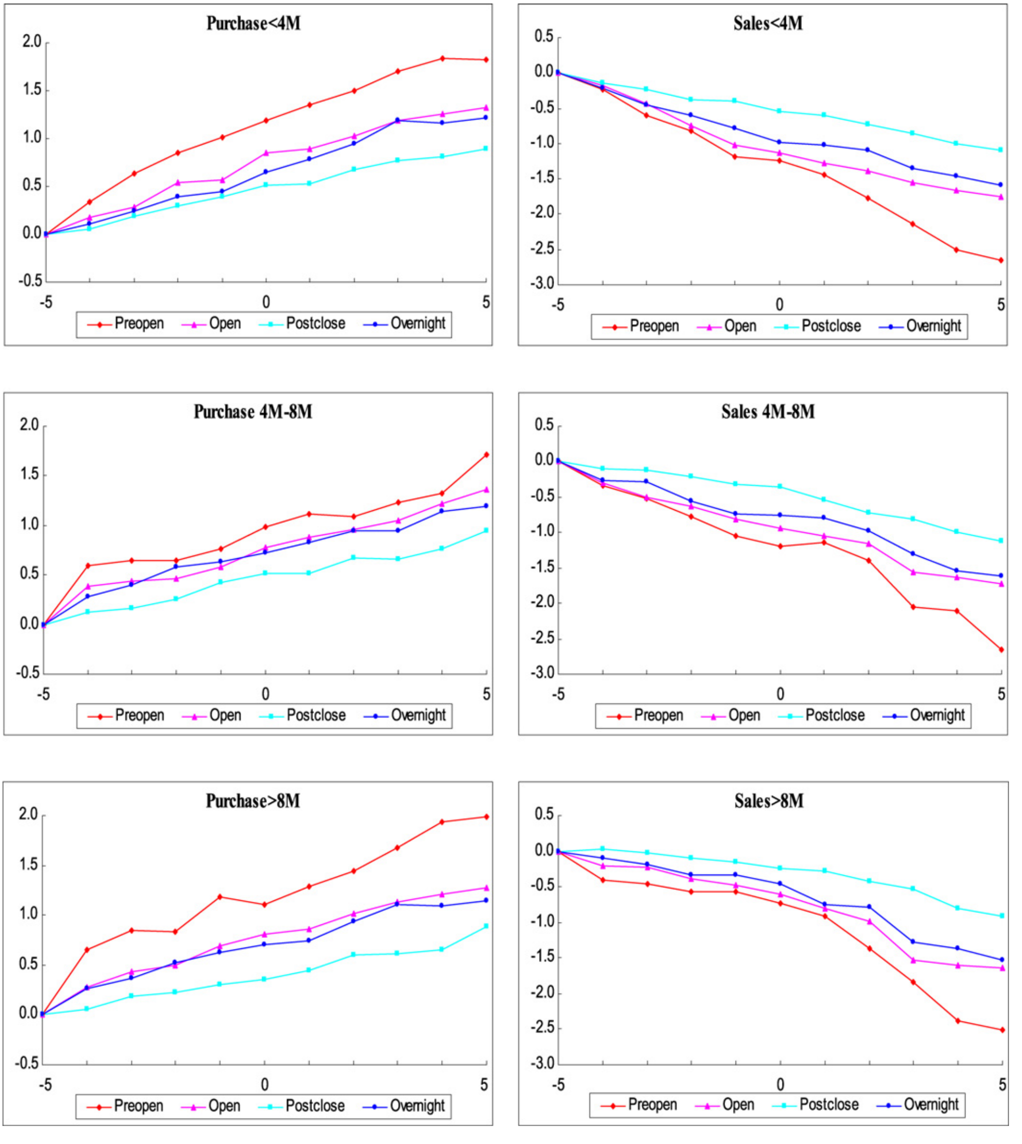


**Fig. 2.** Trading hours and trade impacts. This figure shows cumulative returns based on transaction prices relative to the purchase or sale of interest. Trades are grouped into three size categories: small trades are less than 4 million, medium trades are between 4 and 8 million, and large trades are greater than 8 million. The sample period is from 1/1/1992 to 12/31/1999. The preopen period contains trades between 7:30 and 8:30. The market open period contains trades between 8:30 and 10:00. The postclose period contains trades between 15:00 and 17:30 and the overnight period contains trades between 17:30 and 7:30.

postclose, and overnight periods. Fig. 2 displays the cumulative transaction returns for five trades before to five trades after the trade of interest for each period.[30]

[30] In the present case, we focus on the first 11 buy or sell trades in the preopen, daytime, and postclose periods. For the overnight period, we choose the first 11 buy or sell trades in the London trading hours which are more representative of overnight trading.

The results show that the patterns of price impact of trades are analogous across trading periods. Similar to previous findings, price generally continues to trend upward for purchases and downward for sales, consistent with the negative compensation for liquidity provision in Table 3 (see Green, 2004; Boni and Leach, 2004). Trade size does not appear to have a systematic influence on trade impact, though the price impact of trades is somewhat larger initially for purchase orders. The ambiguous effect of trade size is attributable to the fact that trade size can be negotiated through the interdealer broker. Our findings are consistent with the findings of other Treasury market studies. Huang et al. (2002) examine the information content of the number of trades and trade size and find that trade size does not have any information content. Fleming (2003) relates order flow to price changes and finds that the net number of trades better explains price changes.

The results in Fig. 2 are consistent with the estimate $\theta$ (or the parameter of the permanent price impact of trade) in Table 3. Given the trade size, the impact of trading on price changes is highest in the preopen period and is lowest in the postclose period. The price impact of trades in the overnight period is quite close to that during regular trading hours. Thus, the finding that trades in the preopen and overnight periods are informative in Table 3 is not conditional on the model structure. Results suggest that trading plays an important informational role in the preopen and overnight periods. Price impacts tend to be larger for sales than for purchases, consistent with the finding of Fleming (2003). One possible reason that purchase orders convey less information than sales is because a certain proportion of buys reflects routine rollover by customers from maturing to newly issued securities.

### 5.4. Public information announcement effects

Previous studies have documented that macroeconomic variables are the dominating factors affecting the price of Treasury securities, and trading reacts strongly to macroeconomic news announcements (see, for example, Green, 2004). Macroeconomic announcements induce revisions in market participants' beliefs, and heterogeneous interpretations of the news among traders. These tend to increase information asymmetry in the Treasury market. Furthermore, macroeconomic news announcements impact prices and generate strong hedging demands. Order flow may provide information as to whether the price for a particular security should be higher or lower even if trading provides no fundamental information about the security value. Dealers with larger customer order flows hold a greater informational advantage and so information asymmetry would tend to be higher following the macroeconomic announcement.

An advantage of the structural model employed in our analysis is its ability to capture the effects of different sources of information asymmetry. Other things being equal, we would expect the asymmetric information parameter $\theta$ to be higher subsequent to macroeconomic announcements. Likewise, the public information shock parameter $\sigma_p^2$ should also be higher after news announcements.

To assess the effects of news announcements, we collect data of macroeconomic news announcements from Bloomberg over the period from January 1992 to December 1999. We focus on the news release at 8:30 similar to Green (2004) because it is most influential.[31] We estimate the structural model for days with and without macroeconomic announcements and examine the difference in parameter estimates surrounding the news announcement time. We divide the trading period surrounding the early morning news announcement into three intervals: 7:30–8:00, 8:00–8:30 and 8:30–9:00. The first half of the preopen period, 7:30–8:00, is separated from the rest of the preopen period to provide finer information on the price discovery process ahead of the macroeconomic announcement.

Table 4 shows the results of estimation. In Panel A, we first report the results for the three half-hour intervals based on the entire sample that includes all trading days. Results show that information asymmetry is high in the first half hour (7:30–8:00) of the New York market. It then declines somewhat in the next half hour and rebounds after 8:30. The $\theta$ estimate (0.7138) for the 7:30–8:00 interval is slightly higher than that (0.7095) for the 8:30–9:00 interval.

[31] We supplement the Bloomberg data by the macroeconomic announcements in "The Week Ahead" section of *Business Week*. Macroeconomic news are released to the public at scheduled times. In the current analysis, we focus on the announcements at 8:30 over the period from 1992 to 1999.

**Table 4**
Macroeconomic announcement effects.

| | 7:30–8:00 | 8:00–8:30 | 8:30–9:00 | Wald test statistics |
|---|---|---|---|---|
| | | *Panel A. All trading days* | | |
| $\theta$ | 0.7138 | 0.6134 | 0.7095 | 99.26* |
| (S.E.) | (0.0152) | (0.0076) | (0.0065) | |
| $\phi$ | −0.3342 | −0.2456 | −0.2967 | 46.27* |
| (S.E.) | (0.0140) | (0.0070) | (0.0062) | |
| $\rho$ | 0.4095 | 0.4535 | 0.4867 | 122.75* |
| (S.E.) | (0.0070) | (0.0043) | (0.0029) | |
| $\sigma_p^2$ | 1.0905 | 0.5972 | 0.8414 | 140.66* |
| (S.E.) | (0.0451) | (0.0198) | (0.0202) | |
| $\sigma_e^2$ | 0.0536 | 0.0457 | 0.0586 | 3.05 |
| (S.E.) | (0.0121) | (0.0051) | (0.0054) | |

| No announcements | | | Announcement days | | | Wald test statistics |
|---|---|---|---|---|---|---|
| 7:30–8:00 | 8:00–8:30 | 8:30–9:00 | 7:30–8:00 | 8:00–8:30 | 8:30–9:00 | |
| | | | *Panel B. Announcement versus no-announcement days* | | | |
| *Adverse selection component* | | | | | | |
| $\theta_{N1}$ | $\theta_{N2}$ | $\theta_{N3}$ | $\theta_{A1}$ | $\theta_{A2}$ | $\theta_{A3}$ | $\theta_{A1}=\theta_{N1}$, $\theta_{A2}=\theta_{N2}$, $\theta_{A3}=\theta_{N3}$ |
| 0.7669 | 0.7079 | 0.6166 | 0.6449 | 0.5379 | 0.8174 | 362.63* |
| (0.0213) | (0.0108) | (0.0073) | (0.0213) | (0.0114) | (0.0111) | |
| *Order processing cost* | | | | | | |
| $\phi_{N1}$ | $\phi_{N2}$ | $\phi_{N3}$ | $\phi_{A1}$ | $\phi_{A2}$ | $\phi_{A3}$ | $\phi_{A1}=\phi_{N1}$, $\phi_{A2}=\phi_{N2}$, $\phi_{A3}=\phi_{N3}$ |
| −0.3673 | −0.3224 | −0.2522 | −0.2936 | −0.1944 | −0.3477 | 142.39* |
| (0.0195) | (0.0099) | (0.0069) | (0.0199) | (0.0104) | (0.0105) | |
| *Autocorrelation of trading* | | | | | | |
| $\rho_{N1}$ | $\rho_{N2}$ | $\rho_{N3}$ | $\rho_{A1}$ | $\rho_{A2}$ | $\rho_{A3}$ | $\rho_{A1}=\rho_{N1}$, $\rho_{A2}=\rho_{N2}$, $\rho_{A3}=\rho_{N3}$ |
| 0.4206 | 0.4647 | 0.4941 | 0.3947 | 0.4372 | 0.4781 | 20.55* |
| (0.0092) | (0.0054) | (0.0039) | (0.0106) | (0.0069) | (0.0044) | |
| *Variance of public information* | | | | | | |
| $\sigma_{pN1}^2$ | $\sigma_{pN2}^2$ | $\sigma_{pN3}^2$ | $\sigma_{pA1}^2$ | $\sigma_{pA1}^2$ | $\sigma_{pA3}^2$ | $\sigma_{pA1}^2=\sigma_{pN1}^2$, $\sigma_{pA2}^2=\sigma_{pN2}^2$, $\sigma_{pA3}^2=\sigma_{pN3}^2$ |
| 1.1297 | 0.6175 | 0.5255 | 1.0433 | 0.5678 | 1.1984 | 261.77* |
| (0.0591) | (0.0256) | (0.0186) | (0.0701) | (0.0312) | (0.0374) | |
| *Variance of pricing discreteness* | | | | | | |
| $\sigma_{eN1}^2$ | $\sigma_{eN2}^2$ | $\sigma_{eN3}^2$ | $\sigma_{eA1}^2$ | $\sigma_{eA1}^2$ | $\sigma_{eA3}^2$ | $\sigma_{eA1}^2=\sigma_{eN1}^2$, $\sigma_{eA2}^2=\sigma_{eN2}^2$, $\sigma_{eA3}^2=\sigma_{eN3}^2$ |
| 0.0559 | 0.0439 | 0.0531 | 0.0508 | 0.0499 | 0.0693 | 2.39 |
| (0.0161) | (0.0066) | (0.0046) | (0.0184) | (0.0079) | (0.0105) | |

*Notes*. This table reports parameter estimates for the five-year on-the-run Treasury note in the period of 7:30–9:00. The sample period is 1/1/1992–12/31/1999. Parameters $\theta$, $\phi$, $\sigma_p^2$, $\sigma_e^2$ and $\rho$ are estimated from the moment conditions in (4). Panel A reports the estimation results for the sample including all trading days. Panel B reports the results for the samples including announcement days and no-announcement days, respectively. The subscript "*N*" refers to the estimates on days with no macroeconomic announcements. Subscript "*A*" refers to the estimates on days with announcements. Subscripts 1, 2 and 3 refer to the periods 7:30–8:00, 8:00–8:30, and 8:30–9:00, respectively. We report the Wald test statistic on the hypothesis that parameters at different time intervals are equal.

* Significance at least at the 5% level.

Panel B reports the parameter estimates for the days with and without scheduled macroeconomic announcements, respectively. On days with no announcements, the value of $\theta$ is highest (0.7669) at the 7:30–8:00 interval and then declines over the next two intervals (0.7079 between 8:00 and 8:30, and 0.6166 between 8:30 and 9:00). Thus, information asymmetry is usually quite high in the preopen period in the absence of major economic news announcements.

Results show a different picture on days with macroeconomic announcements. The $\theta$ value starts at 0.6449 between 7:30 and 8:00 but declines to 0.5379 between 8:00 and 8:30. It then jumps to 0.8174 after the announcement of macroeconomic news at 8:30. Similarly, the public information shock parameter $\sigma_p^2$ is highest (1.1984) at the 8:30–9:00 interval on days with macroeconomic announcements. By contrast, $\sigma_p^2$ is quite low (0.5255) between 8:30 and 9:00 on days without macroeconomic

**Table 5**
Monday effect.

| | Preopen | | Daytime trading | | | | | | | | Postclose | | Overnight | | Wald test | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7:30–8:30 | | 8:30–10:00 | | 10:00–12:00 | | 12:00–14:00 | | 14:00–15:00 | | 15:00–17:30 | | 17:30–7:30 | | | |
| | M | O | M | O | M | O | M | O | M | O | M | O | M | O | (1) | (2) |
| $\theta$ | 0.72 | 0.63 | 0.54 | 0.62 | 0.52 | 0.56 | 0.47 | 0.54 | 0.52 | 0.59 | 0.39 | 0.45 | 0.57 | 0.56 | 20.27* | 266.09* |
| (S.E.) | (0.02) | (0.01) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.01) | (0.01) | (0.00) | (0.02) | (0.01) | | |
| $\phi$ | −0.32 | −0.26 | −0.22 | −0.26 | −0.23 | −0.24 | −0.21 | −0.23 | −0.24 | −0.25 | −0.16 | −0.19 | −0.31 | −0.32 | 8.15* | 67.78* |
| (S.E.) | (0.02) | (0.01) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.02) | (0.01) | | |
| $\sigma_p^2$ | 0.90 | 0.71 | 0.33 | 0.59 | 0.37 | 0.43 | 0.30 | 0.40 | 0.33 | 0.48 | 0.35 | 0.40 | 1.51 | 1.30 | 5.99* | 424.72* |
| (S.E.) | (0.07) | (0.02) | (0.01) | (0.01) | (0.02) | (0.01) | (0.01) | (0.01) | (0.02) | (0.01) | (0.02) | (0.01) | (0.08) | (0.03) | | |
| $\sigma_e^2$ | 0.01 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.03 | 4.21* | 8.23 |
| (S.E.) | (0.02) | (0.01) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.02) | (0.01) | | |
| $\rho$ | 0.45 | 0.44 | 0.50 | 0.49 | 0.49 | 0.49 | 0.47 | 0.47 | 0.47 | 0.46 | 0.40 | 0.42 | 0.35 | 0.36 | 0.38 | 10.02 |
| (S.E.) | (0.01) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | (0.01) | (0.00) | | |

*Notes*. This table reports parameter estimates for the five-year on-the-run Treasury note over the period 1/1/1992–12/31/1999. Parameters $\theta$, $\phi$, $\sigma_p^2$, $\sigma_e^2$, and $\rho$ are estimated from the moment conditions in (4) for each of the seven time intervals (7:30–8:30, 8:30–10:00, 10:00–12:00, 12:00–14:00, 14:00–15:00, 15:00–17:30, and 17:30–7:30). M and O represent Monday and other working days, respectively. We report the Wald test statistics on the hypothesis that parameters for Monday and other working days are equal. Wald statistic (1) reports the test that the parameter is significantly different in the preopen between Monday and other weekdays while (2) reports the result for the test that the parameter is significantly different between Monday and other weekdays across all intraday periods of the 24-hour day.

* Significance at the 5% level.

announcements. These findings are consistent with the theoretical prediction, suggesting that the structural model captures the effect of public information flow and the variation in the informational role of trading over different time intervals quite well.

### 5.5. *Why are trades more informative in the preopen period?*

In the previous sections, we showed that information asymmetry is much higher in the preopen period. An important question is what really causes this high information asymmetry. The literature suggests that heterogeneous interpretation of public information and private information of client order flow are two important sources of information asymmetry in the Treasury market. In this section, we examine whether these factors are responsible for high information asymmetry in the preopen period.

One way to assess the importance of heterogeneous interpretation of public information is to examine whether there is a significant Monday effect. News accumulates over the weekend when the market is closed and as a consequence, there is more information to digest in early Monday morning. If heterogeneous interpretation is important, we should observe that the information asymmetry parameter $\theta$ and the variance component due to public information shocks $\sigma_p^2$ in the preopen period to be significantly larger on Monday than on other weekdays.

To test this hypothesis, we re-estimate the structural model by dividing the sample into two groups: Monday and other weekdays. Table 5 reports the results of estimation. Results show that $\theta$ in the preopen period is significantly higher on Monday (0.72) than on other weekdays (0.63). We report two Wald test statistics. The first test statistic shows the significance of the difference between the parameter values on Monday and other weekdays in the preopen period only whereas the second statistic tests the significance of the difference between Monday and other weekdays for the parameter values across all seven intraday periods. Results show that both test statistics for $\theta$ are significant at the five percent level. We also estimate the Monday effect for days with and without macroeconomic announcements separately to control for the effect of anticipated announcements. The results are quite similar. $\theta$ values are 0.73 and 0.68 for Monday and other weekdays, respectively when there are no macroeconomic announcements and 0.63 and 0.56, respectively when there are news announcements.[32] In either case, the $\theta$ value is significantly higher on Monday morning at the five percent level. Results suggest that information accumulation over the weekend contributes to high information asymmetry in the preopen period. In addition, $\sigma_p^2$ is significantly higher on Monday (0.90) than on other weekdays (0.71).[33] The magnitude of this parameter directly reflects differences in traders' interpretation of public news (see Madhavan et al., 1997, p. 1055). Results suggest that heterogeneity in news interpretation heightens in early Monday morning.

We next examine the importance of client order flow for asymmetric information of trading in the preopen period. The trading window surrounding the open of the U.S. Treasury futures trading at 8:20 is ideal for examining this effect. Previous studies on the equity market have found that order flow reveals more private information before the market opens (see, for example, Barclay and Hendershott, 2003). A similar situation is likely to occur in the Treasury bond futures market. If so, we would expect higher information asymmetry before than after the open of the Treasury bond futures trading.

Panel A of Table 6 reports the order flow effect on asymmetric information based on the sample that includes all trading days. Model parameters, $\theta$, $\phi$, $\sigma_p^2$, $\sigma_e^2$, and $\rho$, are estimated for the 10-minute intervals immediately before and after the open of the futures market at 8:20. As shown, standard errors are generally quite low and all parameter estimates are significant at least at the five-percent level. The Wald test shows that information asymmetry ($\theta$) is significantly higher before than after the open of the futures market (0.6478 vs. 0.5470). This finding is consistent with the contention that the order flow in the Treasury markets contains more information immediately before the open of the futures market. By contrast, the cost for supplying liquidity is significantly lower before than after 8:20, suggesting that dealers are more willing to provide liquidity when trading activity increases.

The results above are obtained from the sample including all trading days without controlling for the effect of anticipated announcements. To control this effect, we further divide the sample into days with and without macroeconomic announcements and provide separate parameter estimates for the time intervals before and after the open of the futures market. Results are reported in Panel B of Table 6. As shown, $\theta$ is always higher before the open of the futures market regardless of whether there is a macroeconomic announcement or not. Results suggest that private information of client order flow is an important factor contributing to high information asymmetry in the preopen period.

### 5.6. *The efficiency of overnight price discovery*

Bid–ask spreads are higher and trading volume is lower after hours than during regular trading hours. Higher transaction cost and lower liquidity may cause temporary price changes which are subsequently reversed. This begs the question of whether overnight price changes can provide a reliable guide to the future price to occur during the daytime or they are simply pure noise and contain no information signal.

To examine whether overnight price is efficient, we estimate the following regressions:

$$\ln\left(NY_t^o\right) - \ln\left(NY_{t-1}^c\right) = \alpha + \beta\left(\ln\left(TK_t^c\right) - \ln\left(NY_{t-1}^c\right)\right) + \varepsilon_t, \tag{5}$$

$$\ln\left(NY_t^o\right) - \ln\left(NY_{t-1}^c\right) = \alpha + \beta\left(\ln\left(LN_t^c\right) - \ln\left(NY_{t-1}^c\right)\right) + \varepsilon_t, \tag{6}$$

$$\ln\left(NY_t^o\right) - \ln\left(NY_{t-1}^c\right) = \alpha + \beta_1\left(\ln\left(LN_t^c\right) - \ln\left(NY_{t-1}^c\right)\right) + \beta_2\left(\ln\left(TK_t^c\right) - \ln\left(NY_{t-1}^c\right)\right) + \varepsilon_t, \tag{7}$$

$$\ln\left(NY_t^o\right) - \ln\left(NY_{t-1}^c\right) = \alpha + \beta_1\left(\ln\left(TK_t^c\right) - \ln\left(NY_{t-1}^c\right)\right) + \beta_2\left(\ln\left(LN_t^c\right) - \ln\left(LN_t^o\right)\right) + \varepsilon_t. \tag{8}$$

In (5), we regress the New York overnight return against the Tokyo market return. If price in the Tokyo market is efficient, its change should provide an unbiased prediction of the overnight price change in New York and the $\beta$ coefficient should be close to one. In (6), we regress the New York overnight return against the London market return. Again, the price change in the London market should be an unbiased predictor of the overnight price change in New York, if the London market is efficient. In

[32] In the interest of brevity, we do not report the detailed results here. These results are available upon request.

[33] This result holds even after controlling for the effect of anticipated macroeconomic announcements.

**Table 6**
The order flow effect in the preopen period.

| | 8:10–8:20 | 8:20–8:30 | Wald test statistics |
|---|---|---|---|
| *Panel A. All trading days* | | | |
| $\theta$ | 0.6478 | 0.5470 | 31.64* |
| (S.E.) | (0.0154) | (0.0094) | |
| $\phi$ | −0.3015 | −0.1662 | 66.53* |
| (S.E.) | (0.0142) | (0.0088) | |
| $\sigma_p^2$ | 0.6166 | 0.5133 | 8.60* |
| (S.E.) | (0.0291) | (0.0227) | |
| $\sigma_e^2$ | 0.0408 | 0.0482 | 0.55 |
| (S.E.) | (0.0077) | (0.0061) | |
| $\rho$ | 0.4730 | 0.4393 | 11.53* |
| (S.E.) | (0.0080) | (0.0059) | |

| No announcements | | Announcement days | | Wald test statistics |
|---|---|---|---|---|
| 8:10–8:20 | 8:20–8:30 | 8:10–8:20 | 8:20–8:30 | |
| *Panel B. Announcement versus no-announcement days* | | | | |
| *Adverse selection component* | | | | |
| $\theta_{N1}$ | $\theta_{N2}$ | $\theta_{A1}$ | $\theta_{A2}$ | $\theta_{A1} = \theta_{N1}, \theta_{A2} = \theta_{N2}$ |
| 0.7187 | 0.5943 | 0.5502 | 0.4773 | 65.89* |
| (0.0209) | (0.0121) | (0.0224) | (0.0149) | |
| *Order processing cost* | | | | |
| $\phi_{N1}$ | $\phi_{N2}$ | $\phi_{A1}$ | $\phi_{A2}$ | $\phi_{A1} = \phi_{N1}, \phi_{A2} = \phi_{N2}$ |
| −0.3551 | −0.1948 | −0.2275 | −0.1247 | 35.44* |
| (0.0194) | (0.0115) | (0.0206) | (0.0135) | |
| *Autocorrelation of trading* | | | | |
| $\rho_{N1}$ | $\rho_{N2}$ | $\rho_{A1}$ | $\rho_{A2}$ | $\rho_{A1} = \rho_{N1}, \rho_{A2} = \rho_{N2}$ |
| 0.4798 | 0.4534 | 0.4637 | 0.4175 | 9.51* |
| (0.0105) | (0.0074) | (0.0125) | (0.0098) | |
| *Variance of public information* | | | | |
| $\sigma_{pN1}^2$ | $\sigma_{pN2}^2$ | $\sigma_{pA1}^2$ | $\sigma_{pA1}^2$ | $\sigma_{pA1}^2 = \sigma_{pN1}^2, \sigma_{pA2}^2 = \sigma_{pN2}^2$ |
| 0.6605 | 0.5071 | 0.5555 | 0.5244 | 3.41 |
| (0.0380) | (0.0295) | (0.0452) | (0.0358) | |
| *Variance of pricing discreteness* | | | | |
| $\sigma_{eN1}^2$ | $\sigma_{eN2}^2$ | $\sigma_{eN3}^2$ | $\sigma_{eA1}^2$ | $\sigma_{eA1}^2 = \sigma_{eN1}^2, \sigma_{eA2}^2 = \sigma_{eN2}^2$ |
| 0.0362 | 0.0536 | 0.0488 | 0.0406 | 1.70 |
| (0.0102) | (0.0079) | (0.0116) | (0.0095) | |

*Notes*. This table reports estimates of model parameters for the five-year on-the-run Treasury note before and after 8:20, the time when the Treasury bond futures market opens. The sample period is from 1/1/1992 to 12/31/1999. Panel A includes all trading days whereas Panel B reports the results for days with and without macroeconomic announcements. The last column reports the Wald test statistics on the hypothesis that parameters in 8:10–8:20 equal parameters in 8:20–8:30.

* Significance at the 5% level.

the next regression, we include both the Tokyo and London market price changes as the explanatory variables. If the London market is efficient, $\beta_1$ should be close to one, and including the Tokyo market return in the regression should have no incremental explanatory power for the overnight New York price change because the London market return (from New York close to London close) has already incorporated the information in the Tokyo market. In the last regression, we include the Tokyo market return and the London open-to-close return as explanatory variables. Here we divide the overnight return into two parts to assess the incremental contribution of the London market to price discovery in the New York open.

Regression models in (7) and (8) enable us to jointly test the pricing efficiency of both markets and the incremental contribution of the London market to the price discovery at the New York market open. We set 17:30 as the New York close, 2:30 as the Tokyo close, 7:00 as the London close and

**Table 7**
Efficiency of overnight price discovery.

| | | | | |
|---|---|---|---|---|
| | $\ln(NY_t^o)-\ln(NY_{t-1}^c)=\alpha+\beta(\ln(TK_t^c)-\ln(NY_{t-1}^c))+\varepsilon_t$ | | | |
| | $\alpha$ | $\beta$ | | $R^2$ |
| Parameter | −0.0043 | 0.8793 | | 69.91% |
| Standard error | (0.0035) | (0.0133) | | |
| | Test: $\beta=1$ ($t=-9.08$) | | | |
| | $\ln(NY_t^o)-\ln(NY_{t-1}^c)=\alpha+\beta(\ln(LN_t^c)-\ln(NY_{t-1}^c))+\varepsilon_t$ | | | |
| Parameter | −0.0043 | 0.9764 | | 94.88% |
| Standard error | (0.0015) | (0.0052) | | |
| | Test: $\beta=1$ ($t=-4.54$) | | | |
| | $\ln(NY_t^o)-\ln(NY_{t-1}^c)=\alpha+\beta_1(\ln(LN_t^c)-\ln(NY_{t-1}^c))+\beta_2(\ln(TK_t^c)-\ln(NY_{t-1}^c))+\varepsilon_t$ | | | |
| | $\alpha$ | $\beta_1$ | $\beta_2$ | $R^2$ |
| Parameter | −0.0042 | 1.0154 | −0.0471 | 94.93% |
| Standard error | (0.0015) | (0.0106) | (0.0111) | |
| | Test 1: $\beta_1=1$ ($t=1.45$) | | | |
| | $\ln(NY_t^o)-\ln(NY_{t-1}^c)=\alpha+\beta_1(\ln(TK_t^c)-\ln(NY_{t-1}^c))+\beta_2(\ln(LN_t^c)-\ln(LN_t^o))+\varepsilon_t$ | | | |
| Parameter | −0.0043 | 0.9693 | 1.0136 | 94.91% |
| Standard error | (0.0015) | (0.0056) | (0.0122) | |
| | Test 1: $\beta_1=1$ ($t=-5.48$); Test 2: $\beta_2=1$ ($t=1.11$) | | | |

*Notes*. This table reports the regression tests of price efficiency of Tokyo and London markets. The superscript "c" refers to the close time and superscript "o" refers to the open time. The open and close time of the New York market are set at 8:00 and 17:30. The open and close time of the Tokyo market are set to 18:30 at $t-1$ and 2:30 at $t$. The open and close time of the London market are set at 3:00 and 7:00. Standard errors are in parentheses below coefficient estimates.

8:00 as the New York open.[34] This setting excludes crossover times to obtain cleaner price changes pertaining to a particular trading location.

The beta coefficients should be close to one only if the overnight market is efficient and returns are serially uncorrelated and measured without error. The latter condition is however unlikely to hold for two major reasons. First, overnight trades are subject to the bid–ask bounce which induces a measurement error unrelated to the true price movement. Because the bid–ask spread is higher in the overnight period, this measurement error is expected to be larger than in the daytime period. Second, overnight trading is infrequent. Infrequent trading leads to spurious price variations since the measurement interval itself is subject to variations. When the independent variable in the regression is measured with errors, beta coefficient will be less than one. Specifically, in the case of a univariate regression, it can be shown that the probability limit of the estimated coefficient is $\operatorname{plim}\hat{\beta}=\beta(\frac{\sigma_i^2}{\sigma_i^2+\sigma_u^2})$ where $\beta$ is the true coefficient, $\sigma_i^2$ is the return variance of an overseas market ($i=$ London or Tokyo) and $\sigma_u^2$ is the variance of the measurement error term associated with the overseas market return. The higher the pricing error in the overseas market, the lower the beta estimate.

Table 7 reports the results of regressions. The result for the first regression shows that the coefficient of Tokyo price change (from the New York close to the Tokyo close) is significantly different from zero, indicating that it has predictive ability for New York overnight price change. However, the coefficient is significantly less than one. In the second regression, the beta coefficient (0.9764) of the London price change (from the New York close to the London close) is much higher than the coefficient of Tokyo price change (0.8793) in the first regression. The result indicates that the London price is less noisy and has a greater predictive power for New York opening price.

In the next regression, we include both the Tokyo price change and the London price change (from the New York close to the London close) as explanatory variables. The $R^2$ value is almost unchanged, indicating that including the Tokyo price change in the regression does not significantly increase the explanatory power of the model for the New York opening price. If London price is efficient, it should have incorporated not only the information in the Tokyo market but also the information released in its own market. Since new information reflected in Tokyo price movements is subsequently

[34] Fleming (1997) uses a similar setting to exclude potential crossover time effect.

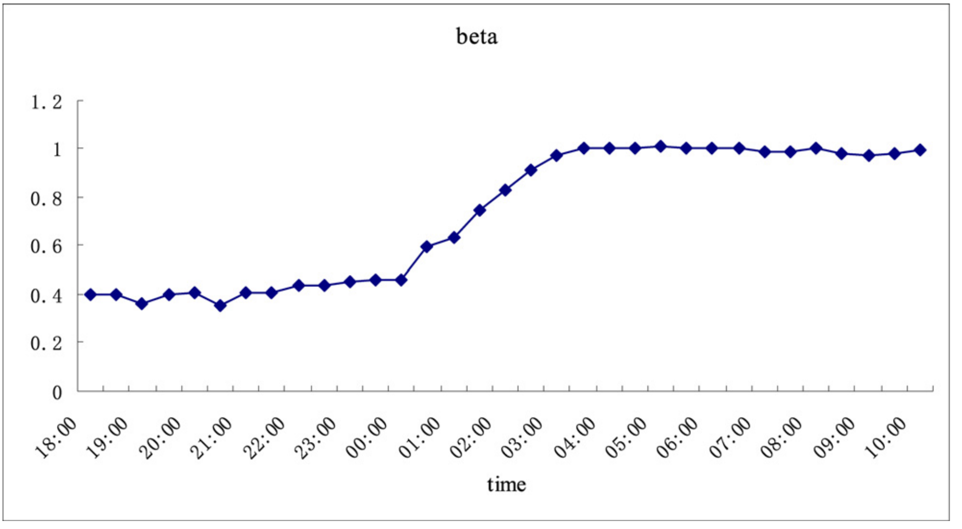


**Fig. 3.** Unbiasedness regression by trading period. This figure shows the $\beta$ coefficient of regressing New York close-to-close return (RETCC) on the return from close to time $t$ (RETCT) at 30-minute intervals from 17:30 to 10:00 next morning. The sample period is from 1/1/1992 to 12/31/1999.

incorporated in London price, adding the Tokyo market return should not increase the predictive power for the future path of New York price. Consistent with this prediction, the coefficient of the Tokyo return ($\beta_2$) is close to zero. On the other hand, the coefficient of the London return ($\beta_1$) is significantly different from zero and insignificantly different from one, indicating that the London price is unbiased.

We next include the Tokyo market return (from New York close to Tokyo close) and the London open-to-close return as explanatory variables to examine the contribution of each market to price discovery in the New York open. The London open-to-close return reflects new information in the London market. As shown, the London market trading adds the explanatory power to the model. Compared to the result in the first regression, which includes only the Tokyo market return as the explanatory variable, the $R^2$ value increases by 25%. The coefficient of the London open-to-close return ($\beta_2$) is significantly different from zero and insignificantly differently from one, suggesting that the London daytime market is informationally efficient. Results show that both Tokyo and London markets contribute significantly to price discovery in the New York market open.

We further examine the efficiency of price discovery in the overnight period using the unbiasedness regression suggested by Biais et al. (1999). Specifically, we regress the close-to-close New York return ($R_{cc}$) on the return from the New York close to the end of time period $t$ ($R_{ct}$):

$$R_{cc} = \alpha + \beta R_{ct} + \varepsilon_t. \tag{9}$$

The unbiasedness regression is essentially a generalization of the regression models in (5) and (6). By estimating (9) for finer time intervals, we provide more detailed information on the price discovery process throughout the entire overnight trading period. We estimate the regression for each 30-minute interval ($t$) from 17:30 to 10:00 next morning. Noise in market prices can be attributed to microstructure effects (e.g., bid–ask spreads) or temporary pricing errors associated with liquidity trades. The $\beta$ value reflects the signal-to-noise ratio. The noisier the price, the lower the $\beta$. The extent to which $\beta$ is less than one measures the noisiness of the overnight market price.

Fig. 3 shows estimates of $\beta$ coefficients. The signal-to-noise ratio ($\beta$) is low at the beginning of the overnight period (Tokyo market trading). The beta estimate hovers initially around 0.4 until midnight and then increases steadily to about 0.9 before the London market opens. The signal-to-noise ratio is much higher during the London trading period. The beta moves closer to one before 4:00 and stays around that level afterwards. Results confirm the finding in Table 7 that the London market

**Table 8**
Variance decomposition.

| | Preopen | Daytime trading | | | | | Postclose | Overnight | New York |
|---|---|---|---|---|---|---|---|---|---|
| | 7:30–8:30 | 8:30–15:00 | 8:30–10:00 | 10:00–12:00 | 12:00–14:00 | 14:00–15:00 | 15:00–17:30 | 17:30–7:30 | 7:30–17:30 |
| Return variance | 37.9943 | 558.5846 | 244.9620 | 145.4515 | 78.7636 | 72.1743 | 45.2305 | 134.0626 | 651.1683 |
| Percentage of total variance | 5.30% | 77.86% | 34.15% | 20.28% | 10.98% | 10.06% | 6.30% | 18.69% | |
| Trading time (h) | 1 | 6.5 | 1.5 | 2 | 2 | 1 | 2.5 | 14 | 10 |
| Percentage | 4.17% | 27.08% | 6.25% | 8.33% | 8.33% | 4.17% | 10.42% | 58.33% | 41.67% |
| Variance per hour | 37.9943 | 85.9361 | 163.3080 | 72.7257 | 39.3818 | 72.1743 | 18.0922 | 9.5759 | 65.1168 |
| Yield change variance | 2.1040 | 31.0628 | 13.6432 | 8.1072 | 4.3416 | 4.0204 | 2.5099 | 5.6365 | 36.2182 |
| Percentage of total variance | 5.48% | 80.84% | 35.51% | 21.10% | 11.30% | 10.46% | 6.53% | 14.67% | |
| Variance per hour | 2.1040 | 4.7789 | 9.0955 | 4.0536 | 2.1708 | 4.0204 | 1.0040 | 0.4026 | 3.6218 |

*Notes*. This table reports the results of variance decomposition using returns and yield changes. The data of when-issued market are used to calculate the overnight return when the on the run security changes so that the return is measured from the same security. The variance of the 24-hour return is decomposed into 7 trading periods. Returns and yield changes are expressed in basis points.

price is more efficient than the Tokyo market price. As the trading progresses, price becomes less noisy, similar to the finding for the after-hours equity market (see Barclay and Hendershott, 2003). Results suggest that trading activity in the overnight market is an important part of the Treasury price discovery process.

Another way of assessing the information revealed by trading is to look into the volatility of returns in each time period. Microstructure theory suggests that information revealed through trading causes volatility. Barclay et al. (1990) and Craig et al. (1995) have focused on return variance to measure information efficiency and price discovery across markets. To analyze information flow through variance over the day, we divide the 24-hour return into seven nonoverlapping intervals as in Table 3 (7:30–8:30, 8:30–10:00, ..., 17:30–7:30). We then calculate the variance of returns for each interval based on daily observations. In calculating the overnight return, we use the when-issued price to ensure that price changes are based on the same on-the-run security when an on-the-run issue becomes off the run whenever there is an auction (see also Fleming and Lopez, 1999).

Table 8 reports the variance decomposition over the trading day. Returns are expressed in basis points. The results show that a large portion of the 24-hour variance of returns occurs in the regular daytime trading period in New York (8:30–15:00). This period represents only 27% of the trading day but captures 78% of the 24-hour return variance. By contrast, the overnight period represents 58% of the trading day and captures only 19% of the total daily return variance.[35] Results suggest that information flow is not constant throughout the day. Instead, more information is revealed per hour during the daytime (85.93) than the overnight period (9.58). This is not surprising given that Treasury securities are the U.S. government debt and most news is released during the trading period of the New York market. The preopen period represents 4% of the day and captures about 5% of the return variance whereas the postclose period represents 10% of the day but captures only 6% of the daily return variance. The variance per hour is 37.99 and 18.09, for the preopen and postclose, respectively. Thus, less information is revealed in the postclose period per hour.

For comparison, we also calculate the variance of yield changes in basis points as in Fleming and Lopez (1999). The results based on yield changes are reported in the lower panel of Table 8. Results show a pattern similar to that of return variance reported in the upper panel. The total yield change variance is 36.22 in New York trading period (from 7:30 to 17:30) and 5.64 in the overnight period. In terms of total volatility per hour, the New York volatility is about nine times that of overnight

[35] We divide the variance in each period by the total daily return variance. The sum of the variance is slightly more than 100% due to modest covariances between the nonoverlapping periods. Daily return and yield change variances are 717.38 and 38.42, respectively.

volatility (or 3.62 vs. 0.40), which is very close to Fleming and Lopez's report. Results again show that the volatility per hour is small in the overnight period and the daytime trading has the most price discovery.[36] Although volatility per hour is low, the information content per trade in the overnight period is comparable to that in the daytime period as shown earlier (see Table 2). Taken together, this suggests that despite low volume and volatility, individual trades in the overnight period contain rich information.

## 6. Conclusions

We investigate the informational role of trading in the round-the-clock U.S. Treasury market using a long-span intraday data sample. We find that the information role of trades varies over the 24-hour day. Trades are more likely to be informed and information cost tends to be higher in the preopen period. Information asymmetry is reduced rapidly in New York after the close of the futures market and trades are less likely to be informed in the postclose period. These results are generally consistent with the findings of Barclay and Hendershott (2003) for the equity market. As the proportion of informed trading cost and the intensity of informed trading drop, the liquidity cost component of bid–ask spread becomes higher in the postclose period than in any other periods. Empirical evidence shows that in the interdealer Treasury market, bid–ask spreads predominantly reflect dealers' compensation for informed trading costs, which declines over the daytime trading period.

Intraday asymmetric information patterns are affected by public information and customer order flow information. Information asymmetry is higher in the preopen period (7:30–8:00) than any other periods on days with no macroeconomic announcements. By contrast, information asymmetry is higher in the opening period of the New York market (8:30–9:00) than in any other periods on days with macroeconomic announcements. Moreover, information asymmetry is higher on Monday morning, reflecting more information to digest after the market closes over the weekend. Information asymmetry is also higher before than after the open of the futures market, indicating that trades reveal more information before the open of the Treasury bond futures trading. These findings suggest that both heterogeneous interpretation of public information and private information of client order flow are key factors contributing to high information asymmetry in the preopen period.

Unlike the equity market, price volatility in the Treasury market is predominantly driven by public information shocks. While private information flow contributes to price volatility, its effect is much lower than that of public information shocks. Although overnight and preopen trading accounts only a fraction of the trading activity that occurs during the trading day, individual trades contain rich information. The preponderance of the public information effect in the Treasury market is at odds with Barclay and Hendershott's (2003) finding for the equity market.

More importantly, we find that overnight trading generates significant price discovery although volume and volatility are low and trading cost is relatively high. The degree of information asymmetry in the overnight period is comparable to that in most of the regular daytime trading period. This finding shows a striking difference from Barclay and Hendershott's (2003) finding that the overnight period has almost no contribution to price discovery in the equity market. Results show that little trading from overseas can generate significant price discovery. Finally, overnight price changes are an unbiased predictor of the New York close-to-open price changes. Results suggest that trading activity in the overnight market is an important part of the Treasury price discovery process.

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[36] Price discovery and volatility are highly related although volatility measures total price changes whereas price discovery is associated mainly with the permanent component of price changes.

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