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What is Special about the Opening ? Evidence from NASDAQ

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Abstract

This paper reports that prices of NASDAQ stocks are more volatile around the market opening than closing. Evidence from individual stocks indicates that there is a systematic relationship between the excess opening volatility and trading activity. Much of the excess opening volatility is related to two factors, bid-ask bounce and price formation. For inactively traded stocks, bid-ask bounce contributes almost all of the transitory volatility as opposed to 20% of the transitory volatility for actively traded stocks. On the other hand, price formation is the primary source of the difference between the opening and closing variances for actively traded stocks. We also find price formation occurs in the absence of trading as quotes updated prior to the 9:30 A.M. start of trading reflect new information.

I . Introduction

That opening prices are more volatile than closing prices for stocks traded on the New York Stock Exchange (NYSE) has become a stylized fact since the work of Amihud and Mendelson (1987) and Stoll and Whaley (1990). Their original

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conjectures cite the structure of trading on the NYSE as making opening prices more volatile than prices in the balance of the trading day. However, subsequent empirical studies by a number of authors report results similar to the NYSE for different exchanges and trading mechanisms. More recently, the focus has turned to the impact of trading on price formation; trading itself plays an important role in the price discovery process because trading conveys private information. In a noisy rational expectations framework, Grundy and McNichols (1989), Brown and Jennings (1989), and Shalen (1993) show that following a non-trading period, greater informational uncertainty on the open than on the close may cause the first price of a trading session to contain a transitory volatility component absent from the last price. By definition, transitory volatility is the variance in excess of that generated by information flow. Amihud and Mendelson (1991) and Gerety and Mulherin (1994) present empirical evidence consistent with the resolution of uncertainty as trading progresses during the day.

The focus of this paper is to investigate the relationship between trading frequency and two factors which are sources of transitory volatility, price formation and bid-ask bounce. Because there is a well known empirical relationship between trading frequency and volatility, trading frequency is a natural candidate for studying transitory volatility. Price formation implies that the uncertainty regarding the price of a security is gradually reduced through multiple rounds of trading. Bid-ask bounce refers to the fluctuation of transaction prices between the bid and ask, which naturally arises as buy and sell orders arrive randomly. The relationship between trading frequency and the sources of transitory volatility is addressed by partitioning the sample into deciles based on trading frequency. In order to separate price formation effects from bid-ask bounce effects we use both bid-ask quotes and transaction prices in the analysis.

Price formation models predict higher opening variance for the true price of an asset. Consequently, inferences should be based on the evolution of the true rather than the observed price. The use of quote data (either the bid price, the ask price, or the average of the bid and ask) has been previously advocated as an alternative to transactions data for drawing inferences about the path of the true price (Kaul and Nimalendran (1990)). While quotes are not to be confused with the true price, quote-based return variance may better reflect the variance of the true return than does transactions data.

Bid-ask bounce affects the estimate of the ratio of open-to-open return variance

to close-to-close return variance in several ways. First, it inflates the closing variance for stocks traded in markets that lack an opening spread, such as the NYSE (Amihud and Mendelson (1987)). Second, it inflates both variances in markets where both an opening and closing spread exist, which may bias the estimated variance ratio (Jones, Kaul, and Lipson (1994a)). Third, if either the bid-ask spread or the distribution of transaction prices within the bid and ask quotes differs significantly between the open and close, the observed variance ratio may deviate from the variance ratio derived from the true equilibrium price. Comparing variance ratios calculated from quote data with those calculated from transactions data provides evidence of the effect of bid-ask bounce on transitory volatility.

To our knowledge there has not been a thorough examination of intraday transitory volatility using quote data. The lack of this line of research can be attributed mainly to the nonexistence of pre-opening quotes on the NYSE. For NYSE stocks, the opening procedure is a call auction, so pre-opening quotes are generally not available. We overcome this problem by examining NASDAQ stocks, for which both pre-opening quotes and closing quotes are available. Another benefit of using NASDAQ data to study price formation is that quotations are typically available for over one hour prior to the start of trading. Therefore, it is possible to test whether price discovery occurs from quotes in the absence of trading. Although the role of pre-play or "cheap talk" signaling remains unresolved in the theoretical literature, the fact that market participants do update their quotes prior to the start of trading indicates that these quotes may contain some economic value.

We begin our analysis by establishing that the open-to-open return variance is significantly greater than the close-to-close return variance for our sample stocks. Since NASDAQ employs the same trading mechanism throughout the day, this is further evidence that there are factors other than trading structure contributing to greater opening volatility. Similar results for other markets that do not open with a call auction are found in Amihud, Mendelson and Murgia (1990), Amihud and Mendelson (1991), Choe and Shin (1993) and Forster and George (1994).

The primary finding of this paper is that there is a systematic relationship between the source of transitory volatility and trading frequency. We identify and explore two potential sources of transitory volatility, price formation and bid-ask bounce. For actively traded securities, price formation is found to be the primary source of transitory volatility in both transactions data and quote data. In contrast, for inactively traded securities, bid-ask bounce is the source of higher

open-to-open variance as open-to-open return variances are elevated in transactions data, but no more volatile than close-to-close returns using quote data.

We perform a test of whether the elevated variance in open-to-open returns is related to price formation. Using the method suggested by Gerety and Mulherin (1994), we show that quote-based 24-hour variance decreases throughout the trading day for the most actively traded stocks. This result is consistent with an implication of price formation models in that price uncertainty is gradually resolved as trading conveys more information to the market through time. For inactively traded stocks, the 24-hour return variance is nearly constant throughout the day, failing to support price formation in inactive securities.

Additional evidence of price formation is provided by the quotes available prior to the 9:30 A.M. opening of trading. Using a measure of prediction error, we show that the latest pre-opening quote contains less prediction error than both the previous closing quote and earlier pre-opening quotes. We also find that the number of pre-opening quotes significantly increases when the magnitude of the overnight return is large. While there is no formal model for analyzing the role of quotes in the absence of trading, these results are also intuitively consistent with the notion that price discovery takes place before the market opens.

To assess the importance of a bid-ask bounce component to the variance ratio, we examine the open-to-open and close-to-close variance ratio by using midquote based returns instead of transaction based returns. On average, the difference in variances between the open and close decreases by about 67% when the bid-ask bounce effect is eliminated. We further find that systematic changes in the location of transactions prices within the bid and ask quotes, but not the width of the posted bid-ask spread, cause the decline. Our regression analysis reveals a strong positive relation between the variance ratio of open- to-open to close-to-close returns and the ratio of the variance of opening locations to the variance of closing locations.

While the bid-ask bounce effect accounts for a substantial portion of the elevated opening variances in the full sample, further analysis reveals that its impact on the opening and closing variances varies substantially across stocks with different trading frequencies. For the least frequently traded decile, the difference in opening and closing variances nearly disappears when the bid-asked bounce effect is eliminated. However, for the most frequently traded decile, the impact of bid-ask bounce is marginally significant. Since the finding for infrequently traded stocks may be caused by the inclusion of a large number of zero returns, we demonstrate that recalculating the variance ratio using only

those days where the open-to-open and/or the close-to-close return is non-zero produces no significant changes in the result.

The balance of the paper proceeds as follows: Section 2 describes institutional background, Section 3 outlines our empirical methods, Section 4 describes the data, Section 5 presents the results, and Section 6 concludes.

II. Institutional Background

The NASDAQ system is a decentralized screen-driven market consisting of broker-dealers transmitting quotes and transactions via an electronic network. Telephone communications between dealers supplement the computerized systems. Dealers are required to post their individual bid-ask prices on the system. The reported bid-ask price or inner spread consists of the highest bid and lowest ask prices recorded by the dealers. The quotes transmitted by NASDAQ almost always represent prices at which the dealers will trade for their own account as customer limit orders are rarely represented. In contrast, the NYSE is a centralized market, organized around specialists who are charged with maintaining "continuous and orderly markets" in the stocks for which they are solely responsible. The NYSE specialist maintains bid-ask prices representing either customer orders in his possession or the willingness of the specialist to trade for his own account.

There are two major differences between NASDAQ and the NYSE which are important to this study. First, the NASDAQ system contains no formal procedure for opening trading. By contrast, trading on the NYSE opens with a call auction with the specialist charged with stabilizing prices. At 9:30 A.M. EST, NASDAQ dealers may begin entering trades into the system. Individual dealers are expected to enter transactions in chronological sequence within three minutes of execution. These conditions prevail throughout the trading day. Thus, for NASDAQ securities, any differences between opening and closing variances cannot be attributed to differences in the trading mechanism between the open and close.

Second, the quotation reporting system of NASDAQ opens much earlier than the trading system. In our sample, most stocks record the first quotation of the day by 8:30 A.M. Consequently, dealers are able to transmit their bid-ask prices to the market well in advance of the opening transaction. Thus, we can observe the dealers' unconditional opening quotes prior to the first trade, which reflect

the information set for the dealers prior to the first transaction. This allows us to directly observe the effect of bid-ask bounce on the opening trade. The existence of quotes before the market opens also provides a unique opportunity to examine price discovery in the absence of trading.

Ⅲ. Empirical Methods

We use the variance ratio test to both assess whether NASDAQ stocks are characterized by higher transitory return volatility at the open and to test for evidence of price formation. This methodology has been used by Amihud and Mendelson (1987, 1991) and Stoll and Whaley (1990) to test whether there is a significant difference between open-to-open and close- to-close return variances. Define the observed logarithmic price of stock i at time t as

$$P_{it} \equiv P_{it^*} + e_{it} \tag{1}$$

P_{it} consists of two components, the true price, P^*_{it}, which is the expectation of the true share value conditional on all public information available at time t, and a shock e_{it} associated with private information, liquidity demands, and dealers' responses. We write the daily return for stock i at time t as

$$r_{it} = r^*_{it} + e_{it} - e_{it-1} \tag{2}$$

The variance ratio of open-to-open returns relative to close-to-close returns is[1)]

$$\frac{\sigma^2(r^o_{it})}{\sigma^2(r^c_{it})} = \frac{Var(r^*_{it}) + Var(e^o_{it} - e^o_{it-1}) + 2Cov(r^*_{it}, e^o_{it} - e^o_{it-1})}{Var(r^*_{it}) + Var(e^c_{it} - e^c_{it-1}) + 2Cov(r^*_{it}, e^c_{it} - e^c_{it-1})} \tag{3}$$

where superscripts "o" and "c" denote open and close. Since variances of true returns measured at the open and close are the same, any difference between the observed variances at the open and close will be due to the effects of transitory volatility which impact the second and third terms in the numerator and denominator.

To test the significance of the difference between opening and closing variances,

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1) We leave time subscripts t in the variance equation to make the lag structure clear.

we use a procedure which is based on cross-sectional median variance ratios. This procedure avoids several problems with earlier tests in the literature. Previously, researchers calculated the variance ratio of open-to-open returns versus close-to-close returns for each firm in the sample, and used the standard t-test, F-test or Binomial test to test the null hypothesis that the mean of cross-sectional variance ratios is one although the cross sectional mean of the variance ratios is upward biased due to Jensen's inequality. Ronen (1994) and Jones and Kaul (1994) point out that the validity of these tests relies on strong assumptions about stock returns. For example, since stock returns are cross-correlated, use of the standard t-test and the Binomial test for testing if the average of the variance ratio is one may not be appropriate. The standard F-test for testing the equality of the opening and closing variances may be biased since the numerator and denominator contain overlapping information and stock returns are not normal. The direction of the bias for the F-test is unpredictable. Ronen proposes a test based on the GMM procedure. In the context of this paper, the GMM test involves more than 1000 moment restrictions. Since a GMM system with 1000 moment restrictions is not tractable, we consider alternative tests.

Our empirical tests are designed to address these criticisms and to maintain tractability. We first calculate the cross-sectional median of the individual stocks' variance ratios in each month of the sample period. Then we use these cross-sectional medians as independent time-series observations to perform a conventional t-test. By using medians rather than means, we avoid the Jensen's inequality problem. Since we only use one stock's variance ratio per month rather than averaging the variance ratios of all the stocks in our sample, cross sectional dependence is not an issue. In addition, overlapping observations are not a problem because we do not use the standard *F*-test for testing variance equality. Another noteworthy point is that the distribution of sample medians is asymptotically normal regardless of the underlying distribution under fairly weak assumptions. Thus, each time-series observation can be treated as a normal variate, which justifies the use of a t-test. Since both the quote-based and price-based monthly median variance ratios are asymptotically normal, we can further apply the conventional t-test to the difference between the price-based and quote-based variance ratios.

Ⅳ. Data

The initial data consist of all trades and quotes for all NASDAQ-NMS stocks that exist continuously on the 1990, 1991 and 1992 ISSM NASDAQ tapes and on the CRSP NASDAQ tape. Trades and quotes flagged by the ISSM as errors, non-standard delivery trades, and all BBO-ineligible quotes (except for pre -opening quotes) are eliminated, where BBO stands for "Best Bid/Offer"[2]. We construct a sub-sample of available firms by selecting those firms that satisfy the following criteria:

- There must be at least 190 valid observations in each of the three years. 190 days corresponds to the number of trading days in a 9 month period. A pair of two consecutive trading days is considered a valid observation if each day contains at least two trades and one quote. This criterion is the minimum for meaningful analysis.
- Stock prices at the open and close must be always greater than or equal to $3 throughout the sample period. The same criterion is employed by Stoll and Whaley (1990). This criterion is severe, but it reduces noise in variance estimates caused by the minimum tick size.

The number of stocks meeting these criteria is 472 out of an original sample of 2342 stocks available in 1990, 2275 in 1991, and 2506 in 1992.

Summary statistics of characteristics of sample firms are presented in Table 1. The capitalization of firms at the end of 1989 ranges from $10 million to $10,935 million with median capitalization of $175 million. About 80% of the firms are in the top three deciles of all NASDAQ firms. Hence our sample represents relatively large NASDAQ stocks.

From this sample, we extract trade prices and quotes for use in the analyses. For trade data, we define the opening transaction as the first standard delivery trade occurring after 9:30 A.M. and the closing transaction as the last standard delivery trade of the day. The opening quote is defined as the last reported quote prior to the opening trade and the closing quote is the last reported quote prior

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2) BBO-ineligible quotes are closing quotations. trading halts, pre-opening indications, and non-firm quotations. Trades which are in sequence but are reported late are retained in the data set. For details, see the ISSM manual (1993), p. 14.

Table 1. Summary Statistics of Stock Characteristics

Summary statistics for market capitalization and average price for the 472 NASDAQ stocks in the full sample for 1990 to 1992. Market capitalization represents the 1989 year-end capitalization measured in million $. Average price is daily average (closing) price over the 3-year sample period measured in dollars. The full sample consists of all CRSP stocks for the 1990 to 1992 period that meet our selection criteria. Selection criteria for the sample are the following. The initial data consist of all trades and quotes for all NASDAQ-NMS stocks that exist continuously on the 1990, 1991 and 1992 ISSM NASDAQ tapes and on the CRSP tapes. We construct a sub-sample of available firms by selecting those that satisfy the following criteria: (1) There must be at least 190 valid observations in each of the three years. A pair of two consecutive trading days is considered a valid observation if each day contains at least two trades and one quote; (2) Stock prices at the open and close must always be greater than or equal to $3 throughout the sample period. There are 472 firms from the original sample of 2342 NASDAQ stocks available in 1990, 2275 in 1991, and 2506 in 1992 that meet these criteria.

	Capitalization (million $)	Average price ($)
Mean	383.7	20.26
Std. Dev.	822.8	11.70
Minimum	10.5	4.89
Quartile 1	81.7	12.10
Median	174.6	17.47
Quartile 3	370.0	25.67
Maximum	10935.2	89.54

to 4:00 P.M.

Table 2 provides summary statistics on the trades and quotes included in our sample. The opening is a significant fraction of daily trading activity with median values of 10.8% of daily trades and 8.6% of daily volume.[3] Typically, the first trade occurs less than 24 minutes after 9:30 A.M. and the first quote occurs 65 minutes prior to 9:30 A.M. On the close, the final trade takes place, on average,

3) In Table 2, the open is defined as the first three minutes of trading when calculating the percent of total daily trades and the percent of total daily volume at the open.

Table 2. Summary Statistics of Trading Characteristics

Summary statistics for trading characteristics for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. For each variable, we calculate the daily average for each firm during the 3-year sample period and report the cross-sectional mean. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each). # of transactions is the number of trades daily. Opening transactions is the ratio of the number of transactions occurring during the first three minutes of trading to the total number of daily transactions measured in %. Share volume is the number of shares traded daily measured in 100s. Opening share volume is the ratio of the number of shares traded during the first three minutes of trading to the total number of shares traded daily measured in %. Minutes elapsed from 9:30 AM to the 1st trade is the time delay in opening the stock measured in minutes. Minutes elapsed from the last trade to 4:00 PM is the time lag from the last trade to the close measured in minutes. Negative values indicate last trade times after 4:00 PM.

Variables	Trading frequency decile									
	All	Least freq.	2	3	4	5	6	7	8	9	Most freq.
# of transaction	61	9	12	16	20	24	31	40	59	93	306
Opening transactions(%)	10.8	20.9	17.6	14.8	12.6	10.8	8.8	7.4	6.2	4.8	3.7
Share volume (x100 share)	1137	141	223	289	380	419	542	751	1082	1802	5788
Opening share volume(%)	8.6	18.4	15.2	12.4	10.3	8.6	6.6	5.2	4.2	2.9	2.0
Minutes elapsed from 9:30 AM to the 1st trade	24	54	46	39	30	25	18	13	9	5	2
Minutes elapsed from the last trade to 4:00 PM	19	53	42	34	27	21	13	9	4	-2	-11

19 minutes before 4:00 P.M. The last updated quote is generally recorded three hours before 4:00 P.M. This last statistic reflects the fact that NASDAQ quotes are updated less frequently than their NYSE counterparts.

The bid-ask spread for NYSE stocks is known to be associated with trading volume and trading frequency. Branch and Freed (1977) and Harris (1994) show that more actively traded stocks have narrower quoted spreads. Peterson and Fialkowski (1994) extend this result to show that the effective spread is also smaller for more actively traded stocks on the NYSE. Furthermore, the number of trades is more closely related to the volatility of returns than trading volume (Jones, Kaul, and Lipson (1994b)). For these reasons, we partition the sample into deciles based on the average number of transactions occurring daily for each stock in the sample. To create the trading frequency deciles, we first rank all the firms in the sample based on the daily average number of transactions and then divide them into ten approximately equal-size groups (decile 1 contains the least frequently traded stocks).

V . Results

5.1 Opening Volatility on NASDAQ

The presence of higher volatility for open-to-open vs. close-to-close returns has been documented for a number of exchanges which use various mechanisms for opening trading. Unlike exchanges previously studied, NASDAQ uses the trading procedure employed throughout the day for the opening as well. To test for elevated opening volatility for NASDAQ stocks, we use transaction price-based returns to calculate the variance ratio $\sigma^2(r^o_{it})/\sigma^2(r^c_{it})$ for each of the 472 stocks in each month for the sample period from January, 1990 to December, 1992. Next, we compute the cross-sectional median of these variance ratios in each month. The time-series mean and corresponding standard error of these medians are reported in Table 3 (See median-based results). For transaction price-based returns, the time-series average of cross-sectional median variance ratios is 1.12 with standard error 0.01, which is significantly greater than 1 at a 5% confidence level. It indicates that, on average, the open-to-open return is about 12% more volatile than the close-to-close return for NASDAQ stocks. Our result is consistent with existing research even though the opening procedure for NASDAQ differs from other markets.

Table 3. Summary Statistics of Open-to-Open vs. Close-to-Close Variance Ratios

Summary statistics for the open-to-open vs. close-to-close varianceratios for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. We calculate the variance ratio for each firm in each month, and get the cross-sectional median (mean) variance ratio in each month. Next, we obtain the time-series average and standard error of median (mean) variance ratios across the 36-month sample period. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each). For the median-based variance ratio, the t-test is for testing whether the mean difference between the price-based and the quote-based variance ratio is zero. Standard errors are in parentheses.

	Based on transaction prices				Based on quoted midpoints				
	Median-based		Mean-based		Median-based		Mean-based		
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	t-stat
All	1.12	(0.008)	1.23	(0.010)	1.04	(0.008)	1.14	(0.012)	12.96
Trading frequency decile									
Least Freq.	1.13	(0.017)	1.25	(0.021)	1.01	(0.008)	1.15	(0.021)	7.15
2	1.11	(0.012)	1.25	(0.015)	1.02	(0.010)	1.13	(0.019)	6.04
3	1.13	(0.015)	1.24	(0.018)	1.02	(0.008)	1.13	(0.014)	6.70
4	1.13	(0.015)	1.24	(0.016)	1.03	(0.009)	1.13	(0.019)	7.08
5	1.14	(0.015)	1.25	(0.016)	1.03	(0.009)	1.12	(0.016)	8.18
6	1.13	(0.014)	1.26	(0.018)	1.04	(0.010)	1.14	0.020)	9.38
7	1.13	(0.011)	1.23	(0.015)	1.06	(0.012)	1.15	(0.015)	5.40
8	1.12	(0.012)	1.20	(0.016)	1.05	(0.012)	1.13	(0.015)	5.07
9	1.11	(0.015)	1.20	(0.017)	1.08	(0.014)	1.13	(0.019)	3.04
Most freq.	1.13	(0.018)	1.21	(0.020)	1.10	(0.016)	1.17	(0.018)	3.40

For the purpose of comparison with the previous literature, we also compute the cross-sectional mean of variance ratios in each month and

report its time-series mean and standard error (See Table 3 mean-based results). The time-series average of cross-sectional mean variance ratios is 1.23, which is comparable to results reported in the literature for NYSE stocks. While the mean-based result suggests a 23% difference between the opening and closing volatilities, the median-based result indicates the difference is only 12%. Our result is consistent with the finding of Jones, Kaul and Lipson (1994a) that mean variance ratios (as a measure of central tendency of the variance-ratio distribution) reported in the literature contain substantial upward biases.

The results for each trading frequency decile, reported in Table 3, are similar to those for the full sample for price-based returns. Since the level of trading activity is correlated with the percentage spread, the trading frequency decile results suggest that both the level of trading activity and the posted bid-ask spread do not affect the relative volatility of open-to-open to close-to-close returns when returns are calculated using transaction prices.

In the next section, we investigate the extent to which the greater volatility at the open is caused by the bid-ask bounce at the open and close.

5.2 Bid-Ask Bounce

Our goals in assessing the role of bid-ask bounce on the variance ratio result are threefold. First, establish that bid-ask bounce effects exist in the variance estimated from transaction prices. Second, determine the extent to which bid-ask effects cause the variance ratio to deviate from one. Finally, investigate the determinants of the bid-ask bounce behavior of individual stocks around market opening and closing.

5.2.1 Variance Ratio

To appraise the existence and relative significance of bid-ask bounce, we examine the variance ratio estimated from the midpoint of the bid and ask quotes instead of transaction prices. As noted by Pfleiderer (1990), systematic patterns in transactions behavior at the open and close of trading may be responsible for some of the increase in opening vs. closing volatility. These patterns may be induced by closing trades motivated by an impending trading halt as described in Brock and Kleidon (1992), or by changes in the quoted or effective bid-ask spreads related to the no trade period. By estimating the variance ratio with quote-based returns, the effects of systematic patterns in

transactions are eliminated.

Table 3 reports summary statistics of monthly variance ratios estimated using quote-based returns. For the full sample, the time-series average of the median variance ratio is 1.04 with standard deviation of 0.01. Again, the median variance ratio is significantly greater than 1. The average of the variance ratio declines from 1.12 to 1.04 when quote-based returns instead of price-based returns are used to estimate variances. In other words, the variance at the open is only 4% higher than that at the close when the bid-ask effect is eliminated, in contrast to a 12% difference when bid-ask bounce is included. This represents a 67% reduction in the deviation of the variance ratio from one and the reduction is statistically significant.

For the sample partitioned by trading frequency, Table 3 shows that the time-series average of the median variance ratio for the least frequently traded decile is 1.01 for quote-based returns and not statistically different than 1. Using price-based data, the least frequently traded decile has a variance ratio of 1.13. Therefore, there is a decline of 92% in the relative volatility of open-to-open to close-to-close returns when bid-ask bounce is eliminated for inactively traded stocks. In the remaining deciles in Table 3, the quote-based variance ratio generally increases as trading frequency increases. The most actively traded decile has a quote-based variance ratio of 1.10, a decline of 0.025 or 20% from price-based returns which is the smallest decline for any decile. Although the decline of the variance ratio is relatively small for the most actively traded stocks, the difference between the price-based and the quote-based variance ratio is still statistically significant at the 1% level using the t-test described in Section 3. The differences between the price-based and quoted-based variance ratios are statistically significant for the other deciles in our sample as well.

Our results indicate that a substantial portion of the increase in opening vs. closing volatility is caused by changes in the systematic patterns of bid-ask bounce at the open and close. The hypothesis that the bid-ask bounce effect is an important source of the elevated opening volatility is supported by the evidence. Furthermore, the results show that the primary source of greater opening volatility for inactive stocks is bid-ask bounce. However, there are other significant sources of transitory volatility for actively traded securities.

5.2.2 Bid-Ask Spreads

As noted earlier, there are two possible sources of the bid-ask bounce effect that cause greater volatility at the open. First, the bid-ask spreads could be

systematically wider at the open than the close.[4] Second, there could be systematic patterns in transactions within the bid-ask spread and these patterns could differ between the open and the close. In this section, we use two measures to study the source of bid-ask bounce, the quoted bid-ask spread and the location of transaction prices within the bid and ask quotes.

We define the bid-ask spread for a stock as the inside spread, i.e. the difference between highest bid and lowest ask price posted on the NASDAQ system. For comparative purposes, we then divide the quoted spread by the midpoint of the bid and ask quotes to obtain a percentage spread. To trace the behavior of the spread, we examine the mean percentage spread at hourly intervals over the trading day as well as at the 9:30 A.M. opening. The 9:30 A.M. quote is taken as the last quote posted prior to 9:30 A.M. The quote at the end of each hourly interval is taken as the prevailing quote at each time point.

As shown in Table 4, the average percentage spread across our sample firms declines over the course of the trading day from 2.71% at 11:00 A.M. to 2.65% at 4:00 P.M.[5] However, these declines are not statistically significant. Surprisingly, the pre-opening spread of 2.66% is narrower than the spread for any other period except the close. This may reflect public limit orders being displayed on NASDAQ, the presence of stale quotes, or it may be a result of the price formation process.[6] Furthermore, when we examine the intertemporal pattern in the average of percentage spreads, there is little variation in the spread over the day. Finally, although the width of the posted spread varies across trading frequency deciles, within each decile the width of the spread is relatively constant over the trading day.[7] These results do not support the hypothesis that changes in the width of the quoted bid-ask spread are the source of bid-ask bounce.

We now turn to the systematic patterns in transactions. In particular, we use a

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4) This possibility is cited by George and Hwang(1994) in their study of the Tokyo Stock Exchange.

5) Our result is consistent with previous research, e.g. Harris(1989), McInish and Wood(1992), Porter(1992), and Chan, Christie and Schultz(1995).

6) One possibility is that the tighter spreads represent different opinions among dealers in the sense of Harris and Raviv(1993). Hencem although there is more uncertainty the spread is smaller.

7) The results for the trading frequency deciles show that the findings of Branch and Freed (1977), Harris (1994), and Peterson and Fialkowski (1994) that inactively traded stocks have wider posted spreads apply to NASDAQ as well.

Table 4. Percentage Bid-Ask Spreads for the Opening vs. Successive Periods

The percentage quoted bid-ask spreads at various time points during the trading day for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. For each time period, we calculate the average percentage spread across the 3-year sample period for each firm and report the cross-sectional mean. The quote at the end of each interval is taken as the prevailing quote at each time point. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	Mean percentage spread by trading frequency decile										
Time	All	Least freq.	2	3	4	5	6	7	8	9	Most freq.
t≤9:30	2.66	3.35	3.46	3.53	3.24	3.00	2.58	2.18	2.27	1.80	1.21
t≤11:00	2.71	3.35	3.48	3.55	3.26	3.03	2.61	2.21	2.33	1.89	1.33
t≤12:00	2.69	3.34	3.47	3.54	3.24	3.02	2.60	2.19	2.32	1.88	1.32
t≤1:00	2.68	3.34	3.46	3.53	3.24	3.00	2.59	2.19	2.31	1.87	1.33
t≤2:00	2.67	3.32	3.44	3.52	3.23	2.99	2.57	2.17	2.29	1.86	1.32
t≤3:00	2.66	3.31	3.43	3.51	3.21	2.97	2.56	2.17	2.28	1.85	1.32
t≤4:00	2.65	3.31	3.42	3.50	3.20	2.96	2.55	2.15	2.26	1.83	1.28

location measure to identify systematic patterns in trading at the open and close. The statistic is defined as

$$Location_t = \frac{p_t - Midqote_t}{\frac{1}{2}(Ask_t - Bid_t)} \tag{4}$$

where P_t is the price at time t, Ask_t and Bid_t are the ask and bid quotes in effect at time t, and $Midquote_t$ is the average of bid and ask quotes.[8] With this measure, trades identified as at the bid, the midquote, or the offer have locations of -1, 0, and 1 respectively. Regardless of the trading price, a location for any trade can be calculated in similar fashion.[9]

Since we are also interested in the effective bid-ask spread, note that the combination of location and quoted spread can be conceived of as a measure of the effective spread. Define bid-ask bounce at time *t*, B_t, to be the difference between transaction price P_t and $Midquote_t$ divided by the $Midquote_t$. We can rewrite B_t in terms of the spread and the location as follows

$$B_t = QuotedSpread. \frac{1}{2} Location \tag{5}$$

Note that the effective spread is usually written as 2 $|B_t|$ hence,

$$\text{Effective Spread} = Quoted\ Spread_t \cdot |\ Location_t| \tag{6}$$

In Table 5, we report the summary statistics for locations as well as the probabilities that an opening or closing trade is identified as at the bid, the midquote, the ask, or in between. We calculate the average location for each firm during the three-year sample period, then we report the cross-sectional mean, standard error and median for all firms. Other statistics reported in Table 5 are calculated in a similar way. From Panel A, the locations of the opening trade and closing trade are, on average, -0.03 and 0.00. The opening location is significantly less than zero implying the average opening trade occurs below the midquote price and closer to the bid than the ask. The difference between average locations at the open and the close is significant at the 5% level. The absolute location, which is directly linked to the effective spread, is 0.91 at the open and 0.78 at the close, suggesting a 17% difference. Since the quoted spread at the open and close are essentially the same (2.66% vs. 2.65% from Table 4), 17% difference in the absolute location implies a 17% difference in the effective

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8) This statistic is related to the Keim (1989) location parameter. We drop stock i's subscript for simplicity.

9) The locations of transactions occurring outside the bid-ask spread may reflect either block trades or stale quotes. Locations outside the bid-ask spread are truncated in calculating the average location for a stock.

Table 5. Locations for the Opening and Closing Trades

Summary statistics for the location parameter at the open and close of trading for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. We calculate the location of the trade (absolute value of the location) for each firm on each day and get the time-series average of the location (absolute value of the location) for each firm. Then we obtain summary statistics across 472 firms.

$$Location_t = \frac{P_t - Midqote_t}{\frac{1}{2}(Ask_t - Bid_t)}$$

For Var(L), we calculate the time-series variance of the location for each firm and report summary statistics across 472 firms. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	Opening trade			Closing trade		
	A. Locations					
Statistic	Mean	S.E.	Median	Mean	S.E.	Median
L	-0.027	(0.006)	-0.003	-0.004	(0.005)	-0.001
|L|	0.909	(0.001)	0.910	0.782	(0.002)	0.779
Var (L)	0.881	(0.002)	0.888	0.747	(0.002)	0.746
	B. Probabilities(%)					
Probability	Mean	S.E.	Median	Mean	S.E.	Median
Pr(L<-1)	0.4	(0.02)	0.3	1.8	(0.10)	1.0
Pr(L=-1)	45.3	(0.30)	45.0	35.0	(0.27)	34.7
Pr(-1<L<1)	2.6	(0.09)	2.3	6.0	(0.15)	5.7
Pr(L=0)	6.1	(0.10)	6.0	15.4	(0.18)	15.2
Pr(0<L<1)	2.3	(0.07)	2.1	5.2	(0.12)	5.1
Pr(L=1)	42.8	(0.34)	43.0	35.2	(0.27)	34.9
Pr(L>1)	0.4	(0.02)	0.3	1.5	(0.10)	0.8
Pr(-1<L<1)	11.0	(0.20)	10.9	26.5	(0.29)	26.7

spread between the open and the close. Similar results are obtained for the individual deciles and for brevity are not reported here. The variance of the location provides further evidence that, when the market opens, locations are more volatile than when the market closes.

Panel B of Table 5 provides strong evidence that bid-ask bounce is due to systematic changes in the location of transactions within the bid-ask quotes. For example, 11.0% of the opening transactions are executed between the bid and ask quotes. In contrast, 26.5% of closing trades are executed between the bid and ask. On the other hand, the probabilities that the closing trade is at the bid or ask quote are 35.0% and 35.21%, and 45.3% and 42.8% on the opening. These results suggest that (1) at the close, trades are equally likely to occur at the bid as at the ask; (2) at the open, trades are more likely to be at the bid than at the ask price; and (3) trades are more likely to be within the quote at the close than at the open.

Table 6 presents the cross-sectional average of the mean percentage effective spreads for the stocks in our sample using equation (6) and the effective spreads for the trading frequency deciles. The average effective spread declines from 2.39% to 2.02% from open to close representing a 15.5% decline in the width of the effective spread. The narrowing of the spread for the trading frequency deciles is similar ranging from 12.8% to 19.5%. The reduction in the effective spread from the open to close may be due to dealers being more willing to execute customer limit orders within the bid-ask quotes, or to an increase in the number of offsetting customer buy and sell limit orders, or to increased dealer to dealer trading within the quotes. While all three possibilities are consistent with a reduction in uncertainty on the part of dealers or customers, other explanations, such as position squaring by dealers ahead of the non-trading period, exist.

Table 6 provides additional insights into the results in Table 3. For inactive stocks, the effective spread is almost three times wider than for active stocks. Therefore, a 12.8% reduction in the effective spread from open to close causes a larger reduction in opening variance for inactive stocks than the 18.3% reduction in the effective spread causes for active stocks.[10] Collectively, changes in trade

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10) The mathematical intuition is as follows. In the equation for the variance ratio (Equation3), bid-ask bounce impacts the second and third terms in the numerator and denominator. Therefore, proportional changes across trading deciles in the e ffective spread need not imply a proportional reduction in the variance ratio across deciles due to (1) the presence of the first term ($Var(r^*_{it})$) in the numerator and denominator, and (2) the possible presence of other factors in the second and third terms.

location imply a narrowing of the effective spread between the open and the close. The cross-sectional effects of the narrowing of the spread are consistent with the cross-sectional differences in bid-ask bounce.

5.2.3 Regression Analysis

Results of the previous section indicate that the variance ratio relates to the effective bid-ask spread, thus to the absolute value of the location variable. To investigate the relationship between the variance ratio of open-to-open relative to

Table 6. Percentage Effective Bid-Ask Spreads for the Opening and Closing Trades

The percentage effective spreads at the open and close of trading and the percentage decline in the effective spread from open to close for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. We calculate the mean effective spread across the 3-year sample period for each firm and report the cross-sectional mean of each decile. The percentage decline is obtained from the difference in the cross-sectional mean for each decile. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	Effective spreads by trading frequency decile										
	All	Least freq.	2	3	4	5	6	7	8	9	Most freq.
Opening trade											
Mean	2.39	2.98	3.05	3.13	2.87	2.67	2.34	1.98	2.07	1.64	1.15
Closing tade											
Mean	2.02	2.60	2.61	2.68	2.44	2.24	1.93	1.63	1.70	1.32	0.94
Percentage Decline											
Mean	15.5	12.8	14.4	14.4	15.0	16.1	17.5	17.7	17.9	19.5	18.3

close-to-close returns and locations, we perform the following regression analysis. We regress the variance ratio of open-to-open returns vs. close-to-close returns on the variance ratio of the location at the open and close. The regression in Table 7 is a cross-section and time-series regression. Specifically, the dependent variable is the variance ratio $\sigma^2(r^o_{it}) / \sigma^2(r^c_{it})$ for each firm in each month using price-based returns. The independent variable is the variance ratio of the location at the open and close for the same firm and month. Since the distribution of the variance ratio is skewed, we take a logarithmic transformation for each variable. The regression equation is given by

$$\ln \frac{\sigma^2(r^o_{it})}{\sigma^2(r^c_{it})} = a + b \ln \frac{\sigma^2(Location^{\ o}_{it})}{\sigma^2(Location^{\ c}_{it})} + \varepsilon_{it} \tag{7}$$

If systematic changes in the variability of the location cause the return variance to be different between the open and close, we would expect a significant positive relationship between the variance ratio $\sigma^2(r^o_{it}) / \sigma^2(r^c_{it})$ and the variance ratio of the location $\sigma^2(Location^o_{it})/\sigma^2(Location^c_{it})$. Thus, b should be positive.

The OLS results are reported in Table 7. The estimate of coefficient b is 0.27 and significant with t-statistic 26.2. Several other variables are also entertained in the time-series and cross-sectional regression analysis. These variables are constructed based on the trading volume (%) in number of trades at the open relative to total volume of the day, the trading volume (%) in number of trades at the close relative to total volume of the day, the trading volume (%) in number of shares at the open relative to total traded shares of the day, the open delay time (between 9:30 A.M. and the first transaction of the day), and the time between last trade and 4:30. However, all of these variables are insignificant and have no power in explaining the variance ratio $\sigma^2(r^o_{it})/\sigma^2(r^c_{it})$ of individual firms.

The results for regressions for the trading frequency deciles produce results consistent with those of Table 3. Table 3 showed that bid-ask bounce was a significant component of higher open-to-open volatility in price data for inactively traded firms, but the variance ratio of actively traded firms showed little evidence of bid-ask bounce effects. Since the location is a measure of systematic bid-ask effects, the results of Table 3 imply that the variance ratios of locations at the open and close would have more explanatory power for inactively traded stocks than for actively traded stocks. The results from Table 7 show that b, which measures the response of the variance ratio of returns to changes in the variance

Table 7. Cross-sectional and Time-series Regression Analysis

The logarithmic variance ratio of price-based open-to-open returns vs. close-to-close returns for firm i in month t is regressed on the corresponding logarithmic variance ratio of the locations at the open and close.

$$\ln \frac{\sigma^2(r^o_{it})}{\sigma^2(r^c_{it})} = a + b \ln \frac{\sigma^2(L^o_{it})}{\sigma(L^c_{it})} + \varepsilon_{it}$$

L^o_{it} denotes location at the open for stock i in month t. $\sigma^2(r^o_{it})$ is the price-based open-to-open return variance for stock i in month t. $\sigma^2(L^o_{it})$ is the variance of location at the open for stock i in month t. Definitions of variables corresponding to market closing are similar. Results are reported for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	a	t-stat	b	t-stat	Adj.R^2 (%)
All	0.08	(22.57)	0.27	(26.23)	4.1
Trading Frequency Decile					
Least frequent	0.05	(4.26)	0.43	(13.42)	10.7
2	0.06	(4.56)	0.40	(1.88)	8.6
3	0.06	(5.00)	0.38	(11.36)	7.7
4	0.07	(6.35)	0.34	(10.01)	6.0
5	0.09	(7.55)	0.31	(8.93)	4.7
6	0.10	(8.36)	0.21	(6.34)	2.4
7	0.10	(9.06)	0.20	(6.54)	2.5
8	0.09	(9.34)	0.12	(4.44)	1.1
9	0.09	(9.41)	0.12	(4.08)	0.9
Most frequent	0.12	(11.94)	0.03	(0.96)	0.0

ratio of locations, declines monotonically from 0.43 for the least actively traded decile to 0.03 for the most actively traded decile. The statistical significance of b and the adjusted R^2 of the regression show similar striking declines from the least actively traded to most actively traded deciles. Therefore, bid-ask bounce seems to affect a stock's variance ratio inversely with respect to the stock's level of trading activity.

To summarize, the regression results reveal a strong positive relationship between the variance ratio of open-to-open returns relative to close-to-close returns and the variance ratio of the locations at the firm level for the overall sample. This effect is due primarily to the behavior of less actively traded stocks. The relationship becomes weaker for more actively traded stocks. This is consistent with our previous result that for less actively traded stocks a substantial portion of the difference between the opening and closing variances are caused by the systematic behavior of the bid-ask effect at the open and close. The bid-ask bounce effect is best characterized as arising from the changes in the effective spread.

5.3 Price Formation

Results of the previous section have shown that patterns in bid-ask bounce explain about 67% of the difference between return variances at the open and close. While the bid-ask effect explains a substantial portion of the difference, the variance is still more volatile at the open than at the close for actively traded stocks. Therefore, for actively traded stocks there are factors in addition to bid-ask bounce that contribute to the difference in opening and closing variances. A possible factor is price formation which has been described in the noisy rational expectations models of Grundy and McNichols (1989), Brown and Jennings (1989) and Shalen (1993). In this section, we test whether the remaining difference between opening and closing variances is consistent with price formation models.

5.3.1 Intraday Pattern of Twenty-Four Hour Variances

According to price formation models, private information is revealed gradually through multiple rounds of trading. After the overnight non-trading period, the level of noise tends to be greater when the market first opens than when the market closes. As trading proceeds, investors learn from the observed prices. At the same time, more information arrives in the market. Such a learning process will force the level of noise to become smaller and smaller. The implication of

price formation models is that transitory volatility due to trading noise is the largest at the open and it gradually declines throughout the trading day.

Since our goal is to determine whether evidence of price formation exists after bid-ask effects are eliminated, we perform our analysis using quote-based returns to eliminate the bid-ask bounce. The employment of quote-based returns is justified as follows. Using the location parameter of equation (4) and defining the proportional bid-ask spread, s_t, as $(A_t - B_t)/M_t$, we can approximate the price-based continuously compounded return, r_{Tt}, as

$$r_{Tt} \approx r_{Mt} + Location_t \cdot \frac{1}{2} S_t - Location_{t-1} \cdot \frac{1}{2} S_{t-1} \quad (8)$$

where r_{Mt} is the quote-based return.[11] Therefore, quote-based returns are free from both changes in the location of trades within the spread and changes in the width of the quoted spread.

Recall that variances of most actively traded stocks (i.e., deciles 9 and 10) are about 10% more volatile at the open relative to the close. For these stocks, bid-ask bounce explains little of the difference in volatility. Therefore, if the remaining unexplained volatility is primarily due to price formation, these stocks should show a strong declining pattern in 24-hour variance over the day.

To test the validity of the price formation model, we use the method suggested by Gerety and Mulherin (1994). Specifically, we calculate the quote-based variance ratio of open-to-open returns to those of *time t-to-time t*. We select values for time t of 11:00 A.M., 12:00 P.M., 1:00 P.M., 2:00 P.M., 3:00 P.M., and 4:00 P.M. If transitory price uncertainty contributes to the elevated open-to-open volatility, the time *t-to-time t* variance should decline gradually throughout the day. Therefore, the ratio of open-to-open variance relative to time t-to-time t variance increases gradually.

A technical difficulty arises from the definition of the opening quote. While other quotes are measured on the basis of clock time, the opening quote is defined relative to the first transaction. Thus, when there is a severe opening delay, the time of the opening quote may not always precede the time of the t o'clock quote. To solve this problem, we use three alternative methods. When the time stamp associated with *t* o'clock quote is earlier than the time stamp of the

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11) We drop firm is subscript for simplicity.

opening quote, (i) the entire day is excluded from the analysis, (ii) the t o'clock quote is treated as missing, or (iii) the t o'clock quote is replaced with the opening quote. Since they yield very similar results, we report the results obtained using the first method only.

Summary statistics of variance ratios are calculated using the same method as described in Section 3 and reported in Table 8 for quote-based returns. For actively traded stocks, the average variance ratio of open-to-open vs. time *t-to-time t* gradually increases as *t* increases. For example, for stocks in the most actively traded decile, the variance ratio is 0.99 for open-to-open vs. 11:00-to-11:00 A.M. and it subsequently rises to 1.10 for open-to-open vs. 4:00-to-4:00 P.M. These results suggest that market participants learn from the observed prices through sequential trading and thus the stock price becomes less volatile as trading proceeds. The evidence is consistent with the prediction of the price formation models and supports price formation as an explanation for the remaining difference between opening and closing variances. In contrast, variance ratios for thinly traded stocks are close to one throughout the day.

5.3.2 Robustness of the Results

While the cross-sectional pattern is striking, it could be simply a manifestation of the quote setting practice on NASDAQ rather than evidence that trading facilitates price discovery. If quotes for less actively traded stocks are excessively wide, quote midpoint returns at successive openings and closings are more likely to be the same for inactive than active stocks as adjustments may take place within the wide quotes. This would imply that the use of midquote data would understate the impact of trading on price formation for inactive stocks. We measure a subset of days where the quote midpoint return is zero for both open-to-open and close-to-close returns as a proxy for the frequency of identical quote midpoint returns at successive openings and closings. For the most actively traded stocks (decile 10), both open-to-open and close-to-close returns are zero on 1.2% of the days in our sample. In stark contrast, for the least actively traded stocks (decile 1), about 32% of days experience zero returns. This indicates that price formation may occur within the quotes for inactive stocks on the days where the quotes do not change. To minimize any influence that may be associated with unchanging quotes, we repeat the experiment after excluding days on which both open-to-open and close-to-close returns are zero. The result, as reported in Table 9, is almost indistinguishable from that in Table 8.

Table 8. Median-Based Variance Ratios for the Opening vs. Successive Times of Day (Excluding days on which the time stamp of the opening quote is later than that of the time-t quote)

Summary statistics for the quote-based open-to-open vs. Time t-to-time t variance ratios of the 472 NASDAQ stocks for the trading frequency deciles for 1990 to 1992. For each time interval, we calculate the variance ratio for each firm in each month, and get the median variance ratio across 472 stocks in each month. Next, we obtain the average and standard error of these median variance ratios across the 36-month sample period. σ^2_{oo} is the variance of the quote-based open-to-open return. σ^2_t is the variance of the time t -to-t return calculated using the most recent quote before time t on each day. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	Trading frequency decile									
	Least freq.	2	3	4	5	6	7	8	9	Most freq.
	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)
$\sigma^2_{oo}/\sigma^2_{11:00}$	0.99 (0.008)	0.98 (0.006)	0.97 (0.007)	0.98 (0.009)	0.97 (0.009)	0.98 (0.007)	0.99 (0.008)	1.00 (0.009)	1.00 (0.013)	0.99 (0.014)
$\sigma^2_{oo}/\sigma^2_{12:00}$	1.00 (0.008)	0.99 (0.010)	0.97 (0.007)	0.99 (0.011)	0.97 (0.010)	1.00 (0.010)	1.00 (0.010)	0.99 (0.010)	1.02 (0.014)	1.02 (0.017)
$\sigma^2_{oo}/\sigma^2_{1:00}$	0.99 (0.010)	0.99 (0.012)	0.97 (0.008)	0.99 (0.011)	0.99 (0.010)	1.00 (0.011)	1.02 (0.013)	1.02 (0.012)	1.03 (0.014)	1.04 (0.017)
$\sigma^2_{oo}/\sigma^2_{2:00}$	1.00 (0.010)	0.99 (0.012)	0.98 (0.012)	1.00 (0.014)	0.99 (0.010)	1.01 (0.014)	1.03 (0.015)	1.03 (0.015)	1.03 (0.017)	1.06 (0.020)
$\sigma^2_{oo}/\sigma^2_{3:00}$	1.00 (0.011)	1.02 (0.015)	1.00 (0.011)	1.02 (0.012)	1.01 (0.013)	1.02 (0.012)	1.05 (0.015)	1.06 (0.014)	1.06 (0.016)	1.12 (0.021)
$\sigma^2_{oo}/\sigma^2_{4:00}$	1.01 (0.009)	1.03 (0.011)	1.02 (0.009)	1.03 (0.010)	1.03 (0.010)	1.05 (0.011)	1.07 (0.015)	1.06 (0.013)	1.08 (0.015)	1.10 (0.016)

Table 9. Median-Based Variance Ratios for the Opening vs. Successive Times of Day (Excluding days when both open-to-open and close-to-close returns are zero)

Summary statistics for the quote-based open-to-open vs. Time t-to-time t variance ratios of the 472 NASDAQ stocks for the trading frequency deciles for 1990 to 1992. For each time interval, we calculate the variance ratio for each firm in each month, and get the median variance ratio across 472 stocks in each month. Next, we obtain the average and standard error of these median variance ratios across the 36-month sample period. σ^2_{oo} is the variance of the quote-based open-to-open return. σ^2_t is the variance of the time t-to- t return calculated using the most recent quote before time t on each day. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	Trading frequency decile									
	Least freq.	2	3	4	5	6	7	8	9	Most freq.
	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)
$\sigma^2_{oo}/\sigma^2_{11:00}$	0.98 (0.013)	0.98 (0.011)	0.96 (0.009)	0.98 (0.011)	0.96 (0.011)	0.99 (0.008)	0.99 (0.008)	0.99 (0.009)	0.00 (0.013)	0.99 (0.013)
$\sigma^2_{oo}/\sigma^2_{12:00}$	0.99 (0.014)	0.99 (0.015)	0.96 (0.008)	0.99 (0.014)	0.97 (0.012)	0.99 (0.012)	1.00 (0.011)	0.99 (0.011)	1.02 (0.013)	1.02 (0.016)
$\sigma^2_{oo}/\sigma^2_{1:00}$	0.99 (0.015)	0.99 (0.015)	0.97 (0.009)	0.99 (0.012)	0.99 (0.010)	1.00 (0.012)	1.02 (0.013)	1.02 (0.012)	1.03 (0.014)	1.04 (0.017)
$\sigma^2_{oo}/\sigma^2_{2:00}$	0.99 (0.016)	1.00 (0.015)	0.99 (0.013)	1.00 (0.016)	0.99 (0.010)	1.01 (0.016)	1.03 (0.015)	1.04 (0.013)	1.03 (0.017)	1.06 (0.021)
$\sigma^2_{oo}/\sigma^2_{3:00}$	1.01 (0.022)	1.03 (0.019)	1.00 (0.011)	1.01 (0.012)	1.01 (0.012)	1.03 (0.013)	1.05 (0.014)	1.06 (0.013)	1.06 (0.016)	1.12 (0.021)
$\sigma^2_{oo}/\sigma^2_{4:00}$	1.01 (0.013)	1.03 (0.013)	1.03 (0.010)	1.03 (0.009)	1.03 (0.010)	1.05 (0.011)	1.07 (0.013)	1.05 (0.012)	1.08 (0.015)	1.10 (0.017)

Table 10. Median-Based Variance Ratios for the opening vs. Successive Times of Day (Using 1990 data instead of 1990-1992 data to get trading-frequency ranking)

Summary statistics for the quote-based open-to-open vs. Time t-to-time t variance ratios of the 472 NASDAQ stocks for the trading frequency deciles for 1991 to 1992. For each time interval, we calculate the variance ratio for each firm in each month, and get the median variance ratio across 472 stocks in each month. Next, we obtain the average and standard error of these median variance ratios across the 24-month sample period. σ^2_{oo} is the variance of the quote-based open-to-open return. σ^2_t is the variance of the time t to- t return calculated using the most recent quote before time t on each day. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions in 1990 and divide them equally into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each).

	Trading frequency decile									
	Least freq.	2	3	4	5	6	7	8	9	Most freq.
	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)	Mean (S. E.)
$\sigma^2_{oo}/\sigma^2_{11:00}$	0.98 (0.007)	0.98 (0.006)	0.98 (0.011)	0.97 (0.010)	0.98 (0.009)	0.97 (0.007)	0.98 (0.011)	1.00 (0.013)	1.00 (0.014)	1.01 (0.016)
$\sigma^2_{oo}/\sigma^2_{12:00}$	0.98 (0.010)	0.98 (0.011)	1.00 (0.014)	0.98 (0.012)	0.99 (0.009)	0.98 (0.012)	0.98 (0.011)	0.99 (0.011)	1.03 (0.016)	1.03 (0.018)
$\sigma^2_{oo}/\sigma^2_{1:00}$	0.98 (0.014)	0.99 (0.012)	1.02 (0.015)	0.99 (0.010)	0.99 (0.014)	0.99 (0.013)	1.01 (0.016)	1.01 (0.014)	1.05 (0.016)	1.04 (0.021)
$\sigma^2_{oo}/\sigma^2_{2:00}$	1.00 (0.016)	0.98 (0.017)	1.03 (0.019)	0.99 (0.012)	1.02 (0.015)	0.99 (0.014)	1.03 (0.017)	1.01 (0.013)	1.06 (0.018)	1.06 (0.021)
$\sigma^2_{oo}/\sigma^2_{3:00}$	1.01 (0.011)	1.00 (0.013)	1.03 (0.016)	1.01 (0.011)	1.02 (0.015)	1.01 (0.011)	1.05 (0.015)	1.03 (0.013)	1.08 (0.021)	1.10 (0.024)
$\sigma^2_{oo}/\sigma^2_{4:00}$	1.02 (0.010)	1.02 (0.009)	1.04 (0.011)	1.02 (0.008)	1.03 (0.015)	1.02 (0.011)	1.06 (0.015)	1.03 (0.013)	1.09 (0.018)	1.08 (0.017)

Therefore, even on the days where the quotes change, there is little evidence of price formation due to trading for inactive stocks.

Another concern may arise regarding the use of trading frequency as the classification variable. While we cannot think of a better variable that captures the essence of price formation models, trading frequency is certainly an endogenous variable, which makes the interpretation of our results difficult. To address this issue, we divide the sample period into two mutually exclusive subperiods: 1990 and 1991-1992. We use the first period to allocate firms to ten trading frequency deciles. Keeping the decile composition constant, we apply the procedure described in the previous subsection to the second period data only. As shown in Table 10, the results are similar to those reported in Table 8.

To summarize the results reported in this section, we find evidence consistent with the view that trading facilitates price discovery more for those stocks that trade more actively. The evidence from actively traded stocks is consistent with the result of Gerety and Mulherin (1994) for the Dow Jones index. Gerety and Mulherin find the variance of the Dow Jones index return measured at the end of each hourly interval declines throughout the day. Our result, as well as that of Gerety and Mulherin, supports price formation models for actively traded stocks. However, thinly traded stocks do not exhibit a pattern of price formation.

5.4 Price Formation Before the Opening

So far, we have examined the latest pre-opening quotes but not other pre-opening quotes because we have used these quotes merely to assess the importance of the bid-ask bounce effect on the opening. For such a purpose, only the quote prevailing at the time of the opening transaction is relevant. However, the existence of multiple pre-opening quotes raises an interesting question: Does price discovery take place prior to the opening transaction?[12] This is a potentially important issue, because the lack of a formal opening procedure on the NASDAQ, coupled with the existence of multiple market makers, may make price discovery around the opening difficult compared to other exchanges. If pre-opening quotes facilitate price discovery before the opening, they can be viewed as a mechanism alleviating such a difficulty.

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12) We are grateful to René Stulz for suggesting this possibility.

To explore the possibility of pre-opening price discovery, we first examine the impact of the overnight price shock on quote revision activities. Although the role of quotes in price discovery when there is no trading remains uncertain, we conjecture that there would be a positive relationship between the magnitude of the overnight shock and the frequency of pre-opening quote changes. This is because market makers would face increased incentives to reveal their information when faced with greater uncertainty about the equilibrium price. These incentives would include reputational costs of appearing poorly informed in communications with their customers and real costs of trading at non-equilibrium prices.

Table 11 shows that there is only one pre-opening quote on many trading days (66%) and the average number of pre-opening quotes is only 1.9.[13] However, the average number of pre-opening quotes increases dramatically to 6.6 on days when the overnight return is greater than 3% or less than -3%, where the overnight return is measured as the logarithmic quote midpoint return from the closing quote to the latest pre-opening quote. This evidence is consistent with the notion that price discovery is needed more on days with larger overnight price shocks.

We further examine whether pre-opening quotes are better predictors of the opening price than is the closing quote from the previous day. We define the percentage prediction error as the difference between the quote midpoint and the opening transaction price divided by the opening transaction price. Because the number of pre-opening quotes varies over days and across stocks, we consider only the earliest and the latest pre-opening quotes. For each predictor, we calculate the square of the percentage prediction error on each day for each firm, and get the cross-sectional median squared error, MSE, on each day. The time-series mean of the MSE is reported in Table 12. We also obtain the difference in the MSE between the two predictors, the closing quote on the previous day and the first pre-opening quote (or the latest pre-opening quote). The time-series mean and standard error of the difference are reported in Table 12.

Panel A in Table 12 shows that the average MSEs are 1.43, 1.31 and 1.09, respectively, when using the closing quote on the previous day, the first pre-opening quote and the latest pre-opening quote to predict the first

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13) As in Table 2, We first calculate the daily average for each firm, and then report the cross-sectional mean.

Table 11. Summary Statistics of Pre-opening Quotes

Summary statistics of pre-opening quotes for the 472 NASDAQ stocks in the full sample and for the trading frequency deciles for 1990 to 1992. For each variable, we calculate the daily average for each firm during the 3-year sample period and report the cross-sectional mean. To create the trading frequency deciles, we first rank all firms in the sample based on the daily average number of transactions and divide them into ten groups (group 1 includes 49 stocks, groups 2 to group 10 include 47 stocks each). # of quotes is the daily average number of pre-opening quotes. # of quotes overnight return exceeding ±3% is the average number of pre-opening quotes when the overnight return exceeded 3%. % of days with 1 pre-opening quote is the percentage of days on which there is only one pre-opening quote. Minutes elapsed from 1st pre-opening quote to 9:30 A.M. is the time lag between the 1st pre-opening quote and 9:30 A.M. when NASDAQ officially opens. Minutes elapsed from latest pre-opening quote to 9:30 A.M. is the time lag between the latest pre-opening quote and 9:30 A.M. when NASDAQ officially opens.

	Trading frequency decile										
	All	Least freq.	2	3	4	5	6	7	8	9	Most freq.
# of quotes	1.93	1.55	1.65	1.60	1.73	1.83	1.81	1.95	2.04	2.36	2.83
Overnight return Exceeding ± 3%	6.63	5.78	5.55	5.80	5.54	5.73	7.20	6.84	7.10	7.64	9.00
% of days with 1 pre-opening quote	66.4	76.6	73.3	75.2	70.6	68.8	69.8	64.8	61.7	55.2	48.4
Minutes elapsed from 1st pre-pening quote to 9:30 AM	65	69	68	68	68	66	66	64	65	62	60
Minutes elapsed from latest pre-pening quote to 9:30 AM	43	50	47	50	50	45	46	43	41	34	28

Table 12. Forecasting Performance of Pre-opening Quotes Relative to the Closing Quote of the Previous Day

This table reports summary statistics of forecasting errors when using the closing quote on day t-1 and the pre-opening quote on day t to predict the first transaction price on day t. For each predictor, we calculate the square of the percentage prediction error on each day for each firm, and get the cross-sectional median squared error, MSE, on each day. The time-series mean of the MSE is reported in the table. We also obtain the difference in the MSE between two predictors, and report its time-series mean and standard error in the table. Several sets of pre-opening quotes are considered in the forecasting comparison: (A) the first and latest pre-opening quotes for all trading days; (B) the first and latest pre-opening quotes when there are at least two pre-opening quotes on a trading day; and (C) the first, second and latest pre-opening quotes when there are at least three pre-opening quotes on a trading day.

	MSE		Difference in MSE		
Predictor	Mean	Predictor	Mean	Mean	(S.E.)
A. All trading days					
Closing quote	1.43	1 st pre-opening quote	1.31	0.12	(0.018)
Closing quote	1.43	Latest pre-opening quote	1.09	0.34	(0.035)
B. Trading days on which there are at least two pre-opening quotes					
Closing quote	1.31	1st pre-opening quote	1.08	0.23	(0.027)
Closing quote	1.31	Latest pre-opening quote	0.61	0.70	(0.040)
C. Trading days on which there are at least three pre-opening quotes					
Closing quote	1.37	1st pre-opening quote	1.28	0.09	(0.030)
Closing quote	1.37	2nd pre-opening quote	0.90	0.47	(0.037)
Closing quote	1.37	Latest pre-opening quote	0.50	0.87	(0.060)

transaction price. In comparison to the closing quote on the previous day, the median squared errors are reduced by about 8% and 24% when using the first pre-opening quote and latest pre-opening quote as predictors of the first transaction price. The reduction is statistically significant. Therefore, pre-opening quotes are indeed better predictors of the opening price than the closing quotes on the previous day, and even the earliest pre-opening quotes perform better than the previous closing quotes.

In the above analysis, we include the days that have only one pre-opening quote. As the opening transaction is based on the latest pre-opening quote, the latest pre-opening quote is likely to have the least prediction error among all quotes that are available prior to the opening. Therefore, if the earliest pre-opening quote is also the latest pre-opening quote, the above result likely overstates the predictability of the earliest pre-opening quote. To avoid this pitfall, we select only those days on which there is more than one pre-opening quote and repeat the experiment. Panel B of Table 12 shows that the earliest pre-opening quote, which is not subject to the above problem, still predicts the opening price better than the previous closing quote. Using the first pre-opening quote to predict the first transaction price will lead to a 18% reduction in the MSE over using the closing quote on the previous day. Furthermore, as Panel C indicates, the magnitude of the prediction error declines through successive updating of the quotes. It suggests that price discovery takes place on NASDAQ before the market opens, even in the absence of trading. This is in sharp contrast to other exchanges, including the NYSE and AMEX, where pre-opening quotes are generally not available.

VI. Conclusion

In this paper, we demonstrate that returns of NASDAQ stocks conform to the patterns reported for NYSE stocks by Amihud and Mendelson (1987) and Stoll and Whaley (1990) by exhibiting greater volatility around the market opening than closing. Since opening and closing mechanisms are the same on the NASDAQ, our results suggest factors other than market structure attribute to the greater opening volatility for NASDAQ stocks.

We find a systematic relationship between the source of excess opening volatility and trading activity. Evidence from individual stocks indicates that

bid-ask bounce contributes, in aggregate, about 67% of the difference in opening and closing volatilities. Furthermore, we find that the bid-ask bounce effect varies substantially across trading frequency deciles, contributing 92\% of the elevated opening variance for inactively traded stocks and 20% for actively traded stocks. The source of bid-ask bounce is identified as significant changes in the location of trades within the bid-ask quote between the open and the close rather than the changes in posted spreads. That is, opening transactions are more likely to occur at either the bid or ask than are closing transactions, and the trade is more likely to be executed within the bid and ask at the close of trading than at the open.

We use mid-quote returns to control for the bid-ask effect and test for evidence of price formation. We find price uncertainty is gradually resolved throughout the day as trading proceeds for actively trade stocks. Thus, the remaining difference between the opening and closing variances after eliminating the bid-ask bounce effect is consistent with the implication of price formation models. For thinly traded stocks, in contrast, the 24-hour return variance is almost the same from the beginning to the end of the trading day, showing no evidence of price formation.

We further investigate whether price discovery takes place on NASDAQ before the market opens. The existence of multiple, pre-opening quotes provides an unique opportunity to examine price discovery in the absence of trading. We find pre-opening quotes are better predictors of the opening price than is the closing quote from the previous day. For those trading days on which there are multiple pre-opening quotes, later pre-opening quotes are better predictors of the first transaction price than are earlier pre-opening quotes. Therefore, price discovery does take place before the market opens and in the absence of trading.

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