Price Formation on Stock Exchanges: The Evolution of Trading within the Day

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Prior analyses of prices of the NYSE and other exchanges find that transitory price volatility is greater at the open of trading than at the close. We extend this line of research by using 40 years of hourly Dow Jones 65 Composite price index data to estimate transitory volatility throughout the trading day. Our results indicate that transitory volatility steadily declines during the trading day. We find a similar intraday decline in transitory volatility for a 2½-year sample of the individual firms in the Dow Jones 30 Industrials Index. The results are consistent with the hypothesis that trading aids price formatton and do not support the argument that particular trading mechanisms are the source of greater volatility at the open of trading.

A central focus of market microstructure analysis is the interaction between market structure and securities price formation. Recent research in this vein

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indicates that the prices formed at the opening of trading have more transitory volatility than those determined at other times of day, such as at the close of trading. In two related analyses of the NYSE, Amihud and Mendelson (1987) and Stoll and Whaley (1990) reported that daily stock returns computed using opening prices have greater variance and show more evidence of reversals than comparable returns computed from closing prices. These results have been supported by evidence from other exchange settings (e.g., Amihud and Mendelson 1991, Choe and Shin 1993, French 1991, Masulis and Ng 1992) and suggest that opening prices are noisier than closing prices.

Two general explanations have been offered for the greater transitory volatility at the open. One set of models proposes that *trading mechanisms* such as the use of a call auction (Amihud and Mendelson 1987) and the participation of the specialist (Stoll and Whaley 1990) at the open are the source of the noisier opening prices. Another explanation, derived from *price formation* models, such as Dow and Gorton (1993), Grundy and McNichols (1989), Leach and Madhavan (1993), and Romer (1993), ties the noisier opening prices to the fact that the overnight interruption of trading clouds the process of price formation provided by trading itself.

In this article we report the results of empirical tests that distinguish between the *trading mechanism* and *price formation* explanations for the greater volatility at the opening of trading. Our analysis uses 40 years of hourly Dow Jones price index data, as well as 2½ years of intraday data on individual securities, to estimate daily stock return variance from open to open, first hour to first hour, etc., through close to close. If the trading mechanism used at the open of trading on the NYSE is the source of the greater opening volatility, we expect a discrete drop in this measure of variance following the open and expect no difference between the variances computed from data at periods other than the open, as the postopening prices are all generated from continuous trading. By contrast, if trading processes information and aids price formation, we expect this measure of stock return variance to decline steadily during the day.

Our results indicate a steady decline in stock return variance during the trading day. Open-to-open variance is significantly greater than close-to-close variance, and there is a smooth decrease in variance between the open and the close. While there are exceptions on some days of the week in some periods, the results generally suggest that trading facilitates the processing of information. Since we find a steady decline in variance during the day rather than a discrete change after the call market at the open, we also share the conclusion of Amihud and Mendelson (1991) and Madhavan (1992) that call markets are not inherently more volatile than continuous trading.

In addition to supporting the models of price formation, our analysis is pertinent to several current policy issues. Our results suggest that recently developed automated trading systems such as Steven Wunsch's Single Price Auction Network (operating under the rubric of the Arizona Stock Exchange) have no intrinsic disadvantages relative to the continuous trading done in markets such as the NYSE, although the results cannot speak to Wunsch's contention that his system is actually less volatile than the trading done in continuous markets (Wunsch 1991). Our results also reaffirm the point made by Grossman (1990), Leach and Madhavan (1993), and Madhavan (1992) that circuit breakers and other forms of trading halts can do more harm than good by interrupting the information flow provided by the trading process.

The following section reviews the literature on price formation and structures our empirical tests. Section 2 reports our primary empirical results of the intraday transitory volatility of the Dow Jones Composite Index. Section 3 compares the index results with a sample of intraday prices of individual securities. The final section offers a summary and some concluding comments.

1. Developing Tests of Price Formation

1.1 Prior empirical analysis

Since its inception, market microstructure analysis has been concerned with the way information is incorporated into financial prices and has focused on the effects of trading mechanisms on the price formation process. (For a survey, see Cohen et al. 1986.) However, devising empirical tests of models that contrast, say, call and continuous markets is problematic because a given financial exchange usually employs only one primary mechanism for trading. Hence, empirical analysis of trading mechanisms can be obscured by comparisons of different assets in different trading environments.[1]

In their 1987 article, Amihud and Mendelson avoided the ambiguity of interexchange comparisons by making use of the trading procedures on the New York Stock Exchange. While the NYSE operates on a continuous basis during the trading day, it commences trading with a call auction in every stock. Taking advantage of this procedure, Amihud and Mendelson (1987) made direct comparisons of price behavior in call and continuous markets.[2]

[1] For a succinct summary of the difficulties in drawing inferences from intermarket comparisons. see "Last Orders?" *Economist* (March 14, 1992), p. 91.

[2] See Smidt (1979) and Garbade and Sekaran (1981) for related analysis of the behavior of prices under the different trading procedures used on the NYSE.

To analyze the two trading mechanisms, Amihud and Mendelson (1987) estimated the variance of stock returns computed from opening prices and made similar estimates from closing prices. Since the total time period used to estimate the open-to-open and close-to-close returns is the same (except for the first and last day in the data), this analysis allowed the authors to compare the behavior of stock returns at different times of the day while extrapolating from differences in the effect of information. Any differences in the estimated variances are due, therefore, to transitory price changes.

Studying the 30 stocks in the Dow Jones Industrial Index in the 1982-1983 period, Amihud and Mendelson (1987) found that open-to-open returns are more variable than close-to-close returns. Related analysis shows that the open-to-open returns exhibit more price reversals than the close-to-close returns. The authors concluded (p. 552) that "trading at the opening exposes traders to a greater variance than in the close, reflecting the difference between the trading mechanisms."

Stoll and Whaley (1990) extended this line of research and reached similar conclusions. They provided a model in which the market power of the specialist can result in greater volatility at the opening call auction. With a broad database of all NYSE stocks for the 1982-1986 period, they found that open-to-open returns are more volatile than close-to-close returns.

While the greater volatility at the open may be due in part to trading mechanisms used by the NYSE, research from other exchange settings suggests that the noisiness of opening prices stems from more general phenomena. In their study of the Tokyo Stock Exchange, Amihud and Mendelson (1991) found that the volatility of the opening morning call exceeds the volatility at the close of trading, but that prices formed in the call market that restarts trading in Tokyo's afternoon session are no more volatile than prices at the close. Similarly, Amihud, Mendelson, and Murgia (1990) found that on the Milan Stock Exchange, where the market opens with continuous trading and moves to a call market, the call trading actually exhibits lower volatility. Recent analysis also reported that opening prices are more volatile than closing prices on futures exchanges (French 1991) and the London Stock Exchange (Masulis and Ng 1992), both of which begin with continuous trading. These results from exchanges other than the NYSE indicate that call markets are not necessarily more volatile than continuous markets and that the greater volatility at the open of the NYSE does not necessarily stem from the use of a call market. Of course, the analysis does not reveal why volatility is greater at the open of trading on the NYSE.

1.2 Models of price formation

Rather than arising from particular trading mechanisms, the greater volatility at the open may more generally reflect the fact that the market has been closed for an extended period. To the extent that this overnight interruption of trading clouds the price formation process, prices at the open can be expected to be relatively noisy compared to the prices formed in active trading. Moreover, if the overnight close is an important hindrance to price formation, we would expect that prices become progressively less noisy as trading proceeds during the day.

Such a role of trading in the price formation process has been formally treated by a number of authors including Dow and Gorton (1993), Grundy and McNichols (1989), Leach and Madhavan (1993), and Romer (1993). Building on the insights of Kyle (1985), these models share the premise that trading is necessary to reveal the information held privately by the many investors in the economy. While prices in these models are always unbiased estimates of future cash flows, multiple rounds of trading can produce prices that are less noisy and reveal more information than that revealed in a single round of trading. In effect, trading itself facilitates learning. Consistent with these models, French and Roll (1986) concluded from their empirical analysis that trading enables private information to be incorporated into securities prices.

While French and Roll (1986) emphasized differences between overnight and trading-time volatility, the general message of the price formation models can be more directly applied to the behavior of prices within the course of the trading day. Assume a setting where an information shock occurs while the exchange is closed. At the resumption of trading, prices will change to reflect unbiased, but noisy, forecasts of the implications of the new information. As trading progresses, investors use reported prices to revise their interpretations of the overnight information and observed prices more accurately reflect the new information. Hence, prices steadily become less noisy during the day.

If this story derived from the price formation models is an accurate depiction of financial exchanges, we would expect a steady decline in transitory volatility as trading proceeds from open to close. The variance of returns computed from opening prices should be greater than returns computed from, say, noontime prices, which should in turn exceed the variance of returns computed from closing prices. This prediction contrasts with that of the trading mechanism analysis, which suggests a difference only for opening prices and says nothing about differences in volatility between returns computed from prices at any other time of day. We make use of the different predictions to contrast empirically the two explanations of the greater volatility at the opening of trading.

1.3 Structuring the empirical tests

In our analysis, we use data from the NYSE, the setting for the original Amihud and Mendelson (1987) analysis. Since we want to study the noisiness of prices throughout the day, rather than only at the open and the close, we employ hourly stock price data. To ensure the robustness of the prior empirical work, we use a lengthy price series spanning the past 40 years, a period encompassing significant changes in trading costs, price volatility, trading volume, and institutional ownership.

Our primary data set entails hourly values of the Dow Jones 65 Composite Index collected from the *Wall Street Journal* and *Barron's* for the 1952-1992 period.[3] We choose this particular index because it is the broadest stock price index available in the public sources on an hourly basis for the period of study. Likewise, our focus on the analysis of a price index rather than firm-level data arises, in part, because the public sources we employ do not report intraday data on individual securities.

Beyond the practical aspect of data availability, the analysis of a price index rather than firm-level data has some appealing methodological features. Amihud and Mendelson (1989) pointed out that firm-specific sources of transitory volatility such as bid-ask bounce cancel out across portfolios such as the Dow Composite Index.[4] Dampening firm-specific bid-ask bounce provides a cleaner interpretation of the reasons for the difference between transitory volatility at the open and the close because, as noted by Pfleiderer (1990, p. 72), prior results using firm-specific data could be related to intraday differences in the tendency of individual securities prices to cluster at bid or ask prices rather than be tied specifically to the trading mechanism at the open. Of course, the use of an index may pose problems for our research design if the greater transitory volatility at the open actually does stem from firm-specific factors that cancel out across a portfolio. But if the index data produce results similar to the analysis of individual securities in the prior studies, this would sug-

[3] Although hourly price index data are available from the source material as early as 1933, we began the sample on September 29, 1952, when the NYSE permanently discontinued its two-hour Saturday trading session. The shorter Saturday session complicates the computation of variance for the different hourly intervals on Monday.

[4] Although Harris, Sofianos, and Shapiro (1992) noted that strategies such as program trading may induce a systematic bid-ask bounce component in a stock index, much of the time period in our study precedes the use of index-related trading strategies. Hence, to the extent that we find similar intraday patterns across time periods, we can safely assume that our results are not driven by a systematic bid-ask bounce component.

gest that the greater volatility at the open is a broad phenomenon that is not firm-specific.

The use of a price index also mitigates a problem raised by Ronen (1992) regarding the statistical analysis of the open-to-open and close-to-close return variances of individual securities. Since the stock prices of individual securities share a systematic component, a cross-sectional test of, say, the 30 firms in the Dow Jones Industrials Index does not entail 30 independent observations. The analysis of a single index eliminates the double-counting involved in the tests of firm-level data. At the same time, to ensure that the aggregation implied by the index data is not masking the actual behavior of securities prices, we also compare the results using the Dow Jones Index with the results from a sample of individual securities prices.

Because we compute variances from overlapping data, issues also arise as to the appropriate methods to test the statistical significance of our results. Conventional *F*- tests for differences in variances were devised for nonoverlapping data; hence, the use of such tests in our application may impute biases. However, simulations described in the Appendix suggest that the nature of the bias in the *F*- tests is against rejection of the null. Because there does not seem to be a bias toward false rejections of the null, we report *F*- tests as a measure of significance, noting that the true significance levels are greater than suggested by the tests. The *F*- statistic we use is the modified Levene statistic suggested by Brown and Forsythe (1974).[5]

To ensure the robustness of our results, we also use a method of testing for a significant difference between variances that was employed by French and Roll (1986). For a period of *n* years in length, we compute a variance ratio for each of the *n* years. We then use a t-test to assess whether the average variance ratio in a period is significantly different from 1.

As outlined in Table 1, the changes in the hours of operation of the NYSE over the period of study divide the primary Dow Jones Price Index sample into five subperiods. We exclude days following holidays and days surrounding shortened trading sessions, as these days complicate comparisons of variance across the hours of the day. The elimination of such days results in a minimal loss of data.

Our analysis extends Amihud and Mendelson's (1987) comparison of opening and closing volatility by estimating the variance of stock returns computed from open to open, first hour to first hour, and so

[5] Brown and Forsythe (1974) found that the traditional variance ratio *test* rejected true nulls in a disproportionate number of trials. The modified Levene statistic provides more robust, unbiased tests by, among other things, trimming the effect of outliers. Consistent with Brown and Forsythe, we obtained, in results available upon request, more significant probability levels using traditional *F*- tests. For other use of the modified Levene statistic in financial applications, see Hsieh and Miller (1990) and Lockwood and Linn (1990).

Table 1
Overview of the hourly Dow Jones 65 Composite Price Index data: 1952-1992

Data set	Time period	Hours	Number of days
1952–1963a	September 29, 1952–November 1, 1963	10:00–3:30	2832
	Note: The source material does not report a 3 P.M. price index level during the 1952b–1963a period.		
1963b–1968	November 4, 1963–January 19, 1968	10:00–3:30	1273
	Note: The NYSE has shortened hours in the following periods: Jan 22–Mar 1, 1968 (10 A.M.–2 P.M.); Jan 2–Jul 3, 1969 (10 A.M.–2 P.M.); Jul 7–Sept 26, 1969 (10 A.M.–2:30 P.M.); Sept. 29, 1969–May 1, 1970 (10 A.M.–3 P.M.). The exchange was also closed on Wednesdays in the latter half of 1968. Due to these special closings, these time periods are excluded.		
1970–1974a	May 4, 1970–September 30, 1974	10:00–3:30	1115
1974b–1985a	October 1, 1974–September 26, 1985	10:00–4:00	2780
1985b–1992	September 30, 1985–December 31, 1992	9:30–4:00	1532
	Note: Due to the abnormal volatility of the October 1987 market break, the period from Oct 15–Nov 30, 1987, is deleted from the analysis.		

This table provides an overview of the hours of operation of the New York Stock Exchange during the 1952-1992 period and notes the subperiods used in the analysis of the Dow Jones 65 Composite Price Index. The sources for the price index data are the *Wall Street Journal* and *Barron's.*

forth, through close to close.[6] We use the estimated variances to test the predictions of the models stressing trading mechanisms and of the models that emphasize price formation.

If the particular trading mechanisms used by the NYSE contribute to greater volatility at the open, we would expect the open-to-open measure of variance to exceed the variances calculated from returns at all other hours of the day. In other words, there should be a discrete drop in volatility following the open. Moreover, we would expect no difference between the variability of the postopen returns since the prices in periods following the opening are all generated from continuous trading.

The price formation models have distinctly different predictions regarding volatility during the trading day. While the models also predict greater variance in open-to-open returns, there should be no discrete drop in volatility following the open. Instead, the noisiness of prices should fall steadily throughout the period from open to close. Throughout the analysis, we maintain the hypothesis that prices are determined in a way consistent with weak form market efficiency. In no way do we assume that the changing noisiness of prices at different points in the trading day allows room for profit opportunities.

[6] This use of hourly data to extend the study of price behavior and trading mechanisms is suggested in Maureen O'Hara's discussion (1987) of Amihud and Mendelson's (1987) original analysis. Richardson and Smith (1988) and Smith (1991) performed similar estimation in their analysis of the random walk model.

Table 2
Open-to-open and close-to-close variance of the Dow Jones 65 Composite Price Index

	Subperiod				
	1952–1963a	1963b–1968	1970–1974a	1974b–1985a	1985b–1992
σ^2_{oo}	0.46	0.35	0.91	0.83	1.38
σ^2_{cc}	0.39	0.27	0.80	0.56	1.24
$\sigma^2_{oo}/\sigma^2_{cc}$	1.15	1.31	1.14	1.49	1.11
p-level, *F*-test	<.001	<.001	.006	<.001	.001
Number of observations	2832	1273	1115	2780	1532
p-level, *t*-test	.002	.007	.002	.001	.027
d.f.	11	5	4	11	7

This table reports estimates of open-to-open and close-to-close variance and the ratio of these estimates for stock returns of the Dow Jones 65 Composite Price Index in the five subperiods in the 1952-1992 time period. See Table 1 for the characteristics of the subperiods. σ^2_{oo} is the variance of stock returns of the Dow Jones 65 Composite Index computed from open to open. σ^2_{cc} is the variance of stock returns of the Dow Jones 65 Composite Index computed from close to close. All variance estimates are multiplied by 10^4. The variance estimates and variance ratios have been rounded to two significant digits for simplification of presentation. *p*- level, *F*- test is the probability level of the *F*- distribution calculated from the modified Levene statistic testing the null that the variance ratio in a subperiod is equal to 1. The number of observations is the number of observations used to compute the variances in a particular period. *p*- level, *t*- test is the probability level of a *t*- test of the null that the mean of the variance ratios computed for each of the *n* years in a subperiod equals 1. d.f. is the degrees of freedom used in computing the *t*- test in a particular period.

2. Estimates of Transitory Volatility Using Index Data

2.1 Comparing the open and the close

We first replicate the tests of Amihud and Mendelson (1987, 1991) and Stoll and Whaley (1990) by estimating the variance of open-to-open and close-to-close returns for the Dow Jones Composite Index. The results are reported in Table 2 for each of the five subperiods. As found in the prior studies, variance from open to open consistently exceeds variance from close to close. As shown by the variance ratios, $\sigma^2_{oo}/\sigma^2_{cc}$, open-to-open variance is between 11 percent and 49 percent greater than close-to-close variance across subperiods.

To test the significance of the variance ratio, we use the modified Levene statistic as suggested by Brown and Forsythe (1974). Under the null of no difference in the variances, the variance ratio is distributed no more disperse than the *F*- statistic, and, using this *F*- test, the open-to-open variance and close-to-close variance are statistically different at conventional levels of significance in each of the periods of analysis.

As an alternative test of significance, we compute a variance for each of the *n* years in a particular subperiod. We then use a conventional *t*- test to see whether the average variance ratio in a particular subperiod was significantly different from 1. The results, also reported in Table 2, confirm the significance found from the *F*- tests employing the modified Levene statistic.

Our results for the value of $\sigma^2_{oo}/\sigma^2_{cc}$ compare with an average value of 1.20 for the individual stocks in the Dow Jones 30 Industrial Index for the 1982-1983 period reported by Amihud and Mendelson (1987), 1.13 for all NYSE common stocks for the 1982-1986 period reported by Stoll and Whaley (1990), 1.18 for the 50 most active stocks on the Tokyo Stock Exchange reported by Amihud and Mendelson (1991), and 1.23 for three futures contracts studied by French (1991). Both the previous research and our historical evidence indicate that variance computed from open to open exceeds the variance computed from close to close.

The comparability of our results with the prior studies indicates that our use of a stock price index, rather than evidence for individual securities, is not distorting the results. Indeed, the robustness of the results to our analysis of the portfolio of 65 Dow Jones stocks indicates that the greater volatility at the open is a general phenomenon that does not arise from firm-specific factors such as bid-ask bounce. The robustness of the results across 40 years of trading history also indicates that the difference between open-to-open and close-to-close volatility is not driven by particular features such as trading costs, the level of price volatility, the amount of trading volume, or the index strategies of institutional investors.

The comparability of the index results with the prior firm-level analysis also allays concerns about some of the statistical procedures used in prior research. Ronen (1992) noted that the prior cross-sectional tests of significance of firm-level returns may be biased because of the lack of independence of individual stock returns sharing a systematic component. These biases do not seem to be driving the prior results, however, as our use of a single index avoids the double counting of the firm-level data but still produces similar results.

2.2 Transitory volatility within the day

We next address the reason for the greater transitory volatility at the open: particular trading mechanisms versus a more general price formation phenomenon. We extend the prior tests by examining the variance at each hour of the trading session. For example, for a five-hour trading day, we estimate variance from open to open (σ^2_{OO}), from the first hour to the next first hour (σ^2_1), and so forth, through the closing fifth hour (σ^2_5).[7] The two theories, trading mechanisms and price formation, have different alternative hypotheses. The alternative hypothesis for the trading mechanism theory is that the open-to-open variance should exceed all other measured variances and that vari-

[7] In footnote 15 of their 1987 article, Amihud and Mendelson stated that they made similar calculations from noon to noon and from 2 P.M. to 2 P.M., but they did not report the results. In private correspondence, Haim Mendelson recalled that the noon-to-noon and 2 P.M.-to-2 P.M. numbers were lower than the open but insignificantly different than the close. He attributed the latter result to a small sample size of five stocks.

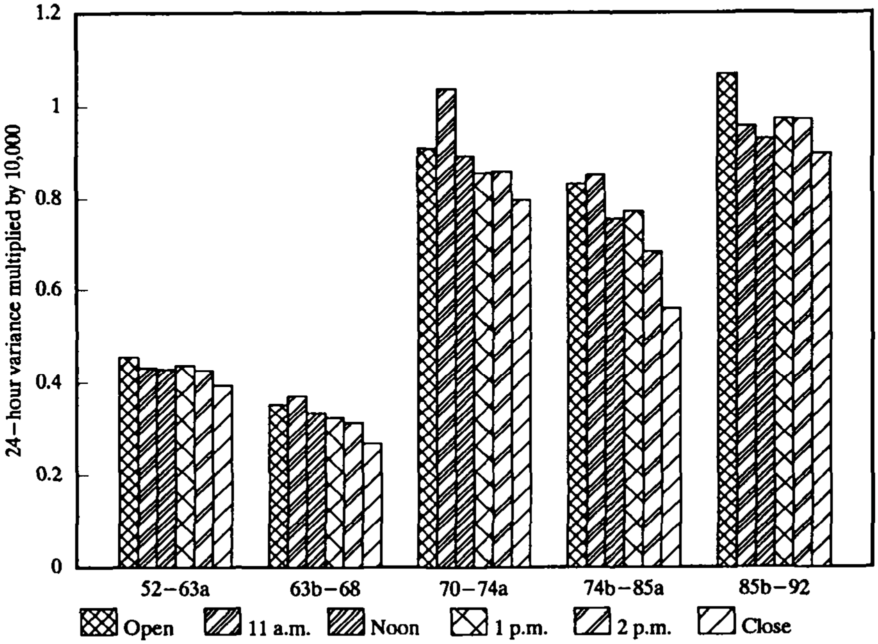

Figure 1
Variance for each hour of the day by subperiod

ances estimated at points other than the open should all be equal. The alternative hypothesis under the price formation theory is that each estimated variance should be smaller than the one estimated at a preceding point in the trading day.

The results, presented in Figure 1 and Table 3, indicate a steady decline in variance as the trading day proceeds. As shown in Figure 1, the variance from open to open is generally the highest variance of the day, while the close-to-close variance is generally the lowest variance of the day.[8] Between these two endpoints, the intraday variances generally are lower as the day progresses-most of the variance ratios in panel A of Table 3 are greater than 1. *F*- tests and *t*- tests of the null that the variance ratios equal 1 are reported in panels B and F, respectively. An F-test that all hours have equal variance, reported in panel C of Table 3, rejects the null in each of the subperiods.

This steady decline in transitory volatility during the day suggests that the opening call on the NYSE is not necessarily destabilizing. Indeed, in three of the five subperiods, variance actually rises between

[8] To aid the ocular comparison across periods, the figure does not report all hours for the latter periods having longer trading sessions.

Table 3
Variance ratios of the Dow Jones 65 Composite Price Index for adjacent hours of the day

	Subperiod				
	1952–1963a	1963b–1968	1970–1974a	1974b–1985a	1985b–1992
	A: Variance ratios				
σ^2_{oo}/σ^2_1	1.05	0.95	0.88	0.98	1.02
σ^2_1/σ^2_2	1.01	1.11	1.16	1.13	1.03
σ^2_2/σ^2_3	0.98	1.03	1.04	0.98	1.00
σ^2_3/σ^2_4	1.02	1.03	1.00	1.13	1.01
σ^2_4/σ^2_5	1.08	1.17	1.04	1.27	1.00
σ^2_5/σ^2_6	n.a.	1.00	1.04	0.96	1.08
σ^2_6/σ^2_7	n.a.	n.a.	n.a.	n.a.	0.98
	B: Probability levels, *F*-test				
σ^2_{oo}/σ^2_1	.063	.991	.999	.999	.242
σ^2_1/σ^2_2	.061	.002	<.001	<.001	.235
σ^2_2/σ^2_3	.983	.012	.006	.738	.552
σ^2_3/σ^2_4	.014	.314	.810	.127	.394
σ^2_4/σ^2_5	<.001	<.001	<.001	<.001	.494
σ^2_5/σ^2_6	n.a.	.999	<.001	.846	.018
σ^2_6/σ^2_7	n.a.	n.a.	n.a.	n.a.	.739
	C: Test of equality of variance				
F-statistic	6.34	6.16	5.32	12.55	2.17
p-level	<.001	<.001	<.001	<.001	.034
	D: Test of equality of variance for nonopening hours				
F-statistic	3.18	5.77	6.04	5.90	2.54
p-level	.023	<.001	<.001	<.001	.018
	E: Number of observations				
	2832	1273	1115	2780	1532
	F: Probability levels, *t*-test				
σ^2_{oo}/σ^2_1	.002	.796	.995	.444	.124
σ^2_1/σ^2_2	.361	.067	.002	.058	.809
σ^2_2/σ^2_3	.926	.080	.005	.651	.798
σ^2_3/σ^2_4	.098	.091	.292	.415	.663
σ^2_4/σ^2_5	.003	.045	.104	.051	.880
σ^2_5/σ^2_6	n.a.	.444	.008	.290	.001
σ^2_6/σ^2_7	n.a.	n.a.	n.a.	n.a.	.674

This table reports the variance ratios of the stock returns of the Dow Jones 65 Composite Price Index for adjacent hours in the trading day. See Table 1 for the characteristics of the subperiods. σ^2_{oo} is the variance of stock returns of the Dow Jones 65 Composite Index computed from open to open.. σ^2_n is the variance of stock returns of the Dow Jones 65 Composite Index computed from hour *n* to hour *n*. The variance ratios have been rounded to two significant digits for simplification of presentation. The *p-levels* in panels B, C, and D are for the *F*- distribution calculated from the modified Levene statistic. The probability levels, *t*- test in panel F are the probability levels of the *t*- test of the null that the variance ratios for particular adjacent hours computed for each of the *n* years in a subperiod equal 1.

the open and the first hour before falling throughout the remainder of the day. Moreover, an *F*- test that all nonopening hours have equal variance, reported in panel D of Table 3, rejects the null in each subperiod. Since these hours all employ continuous trading, this test does not provide support for the hypothesis that the form of trading mechanism is driving the different return variability during the day. By contrast, as implied by the analysis of Madhavan (1992), the particular trading mechanism chosen by an exchange at a given point in the day can be viewed as an endogenous response to trade-offs of factors including immediacy and information gathering.

We interpret our findings as providing support for models of price formation such as in Dow and Gorton (1993), Grundy and McNichols (1989), Leach and Madhavan (1993), and Romer (1993). The results suggest that overnight information must be learned by the market. Initial trading in a given day has more noise than that later in the day. Through trading, information is revealed and prices become less noisy. The results are inconsistent with the hypothesis that trading adds to the noisiness of stock returns and complement French and Roll's (1986) conclusion that trading allows private information to become incorporated into securities prices. Our findings are also consistent with Leach and Madhavan's (1993) theory and evidence that market makers engage in greater price experimentation at the beginning of the trading day.

Note, moreover, that, although transitory volatility in the Dow Jones 65 Index falls steadily as trading proceeds, transitory volatility in the index is not directly affected by the level of trading volume. Across the subperiods, for example, there is no obvious trend in variance ratios, while trading volume has increased significantly between 1952 and 1992. Additionally, within an average trading day, volume follows a U-shaped pattern (Jain and Joh 1988), which differs from the steady decline in transitory volatility during the day.[9]

Similarly, the results also indicate that the variation in transitory volatility within the day is not being driven by the dissemination of public information. Recent research by Atkins and Basu (1991) and Berry and Howe (1992) reported that the greatest number of news stories is released around the opening and closing of financial exchanges. This clustering of public information at both the open and the close contrasts with the steady decline in transitory volatility during the day.

The results of declining intraday stock return variance are robust for each day of the week. As a representative example of the day-of-the-week behavior, Figure 2 presents 24-hour variance on an intraday basis by day of the week in the 1974b-1985a subperiod. For each day of the week, open-to-open variance generally exceeds close-to-close variance, with a steady decline during the day from the open to the close. In results available upon request, we find similar patterns in the other subperiods.

[9] In cross-sectional analysis of firm-level price data, Amihud and Mendelson (1991) did find an inverse relation between trading volume and transitory volatility. This result probably stems from the greater bid-ask bounce in less liquid stocks, a phenomenon that is not captured by our price index data.

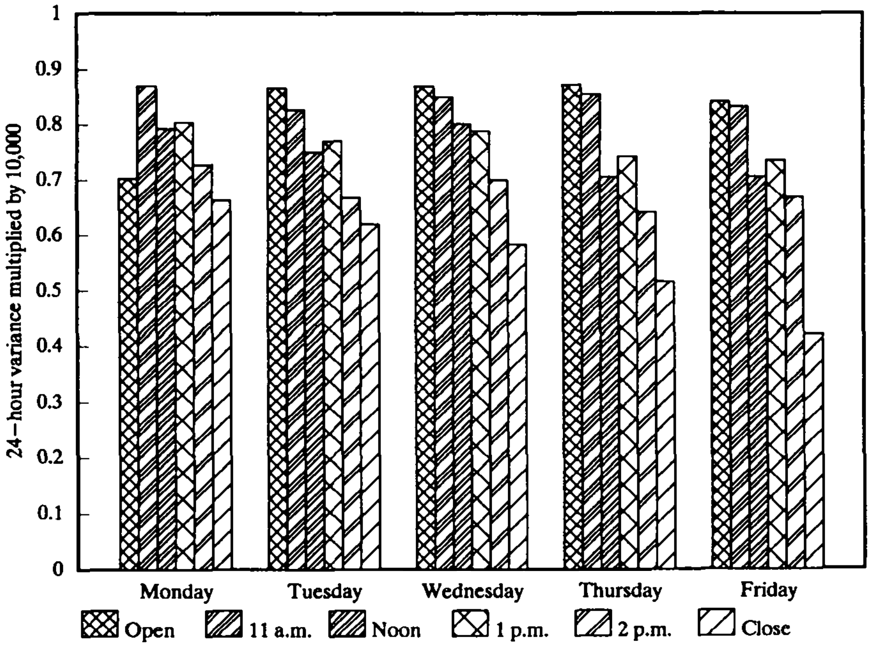

Figure 2
Variance for each hour by day of the week, 1974b–1985a subperiod

A notable exception to the steady decline in variance is seen on Mondays in the first two subperiods.[10] In results available upon request, we find that in both 1952-1963a and 1963b-1968, open-to-open variance on Monday is less than close-to-close variance and variance progressively increases during the day. This seems to stem from the fact that the "weekend effect" was actually a "Monday effect" in those two subperiods. Compared to the significantly negative returns over the weekend and in the early Monday trading hours in recent years (e.g., Harris 1986), the analysis of Smirlock and Starks (1986) for the Dow Jones 30 Industrials Index and our own analysis of the Dow Jones 65 Composite Index, available upon request, show a large, negative return from open to close on Mondays for the first two subperiods of our sample. These large returns have a magnitude that is large enough to affect the variance calculations: the open-to-close return on Monday is -.18 percent and the squared value of this return, an approximation of variance, is roughly 30 percent of the difference between the close-to-close and open-to-open variances in the 1952-1963a and 1963b-1968 periods.

[10] Chang et al.'s (1992) study of TOPIX and Masulis and Ng's (1992) analysis of the *Financial Times* 100 Index also reported some interday variation in open/close variance ratios.

Table 4
Variance ratios of the Dow Jones 30 industrials between open and close and for adjacent hours

Stock	$\sigma^2_{oo}/\sigma^2_{cc}$	p-level	Intraday variance ratios $\sigma^2_{oo}/\sigma^2_{10}$	$\sigma^2_{10}/\sigma^2_{11}$	$\sigma^2_{11}/\sigma^2_{12}$	$\sigma^2_{12}/\sigma^2_{1}$	$\sigma^2_{1}/\sigma^2_{2}$	$\sigma^2_{2}/\sigma^2_{3}$	$\sigma^2_{3}/\sigma^2_{cc}$
Alcoa	1.22	<.001	1.09	1.02	1.00	1.00	1.02	1.17	0.93
Allied Signal	1.03	.302	1.04	1.20	1.04	0.96	1.03	1.02	0.79
American Express	1.01	.440	1.07	0.98	1.09	0.99	1.00	0.98	0.91
AT&T	1.00	.484	0.95	1.04	1.06	1.02	1.04	1.04	0.88
Bethlehem Steel	1.07	.097	1.06	1.04	1.02	1.03	0.98	1.01	0.94
Boeing	1.09	.067	0.97	1.03	1.16	0.94	1.03	1.04	0.92
Chevron	1.55	<.001	1.57	1.09	1.04	1.03	1.04	1.00	0.81
Coca Cola	1.14	.010	1.03	1.09	1.11	0.97	1.01	1.08	0.86
duPont	1.12	.020	1.04	1.11	1.00	1.00	1.06	1.16	0.79
Eastman Kodak	0.98	.654	1.01	1.09	1.03	0.97	0.93	1.11	0.86
Exxon	1.09	.052	1.12	1.13	0.99	0.99	0.95	1.09	0.85
General Electric	1.14	.009	1.08	1.02	1.07	1.02	0.99	1.09	0.88
General Motors	1.02	.362	0.99	1.02	1.12	0.95	0.99	1.06	0.90
Goodyear	1.11	.028	0.95	1.04	1.09	0.96	1.09	1.09	0.91
IBM	1.11	.027	1.00	1.06	1.04	1.01	1.02	1.09	0.90
International Paper	1.15	.006	1.08	1.02	1.06	1.03	1.05	1.02	0.89
McDonald's	1.15	.007	1.01	1.11	1.02	0.97	1.02	1.06	0.96
Merck	1.20	<.001	1.02	1.10	1.07	1.00	0.98	1.13	0.92
Minnesota Mining	1.17	.003	1.13	1.07	1.05	1.02	1.00	1.06	0.86
Navistar	1.10	.050	0.87	1.26	0.97	1.01	1.00	1.01	1.02
Philip Morris	1.17	.026	1.00	1.15	1.00	1.03	0.96	1.08	0.95
Primerica	1.17	.002	1.03	1.12	1.03	1.04	0.92	1.15	0.90
Procter & Gamble	1.22	<.001	1.04	1.10	1.07	0.94	1.02	1.09	0.96
Sears	0.99	.551	0.98	1.07	1.03	0.97	1.00	1.05	0.91
Texaco	1.06	.132	1.10	1.06	0.94	1.01	1.05	1.00	0.91
Union Carbide	1.07	.119	0.89	1.15	1.14	1.03	0.98	1.10	0.82
United Technologies	1.22	<.001	1.02	1.16	1.12	1.03	0.91	1.05	0.93
USX	0.86	.999	0.99	1.04	1.07	1.02	0.98	0.98	0.80
Westinghouse	1.15	.007	0.94	1.08	1.09	1.05	0.97	1.11	0.92
Woolworth	1.12	.025	0.94	1.07	0.96	1.02	1.04	1.07	1.03
Average	1.12		1.03	1.09	1.05	1.00	1.00	1.07	0.90
t-statistic	5.58	<.001	1.56	7.89	5.05	−0.013	0.205	7.24	−9.62
Dow 30 Index	1.30	<.001	1.09	1.11	1.08	0.99	1.01	1.14	0.88

This table reports variance ratios for the individual firms in and the actual index of the Dow Jones 30 Industrials Index. σ^2_{oo} is the variance of stock returns computed from open to open.. σ^2_n is the variance of returns computed from hour n to hour n. σ^2_{cc} is the variance of returns computed from close to close. p- level is the probability level of the F- distribution for the ratio of the open-to-open and close-to-close variances. r-statistic tests the null that the average variance ratio across the 30 securities equals 1. There are 684 trading days per firm, except where noted in the text. The data come from Tick Data Inc. and span July 5, 1989, to March 31, 1992.

The only other noticeable exception to the steady decline in variance during the day occurs on Fridays in the 1985b-1992 period. In that period, 24-hour variance tends to increase in the latter hours of the day on Friday. This phenomenon may be due to order imbalances associated with the expiration of options and futures contracts. However, the patterns are not significantly different when we exclude triple witching days, suggesting a more general Friday effect in the 1985b-1992 period.

3. A Comparison of Intraday Index and Firm-Level Data

The analysis in the prior section indicates that the transitory stock return volatility of the Dow Jones Composite Index declines steadily during the trading day. The consistency of the results across a 40-year time period suggests that the intraday pattern is robust to factors such as the level of price volatility, the magnitude of trading volume, and the composition of the investor population. As an additional assessment of the robustness of the results, this section replicates the analysis with a 2½-year sample of the prices of the 30 securities in the Dow Jones Industrial Index and compares the intraday behavior of the firm-level data with that of the returns of the observed value of the index itself. This analysis of individual securities price data is motivated by the possibility that the aggregation associated with a price index masks the actual intraday behavior of securities prices.”

Our sample of firm-level data is the set of 30 firms listed in Table 4 that made up the Dow Jones Industrial Index as of July 1989. The data span the 684 trading days from July 5, 1989, to March 31, 1992, which is the extent of the intraday data available from our source vendor, Tick Data Inc. of Lakewood, Colorado. Note that Minnesota Mining has only 662 available days of intraday data because the source is missing data from January 1991 for that firm. Six firms-Allied Signal, American Express, Chevron, McDonald’s, Navistar, and United Technologies-have only 641 available days of intraday data because the source is missing data from January 1991 and August 1991 for those firms.

The period of operation of the NYSE for July 1989 through March 1992 is 9:30 A.M. to 4 P.M. Using the intraday prices for the 30 individual securities, we estimate stock returns from open to open, 10 A.M. to 10 A.M., and so forth, through close to close. The estimates of returns account for all stock splits and dividend payments occurring over the sample period. We then estimate the variance of the stock returns estimated at the various hourly points in the trading day. For comparison purposes, we perform similar calculations for the hourly observations of the Dow Jones 30 Industrials Index that were gathered from the weekly editions of *Barron’s* for the same period.

Table 4 reports the estimates of the ratio of stock return variance computed from open to open and from close to close for each of the 30 Dow Jones Industrials firms. The results for the individual securities resemble those of the original Amihud and Mendelson (1987)

[11] Fisher (1966) was among the first to note that factors such as nonsynchronous trading can induce differences between the observed values of price indexes and individual securities prices. Lo and MacKinlay (1988) provided a more recent documentation of the contrasting time series behavior of portfolio returns and the returns of individual securities.

analysis of the 30 Dow Jones Industrial stocks for the February 1982-February 1983 period. The variance ratios reported in Table 4 range from 0.86 to 1.55, which is similar to the range of 0.80 to 1.48 found by Amihud and Mendelson (1987). As in the Amihud and Mendelson (1987) study, the average variance ratio is greater than I-the average variance ratio in Table 4 is 1.12, which compares to 1.20 reported by Amihud and Mendelson (1987) and 1.30 reported in Table 4 for the Dow Jones Index. A cross-sectional f-test of the null that the average variance ratio equals 1 rejects the null at conventional levels.

Between the open and the close, the variance of the individual securities generally declines during the trading day. Table 4 also reports the ratios of the variances of consecutive hours. The ratios are generally greater than 1, indicating a steady decline in transitory volatility during the trading day. Moreover, the intraday pattern of the variance of the individual securities closely resembles that of the Dow Jones Index, which is also reported in Table 4.

The only notable exception to the steady decline is the ratio of the 3 P.M.-to-3 P.M. and close-to-close variance, which is consistently less than 1. These results resemble those reported for the Dow Jones 65 Composite Index on Fridays in the 1985b-1992 subperiod and may reflect settlement practices. More generally, the higher variance in close-to-close returns suggests that, at least in the July 1989-March 1992 period, closing prices are affected by noninformational factors in a fashion developed by Brock and Kleidon (1992). These authors modeled an exogenous demand for trading by investors that arises from the impending daily close of the stock exchange. This may give rise to a marginal increase in the variance of close-to-close returns.

For our purposes, the most important evidence in Table 4 is that the prices of the individual securities exhibit similar intraday behavior as the Dow Jones Industrials Index. Like the index, the average variance ratio of the 30 individual securities is 1 or higher up to the last hour, where it dips below 1. The close comparability of the results for the individual securities with those for the price index attests to the robustness of the analysis of the Dow Jones 65 Composite Index in Section 2.

4. Concluding Comments

In this article we address the previously documented phenomenon that transitory stock return volatility at the opening of trading exceeds that at the close. Using a 40-year sample of hourly stock price index data and a 2½-year sample of intraday data on individual securities, we examine stock return variance computed from open to open, first hour to first hour, and so forth, through close to close. We find that this measure of stock return variance steadily declines during the trading day. This pattern supports the hypothesis that trading facilitates the incorporation of information into stock prices and is consistent with the models of Dow and Gorton (1993), Grundy and McNichols (1989), Leach and Madhavan (1993), and Romer (1993) and the empirical analysis of French and Roll (1986). Since variance steadily declines within the day, rather than falling discretely after the open, the results also indicate that the call market used to open trading on the NYSE is not inherently destabilizing. This latter implication is consistent with Madhavan's (1992) model of trading mechanisms as well as Amihud and Mendelson's (1991) interpretation of their recent evidence from the Tokyo Stock Exchange.

Given our results, it is not surprising that the NYSE prides itself on providing a continuous market for the trading of its securities, one that is open in both good times and bad. Indeed, Garvy (1944) noted that the ability of the NYSE to survive volatile periods was a major reason for its success vis-à-vis its competitors in the 19th century. Not only does the maintenance of operations ensure greater liquidity, but it also implies less noisy stock prices. Correspondingly, our results lend credence to the wariness expressed by Grossman (1990), Leach and Madhavan (1993), and Madhavan (1992) toward the use of circuit breakers and other trading halts in times of market stress. Consistent with Lee, Ready, and Seguin (1994), our results indicate that closing markets can interrupt information flow and increase transitory volatility.

Appendix

In our analysis of transitory volatility, we wish to determine whether 24-hour stock return variances measured at different starting points in the trading day are significantly different. One possible method to use is a modified Levene statistic that tests the null hypothesis that the ratio of two (or more) variances equals 1. A potential problem in our application, however, is that conventional tests of the equality of variance assume independent samples, an assumption that is violated with our returns computed from overlapping price data. To assess the magnitude of any bias from overlapping data, we use GAUSS to simulate the modified Levene statistic estimated from overlapping data.

We structure the simulations to have six prices per day over a 250-day period. The matrix of prices is generated from processes ranging from a basic random walk to more complicated ARCH and drift processes. The six prices per day have six corresponding returns including the overnight return. Twenty-four-hour returns are then generated

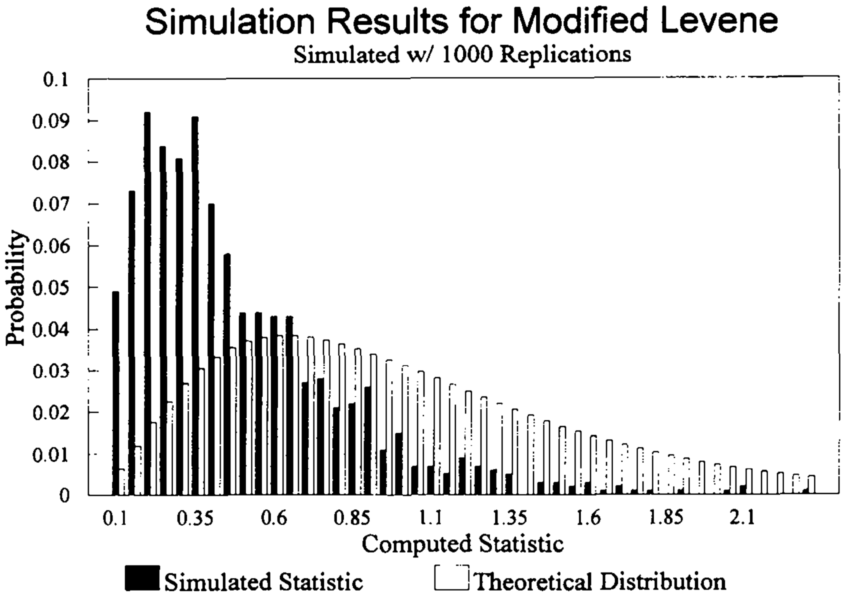

Figure 3
Simulation comparing the modified Levene statistic using overlapping data and the theoretical *F*-distribution

for each hour of the day, where adjacent daily returns share six prices. A modified Levene statistic is then calculated to test the null hypothesis of equal variance throughout the day.

For a given price generation process, the simulation is replicated 1000 times giving a total of 1000 modified Levene statistics computed from overlapping data. The frequency distribution of the computed statistic is then compared against the *F*- distribution that assumes independence, and a chi-squared goodness of fit test statistic is computed. The resulting probability distribution functions are also plotted against the theoretical *F*- distribution.

As one example, Figure 3 plots these distributions when prices are generated by a random walk process. The simulated probability distribution function is significantly more compact than the theoretical F-distribution (the chi-square statistic is 1731.9). Similar results, available upon request, obtain from more complicated return-generating processes. The use of overlapping data seems to make it less likely to draw an extreme observation, suggesting that the use of overlapping data actually biases against rejecting the null.

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