An Examination of Changes in Specialists' Posted Price Schedules

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New York Stock Exchange specialists disseminate information to market participants by displaying price schedules consisting of bid prices, ask prices, bid depths, and ask depths. We examine how specialists update these price schedules in a simultaneous equations model. We find that changes in the best prices and depths on the limit order book have a significant impact on the posted price schedule, while the effects of transactions and order activity are secondary. Furthermore, we show that specialists revise prices and depths differently, but find no evidence that they revise the price schedule in response to changes in inventory.

Despite its importance, the way in which New York Stock Exchange (NYSE) specialists determine posted price schedules, commonly referred to as quotes, has received little attention in the literature. Posted price schedules, which consist of bid and ask prices and bid and ask depths, represent the primary means by which information is aggregated and disseminated to market participants. As such, the price schedule revision process offers insight into the way in which information is integrated into markets—a primary issue in the study of finance. The fact that the posted prices and depths have a direct and substantial effect on trading decisions makes an understanding of the revision process valuable to investors, as well.

We are interested in determining what sources of information the specialist uses when updating the price schedule and how changes in these inputs are reflected in the new quotes. We investigate a variety of changes in the trading environment, each with the potential to cause specialists to revise their price schedules. In particular, we study the effects of transactions; changes

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in the limit order book; cumulative order placement, cancellation, and transaction activity; changes in specialists' inventory; and changes in competing exchanges' quotes. The occurrence of one or more of these events may indicate a change in expectations about the value of the asset, a change in the degree of adverse selection risk, or simply a shift in the liquidity provision in the market. We hypothesize that competition, especially through the collective liquidity provided by the limit order book, is an important determinant of price schedule revisions. Furthermore, we test the hypothesis that specialists have preferred uses for prices and depths.

Although subsets of this issue have been examined previously in the literature, a complete analysis of the entire price schedule is crucial for a number of reasons.[1] First, analyses focusing on a single part of the schedule (e.g., prices) are incomplete, since work by Lee, Mucklow, and Ready (1993), Harris (1994), Dupont (1995), and Kavajecz (1998) demonstrates that quoted prices and quoted depths are often used in conjunction by specialists. Statistics on our dataset corroborate these results, with two or more elements of the price schedule revised simultaneously in almost half of the quote changes in our sample. This suggests that studies using quoted prices to quantify the amount of asymmetric information in the spread, for example, ignore changes in depth as a potentially important alternative to changes in prices. Second, focusing on the effects of a single event leads to an incomplete understanding of the overall quote revision process. By broadening the set of events to include the limit order book, for example, we are able to better understand the role of public liquidity providers.

We estimate NYSE specialists' price schedule revision processes in the context of a simultaneous equations model, which directly incorporates the interdependence among the endogenous variables: the bid price, the ask price, the bid depth, and the ask depth. We find that changes in the best prices and depths on the limit order book have a significant impact on the specialist's posted price schedule. These variables remain important even when the specialist is posting prices that differ substantially from those on the limit order book. Contemporaneous transactions, cumulative order placement activity, and cumulative transaction activity are secondary to the limit order book, both statistically and economically. The posted price schedule bears no reliable relation to either the specialist's inventory or changes in the number of shares elsewhere on the limit order book. In addition, we find that specialists

[1] A substantial segment of the literature focuses on the interaction between *quoted prices* and *transactions* in order to identify and measure the components of the bid-ask spread [e.g. Roll (1984), Glosten and Harris (1988), Choi, Salandro and Shastri (1988), Stoll (1989), George, Kaul, and Nimalendran (1991), Lin, Sanger, and Booth (1995), Greene (1996), Huang and Stoll (1997), and Madhavan, Richardson, and Roomans (1997)] or to study inventory effects, information effects, or the extent of price discovery within and across markets [e.g., Hasbrouck (1988, 1991, 1995), Madhavan and Smidt (1991), and Leach and Madhavan (1993)]. A few articles augment their investigation of changes in quoted prices by including variables related to the quoted depth, or by analyzing the impact of orders [e.g., Petersen and Umlauf (1993), Hasbrouck (1996), Knez and Ready (1996), and Kaniel and Liu (1997)].

revise the quoted prices and depths in response to different events. Depths are revised in response to transactions of any size, while prices are revised only when transactions exceed the quoted depth. Finally, we find that specialists' quote-revision processes vary with trading volume, with transactions playing a much more significant role for actively traded stocks than for inactively traded stocks.

The prominence of the limit order book's impact on the price schedule suggests that the book is an important channel of information to the market. This implies that publicly stated liquidity plays a critical role in the price discovery process and this may be one of the important benefits of a consolidated limit order market. Furthermore, from a regulatory standpoint, the results suggest that policy changes that affect public liquidity provision will also have a large effect on the posted prices and depths. We also find, however, that despite the importance of the limit order book, the specialist does not simply reflect the liquidity on the book when posting quotes. This finding has implications for the debate concerning pure limit order book markets. In particular, there is a trade-off between the transparency of a pure limit order market and the probable increase in volatility relative to markets in which specialists smooth prices.

The remainder of the article is organized as follows. Section 1 contains the empirical model. The data and methodology are discussed in Section 2. Section 3 presents the results and Section 4 concludes.

1. Empirical Model

We model the price schedule revision process as a system of four simultaneous equations because specialists often revise the elements of the price schedule at the same time. Each equation represents the change in one of the elements of the specialist's posted price schedule, with changes in the bid and ask prices measured in dollars and changes in the bid and ask depths measured in thousands of shares. We avoid issues associated with cointegration of the bid and ask price levels [see Hamilton (1994)] by using price changes, which are assumed to be covariance stationary.

Each equation in our system is a function of changes in the other elements of the price schedule as well as additional explanatory variables. This structure is based on a number of empirical and institutional facts. Holthausen, Leftwich, and Mayers (1987) and Chan and Lakonishok (1993) find asymmetric effects of buy and sell transactions and Jones (1993) shows that specialists may set more favorable quotes on one side of the market to manage inventory or adverse selection risk. Consequently the bid and ask prices and depths are modeled as four separate equations rather than focusing on the spread midpoint and total depth.

The inclusion of the other elements of the price schedule in each equation stems primarily from the NYSE rules and procedures. Specialists' success in maintaining a "fair and orderly market" is continuously monitored by the exchange. Practically speaking, compliance with this duty amounts to (i) maintaining a narrow bid-ask spread, (ii) maintaining price continuity, and (iii) providing reasonable depth. The requirement for a narrow spread, coupled with price continuity, links the bid and ask prices. The provision for reasonable depth may connect the two depth quotes. In addition, studies by Lee, Mucklow, and Ready (1993), Harris (1994), Dupont (1995), and Kavajecz (1998) demonstrate that the price and depth quotes are used together, often as substitutes, to manage adverse selection and inventory risk. This prompts the inclusion of the price variable in the depth equation and vice versa.

The additional explanatory variables in the model are chosen to reflect events that potentially cause the specialist to revise the posted price schedule. We draw upon existing empirical and theoretical evidence when selecting these variables. Our model includes variables that measure transactions, changes in the limit order book, price changes on regional exchanges, changes in the specialist's inventory position, and cumulative transaction, order placement, and order cancellation activity.

Transactions are an obvious potential predictor of price schedule revisions—particularly given the existing empirical literature. In our model, contemporaneous transactions are captured with two pairs of variables—transaction volume (one buyer initiated and one seller initiated) and dummy variables describing the transaction size relative to the posted depth. The transaction volume variables are included because they could affect the magnitude and/or likelihood of a price schedule revision, and can be viewed as a measure of the information content of the event, as shown in Lin, Sanger and Booth (1995), among others. The dummy variables allow for the possibility that transactions that exceed the quoted depth contain more information and therefore induce larger quote revisions. Results from Petersen and Umlauf (1993) and Knez and Ready (1996) provide evidence in support of this specification. The dummy variables in the model assume a value of one when the buy (sell) transaction size exceeds the posted ask (bid) depth and a value of zero otherwise.

Theoretical work by Rock (1990) and Seppi (1997) suggests that the limit order book has a substantial impact on the price schedule revision policy of the specialist. We use a number of limit order book variables in our model. These include changes in the best bid and ask prices on the limit order book since the last quote revision, changes in the number of shares on the book at those prices, changes in the cumulative depth on each side of the limit order book up to $0.25 away from the best prices on the book, as well as the ratio of the ask-side cumulative depth to the bid-side cumulative depth. Changes in the number of shares at the best prices on the book and cumulative depth measure the liquidity provided by the limit order book. The ratio of the cumulative depth variables reflects the potential importance of liquidity imbalances between the buy and sell sides of the market.

Blume and Goldstein (1992) show that regional exchanges contribute to liquidity provision and price discovery, potentially making the regional quotes a significant consideration for the NYSE specialist. The difference between the best bid (ask) price posted on the NYSE and best bid (ask) price posted on the regional exchanges captures this effect. These variables are nonzero only when there is a shift in the exchange (NYSE versus regional) that is determining the best bid or best ask on the National Market System (NMS). The posted depths on the regional exchanges are absent from our analysis because they are often autoquotes, set to follow the NYSE specialist's quote. For further discussion, see Blume and Goldstein (1992) and Hasbrouck (1995).

Garman (1976) argues that specialists must account for inventory when setting their price schedule. Empirical studies of inventory effects, such as Hasbrouck and Sofianos (1993) and Madhavan and Smidt (1993), suggest that inventories tend to be highly persistent, meaning it takes a substantial amount of time for inventories to revert back to their desired levels. We capture this slow-moving inventory process in our model by including a variable that measures the cumulative change in the specialist's inventory of the stock since the beginning of the sample period.

The final set of explanatory variables included in the analysis reflects the amount of activity that has occurred in the market for the stock since the last quote revision and captures the importance of noncontemporaneous events. While a single event may result in no price schedule revision, the cumulated sequence of events may warrant a change in the price schedule. Cumulated events may be important because a series of trades or observed trading patterns could reveal information not contained in a single transaction. For example, the specialist may revise the price schedule differently in response to a sequence of ten 100-share orders and a single 1000-share order. Alternatively, the existence of a minimum tick size, which at the time of our sample was 1/8, could lead specialists to revise the price schedule only when the total price change (over several events) exceeds the tick size.

Our bid-side activity variables are broken down into seller-initiated transactions, newly placed buy limit orders, and cancellations of buy limit orders. Each is computed by summing shares within their respective category since the last quote revision.[2] The ask-side activity variables are computed analogously by cumulating shares from buyer-initiated transactions, newly placed sell limit orders, and canceled sell limit orders. In all cases, the current event is excluded from the sum since it is contained in other variables. The activity variables are designed to measure the degree of uncertainty or adverse selection risk in the market because microstructure models [e.g., Admati and Pfleiderer (1988)] predict that informed traders will prefer to trade in periods

[2] A concern with any cumulative time-series variable is the potential for nonstationarity. However, the cumulative series we construct are cumulated only since the last quote revision. Dickey–Fuller tests reject the null hypothesis of a unit root at the 1% level in 857 of 858 cumulative activity series.

where liquidity traders cluster, thus providing sufficient noise to conceal their informed order flow.

It could be argued that the time elapsed since the last event affects the likelihood and/or size of the quote revision and should be included as an explanatory variable. For example, Engle and Russell (1998) find evidence of transaction clustering for IBM. While our model does not explicitly contain a variable that reflects this, the importance of time is captured through the use of an event window described in detail in Section 2.

If we let y_t denote a (4×1) vector containing the endogenous (price schedule) variables, x_t denote a (21×1) vector of exogenous variables (described above), and u_t denote a (4×1) vector of disturbances, then our model can be represented using the following equation:

$$\mathbf{B}y_t + \Gamma x_t = u_t, \tag{1}$$

where $\mathbf{B}$ and Γ represent coefficient matrices of size (4×4) and (4×21), respectively. A description of the variables in the model is contained in Table 1.

Table 1
Variable definitions

Variable	Description
Endogenous	
Δ*Bid Price*	Change in the bid in dollars
Δ*Ask Price*	Change in the ask in dollars
Δ*Bid Depth*	Change in the bid depth in 1,000 shares
Δ*Ask Depth*	Change in the ask in 1,000 shares
Exogenous	
Buy Transaction Volume	Buy transaction volume = the size in 1,000 shares of the buy transaction (=0 for nontransaction records)
Buy Depth Exceeded Dummy	Buy depth-exceeded dummy (for buy transaction events only) =1 if buy transaction volume exceeds the posted ask depth (0 otherwise)
Bid-side Transaction Activity	Bid-side transaction cumulative lagged activity = the sum of all shares (in 1,000s) from sell transactions since the last quote revision (excluding the current event volume)
Bid-side Order Placement Activity	Bid-side order placement cumulative lagged activity = the sum of all shares (in 1,000s) from newly placed buy orders since the last quote revision (excluding the current event volume)
Bid-side Cancellation Activity	Bid-side cancellation cumulative lagged activity = the sum of all shares (in 1,000s) from canceled buy orders since the last quote revision (excluding the current event volume)
ΔBest Bid Price on the Book	Change in the best bid price on the (limit order) book in dollars since the last quote revision
ΔShares at Best Bid on the Book	Change in the number of shares at the best bid price on the book in shares since the last quote revision
ΔNear Depth on Book Bid-side	Change in the number of shares within 1/4 of the best bid price on the book in shares since the last quote revision
Regional Bid Price	Better bid on regional exchange = $\text{Bid}_{\text{RE}} - \text{Bid}_{\text{NYSE}}$ in dollars
Near Depth Ask/Near Depth Bid	Ratio of the Near depth ask-side to the Near depth bid-side
Specialist's Inventory	Cumulative change in the specialist's inventory position

Although not shown, the ask- and sell-side exogenous variables are defined analogously.

2. Data and Methodology

We use the TORQ database, which contains order, transaction, and quote data for 144 NYSE stocks from November 1, 1990, to January 31, 1991. All orders submitted through one of the automated routing systems are included in the data, as are all transactions on the NYSE and both NYSE and regional quotes.[3] While the 3 months spanned by the TORQ data may not be representative of other time periods, we have no reason to suspect that any systematic biases existed during this period. In addition, the benefits of these data—specifically the ability to estimate limit order books and to identify the true initiator of transactions—are important to this study.

To create the dataset necessary for our analysis, we begin with the NYSE specialist's posted quote and transaction records used in Odders-White (2000). These TORQ records contain original order information for each side of the transaction, thus making determination of the initiator possible. When the initiator is unknown, one of the Lee and Ready (1991) trade classification algorithms must be employed. Odders-White (2000) demonstrates that the Lee and Ready method misclassifies approximately 15% of transactions and that the misclassification can bias results. In addition to NYSE quote records, regional quote records are included when there is a shift in the exchange posting the best bid or offer on the NMS.

The TORQ order data are then processed to create the limit order book estimates as well as activity and inventory variables. We estimate each stock's limit order book using the procedure outlined in Kavajecz (1999). First, we estimate the limit order book at the beginning of the TORQ sample by searching the TORQ database for execution or cancellation records that refer to orders placed prior to the start of the database. These records reveal orders that must have existed on the limit order book prior to the start of the sample; therefore we use these records to reconstruct the initial limit order book estimate. The second step involves sequentially treating each record in the database, modifying the limit order book based on whether the record is a newly placed order, an execution, or a cancellation. Given the sequence of limit order book estimates, changes in the limit order book are computed for each event.

The order and cancellation records that affect the best prices and depths on the limit order book are used in conjunction with the transaction records to create the lagged cumulative activity variables. The specialist's inventory is estimated using the algorithm outlined in Panchapagesan (1997). The algorithm begins with execution records for which one side of the transaction (buy or sell) was not assigned to a standing system order. Filters are then applied to this subset and the remaining transactions are labeled as specialist purchases (sales) if the buy-side (sell-side) order was unassigned.

[3] Orders submitted through an automated routing service consist of approximately 70% of all orders and make up 30–50% of total share volume. See Hasbrouck (1992) for a detailed discussion of the TORQ database.

We create our dataset by combining the transaction, quote, and order records described above chronologically, to the nearest second. Since the events that induce quote revisions and the quote revisions themselves do not generally occur at the same time, we must allow for slight differences in timing. Following Hasbrouck (1991), we account for this by assigning all events occurring within a short interval preceding the quote revision the same time subscript as the revision itself. The length of the interval is the median time between events and subsequent quote changes for each stock (MED), which varies across stocks, ranging from 5 to 20 seconds, with a median length of 9 seconds.

We also assign the same time subscript to events occurring within a brief interval *following* a quote change. This corrects for the possible misalignment of quotes and other events due to time-stamping differences documented by Lee and Ready (1991). The length of the post-quote-change interval is $1/4 * \text{MED}$. The median length of this interval across stocks is 2 seconds, with a minimum of 1 second and a maximum of 5 seconds. Lee and Ready advocated a 5-second adjustment rule but acknowledged that "a different delay may be appropriate" in different cases. We also estimated the model using $2 * \text{MED}$ before to $1/2 * \text{MED}$ after and $1/2 * \text{MED}$ before to $1/8 * \text{MED}$ after and obtained both qualitatively and quantitatively similar results.

The resulting dataset contains roughly 996,000 observations for 143 stocks. One stock was excluded because it was delisted after 1 month and provided insufficient data for the analysis. Summary statistics on stock characteristics and basic liquidity measures are contained in Table 2. As expected, the average quoted spread is smaller than the average limit order book spread for all stocks. In addition, although the TORQ data are stratified by market capitalization by construction, the sample also displays heterogeneity across stocks in trading volume and in the number of quote revisions. Additional statistics on the frequency of quote revisions (not shown in Table 2) reveal that 32.4% of the observations in our dataset consist of a revision to at least one of the price schedule variables. The bid (ask) price changes are nonzero for 7.9% (8%) of the observations, of which 7.3% (7.3%) are $\pm 1/8$. The bid (ask) depth variables are revised more often, with nonzero changes in 15.8% (16.1%) of the observations, where 11.5% (11.3%) are changes of $\pm 5{,}000$ shares or less.

As the statistics on the bid and ask price changes suggest, discreteness is an important property of our price series, although changes in the quoted depths appear to be roughly continuous. Unfortunately accounting for discreteness in the context of our model is problematic for a number of reasons. First, a necessary condition to formally account for the price discreteness within the model is that the price series be generated by a continuous latent variable crossing thresholds. We do not believe our model fits into this specification. Second, even if our model were of the continuous latent variable type,

Table 2
Summary statistics

Variable	Mean	Standard deviation	Median
Market capitalization	6,206	25,913	323
H	18,209	28,237	4,635
M	376	469	297
L	10,750	49,140	50
Trading volume	9,369	21,881	1,779
H	36,825	36,823	17,198
M	1,843	500	1730
L	265	142	234
Price level ($)	19.39	19.34	15.87
H	32.91	24.31	27.22
M	17.16	10.99	16.52
L	17.21	27.27	8.01
Quoted spread ($)	0.20	0.14	0.13
H	0.18	0.12	0.13
M	0.24	0.11	0.25
L	0.31	0.29	0.25
Quoted depth	21.43	27.00	12.00
H	27.10	28.95	16.50
M	8.47	13.14	4.30
L	4.18	8.27	2.00
LOB spread ($)	0.33	0.66	0.25
H	0.25	0.25	0.25
M	0.72	1.61	0.25
L	1.13	2.73	0.34
LOB depth	15.72	33.81	8.00
H	16.70	21.24	11.22
M	10.73	23.66	4.20
L	5.06	7.48	2.60
Number of trades/day	45	95	16
H	147	163	79
M	15	10	13
L	4	4	3
Number of quote updates/day	38	69	17
H	113	116	72
M	17	11	15
L	5	5	4

Means, medians, and standard deviations are presented for the entire sample of 143 stocks (first row), as well as by trading volume quintile (second through fourth rows). H, M, and L represent high-, middle-, and low-volume stocks, respectively. Market capitalization is in millions of dollars as of 1990 year end. Trading volume is in shares per half-hour. Price level is taken at 1990 year end. Quoted depth is the total of the bid and ask depth in thousands of shares. The limit order book spread and depth represent the difference between the best sell-side and buy-side limit prices and the total depth at the best prices (in thousands of shares), respectively.

other complications remain. For a solution to exist, the "coherency condition" [see Amemiya (1978)] or "principle assumption" [see Heckman (1978)] requires that a unique reduced form exist for both the latent and observable endogenous variables. Moreover, despite the fact that there are standard techniques for computing coefficient estimates, obtaining the asymptotic variance-covariance matrix of the estimates can be extremely complicated and "may be too cumbersome to compute in practice" [Amemiya (1978)].

Given the complications in formally modeling discreteness and the need for tractability, we simplify the estimation by assuming that the price series are continuous. As a robustness check, we partition our results by price level, since there is evidence to suggest that discreteness has a larger effect on lower-priced stocks [see Harris (1994)]. We find largely similar estimates when comparing our results across price level quintiles, which suggests that this simplification is unlikely to affect our results.

We estimate our simultaneous equations model for each individual stock in our sample using the two-stage least squares methodology. For the six most frequently traded stocks (IBM, AT&T, Exxon, Phillip Morris, Boeing, and General Electric) we used only 1 month of data rather than all 3 months of the TORQ sample due to the size of the datasets. We have chosen to use two-stage least squares (2SLS) rather than limited information maximum likelihood (LIML) or more efficient system estimation methods [i.e., three-stage least squares or full information maximum likelihood (FIML)] to avoid problems associated with these alternatives. We prefer 2SLS to LIML because both methods are asymptotically efficient and, as explained by Johnston (1984), 2SLS "has largely replaced [LIML] on grounds of greater simplicity." We select 2SLS over 3SLS and FIML to avoid introducing any misspecification bias into the coefficient estimates. The use of the variance-covariance matrix as a weighting matrix in these system estimation methods spreads any bias introduced by model misspecification throughout all equations, contaminating all coefficient estimates.

A crucial element of simultaneous equations models is the specification of the identifying restrictions. Fisher (1965) argues that among the pool of potential instruments, precedence should be given to the variables with the closest relation to the endogenous variable. Consequently we place the following restrictions on the explanatory variables in the model. The bid-side limit order book variables, the bid-side activity variables, and the bid-side regional quote variable appear only in the bid and bid-depth equations. Likewise, the ask-side limit order book variables, the ask-side activity variables, and the ask-side regional quote variable appear only in the ask and ask-depth equations. These are the logical restrictions since each omitted variable affects the opposite side of the market directly. This leaves the set of current transaction variables, the ratio of near limit order book depth, and the specialist's inventory as exogenous variables included in all four equations.

The resulting model is overidentified, since each equation in the model contains four endogenous variables and excludes seven exogenous variables. Tests of the overidentifying restrictions imposed on the model [performed using Basmann's (1960) test] produce an 8.7% overall rejection rate, which provides evidence in support of these restrictions. The null hypothesis that the omitted exogenous variables have coefficients of zero is rejected at the 5% level 13 out of a possible 143 times for the bid equation, 17 times for the ask equation, 9 times for the bid-depth equation, and 11 times for the ask-depth equation.

3. Results

The results are presented in Table 3. Equations are displayed as columns. For each explanatory variable, the table displays the mean coefficient estimate (across stocks) as well as the percentage of stocks in the sample having coefficient estimates that are different from zero at the 5% significance level. An asterisk denotes a percentage that is significant at the 0.1% level.

The most notable result is the important role played by changes in the limit order book in the revision of all four elements of the posted price schedule. Specialists update posted prices primarily in response to changes in the best prices on the limit order book and posted depths in response to changes in the number of shares at those prices. Changes in the best prices and the corresponding depths on the limit order book are statistically significant determinants (at the 5% level) of changes in the posted prices and posted depths, respectively, for 60–80% of the stocks in our sample—percentages that are not only significant at the 0.1% level, but are far higher than those for the other factors. Although the size of these coefficients varies across stocks, the relation between changes in the book and changes in the posted price schedule is consistently positive. Changes in the cumulative depths on the book up to $0.25 away from the best prices have no significant effect on the price schedule after controlling for changes in the best prices and depths on the limit order book.

The magnitude of the limit order book coefficients demonstrates that while changes in the best prices and depths on the limit order book are important determinants of changes in the posted price schedule, the specialist is not simply hiding behind the limit order book, matching (reflecting one-for-one) each change in the book. If this were the case, we would expect to find a coefficient of one on the relevant limit order book variable and of zero on all other explanatory variables. Instead, we find that on average, a $1/8 increase in the best bid (ask) price on the book causes the specialist to increase the posted bid (ask) price by approximately 0.59 (0.46) cents. In fact, even the 90th percentile coefficient (not shown) reflects a decrease in the posted bid of only 1.5 cents in response to a $1/8 decrease in the best bid price on the book. Furthermore, a 1,000-share increase in the number of shares at the best bid (ask) price on the limit order book leads to a mean increase in the posted bid (ask) depth of 93 (103) shares.

Since the specialist cannot actually revise his prices by fractions of a cent, these coefficients represent averages over times in which he reflects changes in the limit order book fully and times in which he does not. We refer to the latter behavior as "smoothing." As stated earlier, one of the specialist's responsibilities is to maintain a "fair and orderly" market. This includes minimizing price variation. Consequently the specialist will not fully reflect a change in the limit order book if it would result in a large price jump. The small magnitude of the limit order book coefficients in our model may suggest that the specialist frequently smoothes prices. Alternatively they could

Table 3
Simultaneous equation model results

	Equations							
	ΔBid price		ΔAsk price		ΔBid depth		ΔAsk depth	
Variables	*β*	%	*β*	%	*β*	%	*β*	%
Intercept	0.0024	21.7*	−0.0015	11.2*	−0.0040	2.8	0.1164	4.2
ΔBid price			0.3265	59.4*	−29.614	14.7*	−1.8248	4.2
ΔAsk price	0.3057	68.5*			9.4601	5.6	34.789	11.2*
ΔBid depth	0.0052	15.4*	−0.0018	6.3			0.0605	5.6
ΔAsk depth	−0.0009	6.3	0.0045	14.0*	−0.0612	5.6		
Buy transaction volume	−0.0006	4.9	0.0016	9.1	−0.0131	2.1	−0.0820	26.6*
Sell transaction volume	−0.0021	9.1	−0.0002	5.6	−0.0561	28.0*	−0.0069	1.4
Buy depth exceeded dummy	−0.0028	5.6	0.0223	33.6*	−0.0822	4.2	0.4222	10.5
Sell depth exceeded dummy	−0.0178	39.2*	0.0014	2.8	0.6030	7.7	−0.1222	2.8
Bid-side transaction activity	−0.0097	49.0*			−0.0741	27.3*		
Bid-side order placement activity	−0.0008	28.0*			0.0638	15.4*		
Bid-side cancellation activity	−0.0029	5.6			−0.0446	10.5		
Ask-side transaction activity			0.0130	44.8*			−0.1553	21.7*
Ask-side order placement activity			−0.0060	26.6*			0.0346	10.5
Ask-side cancellation activity			0.0021	3.5			−0.0314	9.1
ΔBest bid price on book	0.0471	78.3*			−1.5206	18.2*		
ΔBest ask price on book			0.0369	67.8*			−2.1333	16.1*
ΔShares at best bid on book	−0.0044	8.4			0.0930	65.7*		
ΔNear depth on book bid side	0.0005	0.7			−0.0063	1.4		
ΔShares at best ask on book			0.0011	6.3			0.1032	61.5*
ΔNear depth on book ask side			−0.0005	3.5			−0.0022	4.2
Near depth ratio (ask/bid)	−0.0004	11.9*	0.0005	3.5	0.0019	1.4	0.0112	1.4
Specialist's inventory	0.0002	0.0	0.0002	0.7	0.0018	0.0	0.0007	0.0
Regional bid price	−0.1256	28.7*			−0.2072	4.9		
Regional ask price			0.0907	22.4*			−1.1158	2.1
R^2	0.1242		0.1145		0.0557		0.0570	

For each explanatory variable in each of the four equations, the mean coefficient estimate across the stocks in the sample is provided (β), as well as the fraction of the stocks in the sample having coefficient estimates that are significant at the 5% level (%). *Signifies that this fraction is significant at the 0.1% level. Standard errors were adjusted using the Newey and West (1987) correction for heteroskedasticity and serial correlation. Quantities are denominated in units of 1,000 shares and prices are denominated in dollars.

simply be the result of the discrete nature of our price change data. We find additional evidence in support of the smoothing explanation, however. Statistical analysis of our sample reveals that for roughly 80% of the changes in the limit order book, the specialist does not change his posted price at all or changes his posted price by an amount less than the change in the book.[4]

One implication of price-smoothing behavior is the presence of information on the limit order book that does not get incorporated into the price schedule. Kavajecz and Odders-White (2001) provide further evidence of price smoothing and suggest that the limit order book may represent a primary point of entry for information. Specialists' smoothing behavior may be a way of "conserving" this valuable store of information.

Transactions play a secondary role in the quote-revision process, especially for prices. The specialist updates the posted depths in response to transaction volume, but revises the posted prices only in response to those transactions with sizes exceeding the quoted depth. Large transactions tend to widen the spread for roughly 35% of the stocks in the sample, and higher transaction volume tends to reduce the posted depths for approximately 27% of the stocks. Consequently the posted depths can be thought of as a specialist's first line of defense in response to single transactions. The specialist may decrease the depths following a transaction as a protective measure because the transaction conveys information. Since we have controlled for changes in the limit order book as well as changes in inventory, however, it is not the case that the specialist is simply reflecting the number of shares on the book or reacting to inventory shocks.

The fact that the specialist also adjusts the posted prices when a transaction exceeds the quoted depth may imply that larger transactions convey more information. This is consistent with theoretical notions that informed traders, who are more likely to want to transact at quantities larger than the posted amount, signal an undervalued (overvalued) asset if they are buying (selling). Alternatively, the specialist may adjust prices after a large transaction because the trade exhausted all the liquidity at the previous price. For example, suppose the best bid price on the limit order book is $20 and there are 900 shares on the book at that price. Also assume that the specialist is posting a bid price of $20 1/8 and a bid depth of 500 shares. Consider the arrival of a 400-share market sell order. Our results are consistent with the specialist taking the other side of the order and reducing his posted depth. His new quotes, for example, might be 100 shares at $20 1/8. Now instead suppose the market sell order were for 1,000 shares rather than 400 shares.

[4] Another possible explanation for the small size of these coefficients is that they reflect only the direct effect of changes in the limit order book. The limit order book variables also have an indirect influence through the endogenous variables appearing on the right-hand side of each structural equation. We examined the net effects of the exogenous variables by solving for the reduced form of the model, characterizing each endogenous variable as a function of exogenous variables only. We find that the mean reduced-form limit order book coefficients are of the same magnitude as the structural form parameters contained in Table 3.

In this case, the transaction size exceeds the posted depth and the specialist might react by changing both his bid depth and his bid price, say to 400 shares at $20.

One feature common to both prices and depths is that buyer-initiated transactions affect only the ask side of the market and seller-initiated transactions affect only the bid side of the market. This may stem from the fact that most buyer-initiated (seller-initiated) trades take place at, or closer to, the ask (bid) price.

As discussed above, a series of trades may reveal information not contained in a single transaction and, consequently, could lead to changes in the price schedule. We find that like single transactions, cumulative transaction activity has a significant, but secondary, effect on the posted price schedule both in magnitude and statistical significance. In contrast to single transactions, cumulative transaction activity has a more significant effect on the posted prices than on the depths. On average, transaction activity of 1,000 shares on the bid side of the market decreases the bid price by 1 cent and decreases the bid depth by 74 shares. Transaction activity of 1,000 shares on the ask side of the market increases the ask price by 1.3 cents and decreases the ask depth by 155 shares on average. The larger impact of buy orders relative to sell orders may partially explain Keim and Madhavan's (1995) finding that institutional investors attempt to reduce the impact of buy orders but are willing to accept the (smaller) price concessions associated with selling shares.

In summary, transactions convey only a fraction of the activity in the market. This stems from the fact that transactions closely track liquidity demanders' actions, but reveal much less about liquidity providers' activities. Along with the limit order book variables, the cumulative order placement activity and cumulative cancellation activity variables capture the importance of this other segment of the market.

Cumulative order placement activity has a significant effect on the posted price schedule—particularly for prices—but its importance is secondary to both the limit order book and transactions. Order cancellation activity, on the other hand, is not statistically significant for either prices or depths. On average, order placement activity of 1,000 shares on the bid side of the market decreases the bid price by less than 0.1 cent and increases the bid depth by 64 shares. Order placement activity of 1,000 shares on the ask side of the market decreases the ask price by 0.6 cents and increases the ask depth by 35 shares on average. Although order activity has a more statistically significant effect on the quoted prices, it appears to have a more economically significant impact on quoted depth.

Posted prices on the NYSE are also related to the posted prices on the regional exchanges. The regional variables are significant in the price equations for approximately 28% of the stocks in our sample. The negative coefficient in the bid change equation and the positive coefficient in the ask change equation for the regional variables seem to suggest that, when the regional quotes are better than the NYSE quotes, the NYSE bid price decreases and the NYSE ask price increases. The signs of the coefficients actually imply, however, that the regional exchanges are typically *following* the NYSE quotes. For example, if the NYSE specialist decreases the bid by $1/8 and the regional exchanges follow with a lag, then a positive value for the regional bid variable will be accompanied by a negative change in the NYSE specialist's bid. For the 15 most actively traded stocks in our sample, roughly 58% of the better regional quotes result from the NYSE moving its prices and the regional exchange(s) responding with a lag. This is not surprising given that market makers on many regional exchanges (e.g., Boston and Cincinnati) program their computers to mimic the NYSE quotes. This is also consistent with Hasbrouck's (1995) finding that the majority of price discovery occurs at the NYSE and that the regional exchanges follow the NYSE specialist's quotes.

Perhaps surprisingly, the specialist's inventory has no effect on the price schedule. There are a number of explanations for the lack of inventory effects in our model, however. First, existing research by Madhavan and Smidt (1993) suggests that specialists' inventory levels exhibit mean reversion but adjust very slowly, with a half-life exceeding 49 days. Given the intraday nature of our study, these long-term inventory effects may simply be captured by the constant in the regression. Second, if specialists are concerned about holding stock positions overnight, then inventory effects are likely to play a larger role near the close of trading, and estimating the model using data from the full day will mask these effects. To investigate this possibility, we reestimate the model after partitioning the data into three time periods within a day: open (9:30–11:00 A.M.), midday (11:00 A.M.–2:30 P.M.), and close (2:30–4:00 P.M.). Although not shown, the results are similar across time periods and continue to show little impact attributable to changes in inventory.[5]

The lack of inventory effects on the price schedule does not imply that specialists do not manage inventory positions, however, even in the short-run. Rather than altering the price schedule, specialists may manage their inventory passively, consistent with Madhavan and Sofianos (1998). For instance, specialists may offer depth improvement as in Bacidore, Battalio, and Jennings (2000) or may stop orders as in Ready (1999). Each of these strategies allows specialists the chance to trade for his own account without changing the posted price schedule.

The relation among the four price schedule variables suggests linkages consistent with the existing literature and with exchange-mandated requirements. Not surprisingly, the bid and ask prices are positively correlated, consistent with the specialist maintaining a relatively constant spread. Note,

[5] The model results for the open, midday, and closing periods are available from the authors upon request.

however, that the coefficients on the bid and ask in the price equations are substantially less than one. The size of the coefficients suggest that specialists do not simply reposition a fixed spread (parallel shift in the bid and ask prices), rather they adjust the price on one side of the market at a time or by different amounts. The "reasonable depth" requirement does not appear to cause an analogous link between the bid and ask depths. The bid (ask) price and bid (ask) depth are also correlated, and the relation between the price and depth on each side is generally consistent with the specialist using the prices and depths as substitutes for liquidity provision. (The one exception is the positive coefficient on the bid depth variable in the bid price equation.)

Finally, the intercept terms show that the specialist is likely to narrow the spread when no activity is taking place (no transactions, no changes in the best prices on the book, etc.). This response is consistent with theories of adverse selection since specialists post narrower spreads, ceteris paribus, when they have no need to protect themselves against the possibility of informed trading.

The results demonstrate that specialists update their posted prices primarily in response to changes in the best prices on the limit order book. They also react to increased transaction and order activity, and to transactions with sizes that exceed the quoted depth, but each of these factors has substantially less impact than the limit order book in both statistical and economic terms. These findings support our hypothesis that factors other than transactions, particularly changes in public liquidity provision, are important determinants of the price discovery process.

Like prices, the posted depths are strongly affected by changes in the limit order book. In addition, the depths are revised in response to cumulative transaction and cumulative order placement activity and to current transactions, but the impact of this activity on depths differs from its effect on prices. For example, the posted depths are changed in response to transaction volume, not only to those transactions that exceed the quoted size. The results confirm the hypothesis that specialists use both prices and depths when managing the market for their stocks and that they utilize these tools differently.

3.2 Proximity to the limit order book

Part of the significance of the limit order book in the specialist's price schedule revision process stems from the limit order precedence rule, which states that the specialist can take precedence over a limit order only by improving upon the limit price. As a result of this rule, the specialist must be mindful of the limit order book if he wishes to manage his inventory or mitigate adverse selection problems. For example, suppose the specialist posts a bid price of \$20 1/8 when the best bid on the limit order book is \$20 because he wants to buy stock for his own inventory. If the best bid on the book increases by one-eighth and the specialist still wants to take precedence over the book, he must also increase his posted bid to again improve upon the book. On the other hand, suppose the specialist posts a bid price of \$20—the same as the best bid on the book—because he wants to pass the order flow onto the existing limit orders. Now if the best bid on the limit order book decreases by one-eighth, the specialist must also decrease his bid to avoid posting a better price than the book and therefore having to take the other side of subsequent bid-side transactions.

During the time period covered by this data, specialists were allowed to hide limit orders if they felt they were not representative of the market. Consequently the specialist was not required to reflect changes in the best prices on the limit order book, even if they improved upon the quotes (e.g., if both the specialist's bid and the best bid on the book were \$20 and then the best bid on the book increased to \$20 1/8). Changes in the limit order book improve upon the specialist's quotes only 8.27% of the time in our sample. As a result, price schedule revisions that result from quote-improving limit orders play only a minor role in our analysis. Furthermore, recall that in Table 2, the limit order book spread exceeds the quoted spread on average, which implies that the specialist is typically reflecting only one side of the book at a time.

Although no automatic or mandatory updating of the quotes takes place following changes in the limit order book, the limit order precedence rule could still be responsible for the strong significance of the limit order book variables. To further investigate this possibility, we separate those changes in the limit order book for which the precedence rule is likely to have some effect from those changes for which it is unlikely to have any impact. We do so by conditioning on the proximity of the specialist's quoted prices to the best prices on the limit order book. The idea is that when the specialist is either reflecting the interest on the limit order book or is "close to" the limit order book, his behavior is more likely to be affected by the limit order precedence rule. When the posted prices are significantly better than those on the book, the precedence rule becomes less relevant.

We begin by creating a dummy variable for each side of the market that assumes a value of one whenever the specialist is more than one-eighth from the best price on the limit order book (i.e., when |quoted price − best price on book| > 1/8). The dummy is included alone, to capture any fixed effects of the specialist being "far" away from the book, as well as in interaction with the relevant limit order book variable for the given equation. Specifically, the original limit order book variables are partitioned into two variables in each equation. One variable is defined as the product of the dummy variable and the change in the limit order book. As such, it contains changes to the book that occur when the specialist's prices are more than one-eighth away from the limit order book prices. The other variable is equal to the product of (1 − dummy variable) and the change in the limit order book, so it contains changes to the book that occur when the specialist's prices are within one-eighth of the best prices on the book. This differentiation allows for the possibility of a kink in the specialist's reaction function. If changes in the book are important even when the specialist is far from the book, then we will conclude that our results are not driven entirely by the limit order precedence rule.

The estimation results are shown in Table 4. The coefficients and p-values for the nonlimit order book variables are largely the same as the unconditional results and are therefore not shown for brevity. Not surprisingly, changes in the limit order book that occur when the specialist's posted prices are in close proximity to the book are more likely to affect the price schedule, as evidenced by the higher statistical significance of these variables. The impact of the limit order book is still an important consideration *even when the specialist's quotes are more than one-eighth away from the limit order book*, however. In fact, although the specialist is less likely to react to changes in the book when the quoted prices are far from the book, when he does react, he changes his quoted prices by a larger amount on average. Notice that even when the specialist is close to the book, the magnitude of the limit order book coefficients does not approach the benchmark value of one in which the specialist fully reflects all changes in the book. This provides additional evidence that the specialist is smoothing prices as described above.

All of the results for the limit order book variables are consistent with specialists closely monitoring changes in the best prices and quantities on their limit order books and reacting to these changes a significant portion of the time. Although specialists sometimes play a passive role by simply mirroring changes in the limit order book, they more often assume an active role in which they smooth price changes by providing extra liquidity to the market.

3.3 Trading volume effects

Although not shown, the distribution of coefficient estimates across stocks displays a great deal of variation, which suggests that there are important differences across stocks. This variation may be due in part to differences in trading volume since existing studies, such as Easley et al. (1996) and Kavajecz (1999), show that specialists may manage frequently traded stocks differently from infrequently traded stocks. Consequently we divide the stocks in our sample into quintiles based on average daily trading volume (see Table 5). Due to space constraints, only the results for quintiles one (high volume) and five (low volume) are shown.

The results demonstrate a sharp contrast between high- and low-volume stocks. The transaction variables are extremely important for frequently traded stocks, but have little ability to explain changes in the posted price schedule for low-volume stocks. While the higher statistical significance of variables for high-volume stocks is probably due in part to the larger sample

Table 4
Simultaneous equation model results based on proximity to the book

	Equations							
	ΔBid price		ΔAsk price		ΔBid depth		ΔAsk depth	
Variables	β	%	β	%	β	%	β	%
ΔBest bid price on book					1.3144	12.6*		
ΔBest bid on book, quote within 1/8	0.0511	73.4*						
ΔBest bid on book, quote farther than 1/8	0.0807	38.5*						
Bidside farther than 1/8 dummy	0.0162	20.3*			−0.1420	16.8*		
ΔBest ask price on book							−0.6141	10.5
ΔBest ask on book, quote within 1/8			0.0389	64.3*				
ΔBest ask on book, quote farther than 1/8			0.0436	30.8*				
Askside farther than 1/8 dummy			−0.084	10.5			−0.0726	9.8
ΔShares at best bid on book	−0.0005	10.5						
ΔShares at best bid on book, quote within 1/8					0.1027	62.2*		
ΔShares at best bid on book, farther than 1/8					0.0742	7.0		
ΔShares at best ask on book			0.0021	9.8				
ΔShares at best ask on book, quote within 1/8							0.1089	57.3*
ΔShares at best ask on book, farther than 1/8							0.0632	9.1

The results for the nonlimit order book variables in the model are omitted for brevity, but are available from the authors upon request. The results are based on the 118 stocks in the sample that had limit order book observations greater than 1/8 from the market. For each explanatory variable in each of the four equations, the mean coefficient estimate across the stocks in the sample is provided (β), as well as the fraction of stocks in the sample having coefficient estimates that are significant at the 5% level (%). Contains the results for the limit order book variables when these variables are sorted based on the specialist's proximity to the limit order book. *Signifies that the fraction is significant at the 0.1% level. Standard errors were adjusted using the Newey and West (1987) correction for heteroskedasticity and serial correlation. Quantities are denominated in units of 1,000 shares and prices are denominated in dollars.

sizes for these stocks (since volume and trading frequency are positively correlated), the results are also consistent with the hypothesis that specialists manage high-volume stocks more actively than lower-volume stocks. The different approaches to managing these stocks may stem from the fact that high-volume stocks essentially trade in a quote-driven market due to the presence of the trading crowd and low-volume stocks trade in an order-driven market. Furthermore, the fact that specialists tend to participate in a larger fraction of the trades in low-volume stocks suggests that the limit order book may provide more "new" information than transactions provide for this group of stocks. Using our inventory measure, we estimate that the specialist participates in 12.1% of the trades (20.5% of the transaction volume) for high-volume stocks and 26.4% of the trades (28.7% of the volume) for low-volume stocks. The fact that the limit order book variables are *relatively* more significant (compared to transactions) for inactive stocks than for active stocks is consistent with this theory. Since specialists of frequently

Table 5
Simultaneous equation model results by trading volume quintile

		Equations							
		ΔBid price		ΔAsk price		ΔBid depth		ΔAsk depth	
Variables	Qntl	β	%	β	%	β	%	β	%
Intercept	H	0.0015	56.7*	−0.0009	36.7*	0.1142	6.7	0.0910	6.7
	L	0.0029	0.0	−0.0051	11.1	−0.4582	0.0	0.3595	3.7
ΔBid price	H			0.2535	73.3*	−80.810	20.0*	6.1765	6.7
	L			0.3962	51.9*	−19.071	14.8	−25.802	3.7
ΔAsk price	H	0.2602	83.3*			2.3476	13.3	58.7786	20.0*
	L	0.3425	48.1*			85.1620	0.0	0.6001	11.1
ΔBid depth	H	−0.0028	23.3*	0.0002	6.7			0.0803	6.7
	L	0.0446	18.5*	−0.0169	7.4			0.0725	7.4
ΔAsk depth	H	−0.0011	10.0	0.0066	23.3*	0.0400	13.3		
	L	−0.0007	0.0	0.0068	11.1	−0.7017	0.0		
Buy transaction volume	H	−0.0001	6.7	0.0007	16.7	−0.0053	0.0	−0.1112	60.0*
	L	−0.0017	3.7	0.0024	11.1	−0.0870	3.7	−0.0388	3.7
Sell transaction volume	H	−0.0003	16.7	0.0000	0.0	−0.0829	73.3*	−0.0044	3.3
	L	−0.0080	3.7	−0.0020	7.4	0.0222	3.7	0.0041	0.0
Buy depth exceeded dummy	H	−0.0004	6.7	0.0173	46.7*	−0.1136	6.7	2.1157	20.0*
	L	−0.0168	11.1	0.0362	14.8	0.1183	0.0	−0.1237	0.0
Sell depth exceeded dummy	H	−0.0219	66.7*	0.0023	3.3	1.1217	16.7	−0.3184	6.7
	L	−0.0088	3.7	0.0043	0.0	−0.3770	3.7	0.1210	7.4
Bid-side transaction activity	H	−0.0007	53.3*			−0.0550	46.7*		
	L	−0.0373	40.7*			0.0313	18.5		
Bid-side order activity	H	0.0003	30.0*			0.0070	6.7		
	L	−0.0103	25.9*			0.1946	18.5		
Bid-side cancel activity	H	0.0000	13.3			−0.0254	0.0		
	L	−0.0136	3.7			−0.1050	14.8		
Ask-side transaction activity	H			0.0008	53.3*			−0.0654	53.3*
	L			0.0532	48.1*			−0.2344	7.4
Ask-side order activity	H			−0.0004	26.7*			0.0109	10.0
	L			−0.0239	18.5			0.0937	7.4
Ask-side cancel activity	H			−0.0001	3.3			−0.0035	6.7
	L			0.0110	0.0			−0.1151	7.4
ΔBest bid price on book	H	0.0372	96.7*			2.9555	16.7		
	L	0.0325	48.1*			24.196	18.5		
ΔBest ask price on book	H			0.0348	86.7*			−2.0439	13.3
	L			0.0265	25.9*			7.1619	14.8
ΔShares at best bid on book	H	0.0002	13.3			0.0765	90.0*		
	L	−0.0213	7.4			0.0669	25.9*		
ΔNear depth on book (bid)	H	0.0000	0.0			0.0026	3.3		
	L	0.0028	3.7			−0.0286	3.7		
ΔShares at best ask on book	H			−0.0003	10.0			0.0752	86.7*
	L			0.0036	0.0			0.1019	25.9*
ΔNear depth on book (ask)	H			0.0000	6.7			0.0013	3.3
	L			−0.0026	3.7			−0.0172	7.4
Near depth ratio (ask/bid)	H	−0.0001	30.0*	0.0000	6.7	−0.0111	3.3	−0.0034	3.3
	L	−0.0012	0.0	0.0033	7.4	0.0820	0.0	0.0857	3.7
Specialist's inventory	H	0.0000	0.0	0.0000	3.3	0.0002	0.0	−0.0002	0.0
	L	0.0008	0.0	0.0010	0.0	−0.0019	0.0	0.0029	0.0
Regional bid price	H	−0.2933	70.0*			−22.626	10.0		
	L	−0.0802	7.4			−4.9669	7.4		
Regional ask price	H			0.1919	50.0*			−10.362	6.7
	L			0.0713	3.7			−0.4701	0.0

H [L] denotes high [low] trading volume stocks. For each explanatory variable in each equation, the mean coefficient estimate is provided (β) as well as the fraction of the stocks in the sample having coefficient estimates that are significant at the 5% level (%). *Signifies that the fraction is significant at the 0.1% level. Standard errors were adjusted using the Newey and West (1987) correction for heteroskedasticity and serial correlation. Quantities are denominated in units of 1,000 shares and prices are denominated in dollars.

traded stocks clear a smaller fraction of trades, transactions present additional information, while specialists of infrequently traded stocks clear a higher fraction of trades, making the limit order book relatively more informative.

Alternatively, the increased importance of the limit order book relative to transactions for inactive stocks could reflect a difference in trading strategies. Actively traded stocks have a constant flow of uninformed liquidity trading taking place; consequently informed traders may be able to trade without compromising their information. In contrast, informed traders transacting in inactively traded stocks have much less ability to conceal their information. Consequently they may choose to submit limit orders instead, which would result in the limit order book conveying more information to the specialist than transactions.

The trading volume results also demonstrate that cumulative order and transaction activity is a significant determinant of changes in the posted price schedule for both high- and low-volume stocks. The mean values of these activity coefficients in the price equations increase in absolute value as the average trading volume decreases. One explanation of the importance of the activity variables in lower-volume stocks is the inverse relation between trading frequency and adverse selection proposed by Easley et al. (1996), among others.

The intercept terms in the price equations are much more significant for high-volume stocks than for lower-volume stocks. This may be due in part to the fact that specialists are more willing to narrow the spread on high-volume stocks since they are able to profit from the sheer volume of trade. An active trading crowd can also help to increase liquidity, thereby inducing the specialist to narrow the spread. Lastly, the regional competition variables, like many of the explanatory variables in the model, are substantially more important for high-volume stocks, probably because regional exchanges are more likely to quote prices for actively traded stocks.

The results conditional on trading volume imply differences in the way in which information may be incorporated into the market for actively traded and inactively traded stocks. Transactions play a much greater role in the revision process for active stocks than for inactive stocks, while the limit order book is relatively more important for inactive stocks. This variation across volume groups may stem from differences in specialist participation rates or from differences in the strategies used by informed traders.

4. Conclusion

We investigate the way in which NYSE specialists revise their posted price schedules, which consist of bid and ask prices and bid and ask depths, by addressing two primary issues. First, we investigate the possibility that changes in the price schedule are induced not only by transactions, which have been the main focus of the existing literature, but by other events as well. In particular, we hypothesize that the activities of competitors, such as public liquidity providers placing limit orders, have a significant impact on the price schedule. Second, we test the hypothesis that specialists react to changes in the trading environment by updating their quoted depths along with their quoted prices and that they use these tools differently.

We find that changes in the best prices and depths on the limit order book have a significant impact on the posted price schedule, which supports our first hypothesis. We also show that the limit order precedence rule imposed by the exchange does not drive the results, since the limit order book variables remain important even when the specialist is posting prices that differ substantially from those on the book. In addition, the results demonstrate that the effects of transactions and cumulative order activity on the price schedule are secondary to those of the limit order book both statistically and economically, particularly for infrequently traded stocks. Changes in the specialist's inventory or in the number of shares elsewhere on the limit order book have no significant effect on the price schedule after controlling for changes in the best prices and depths on the book. Finally, we find evidence in support of our second hypothesis that specialists revise quoted prices and depths in response to different events. For example, the posted depths are revised in response to transactions of any size, while the quoted prices are revised only when transaction sizes exceed the quoted depth.

Our results have implications for several policy debates. The prominence of the limit order book's impact on the price schedule suggests that the book is an important channel of information to the market. This implies that directing order flow to a single, consolidated limit order book is likely to increase its importance as an aggregator of information. Furthermore, the results suggest that policy changes that affect public liquidity provision will also have a large effect on the price discovery process. These findings highlight the importance of considering the impact of current regulatory policy on liquidity suppliers as well as liquidity demanders.

We also find, however, that despite the importance of the limit order book, the specialist does not simply reflect the liquidity on the book when posting quotes. This finding suggests that opening the limit order book to the public, as in a pure limit order market, provides all investors with a valuable information source, but is also likely to increase the volatility of quoted prices if no specialist is present to smooth prices.

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