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Price rounding and bid–ask spreads before and after the decimalization

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Abstract

We investigate price rounding before and after the pilot decimalization on the NYSE. We find that although rounding exists in transaction, bid, and ask prices in both the pre- and postdecimalization periods, it becomes less salient after the decimalization. The cross-sectional relationship between rounding and trading variables is similar before and after the decimalization, and so is the relationship between execution costs and rounding when trading variables are held constant. More importantly, the quoted and effective bid–ask spreads decrease after decimal trading, and this decrease can be ascribed to the decrease in rounding frequency after controlling for the changes in trading variables.

JEL classification: G1
Keywords: Price rounding; Bid–ask spreads; Decimalization

1. Introduction

In security trading, prices are often constrained to a limited set of observations by minimum tick size. Previous studies document that prices are frequently rounded to multiples of the minimum tick. Osborne (1962) first recognizes the tendency for transaction and quote prices to cluster on their fractions. Harris (1991) provides evidence on the rounding of quote and transaction prices for NYSE- and AMEX-listed equities. He reports that stock prices cluster on round fractions: integers are more common than halves; halves are more common than odd quarters; odd quarters are more common than odd eighths; and other

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fractions are rarely observed. Cooney, Van Ness, and Van Ness (2001) show that both individual and institutional investors exhibit a preference for even eighth prices when they submit limit orders to buy and sell NYSE stocks. In addition, Bessembinder (1994) presents evidence regarding the rounding of foreign exchange quotes. Ball, Torous, and Tshoegl (1985) document rounding in gold futures prices. Koch and Lazarov (2001) report that trades in DAX (the Deutscher Aktienindex) index options with identical maturities cluster around particular classes of strike prices.

According to market microstructure theory, rounding can be regarded as a byproduct of the price discovery process. Ball et al. (1985) hypothesize that clustering is positively related to the degree of uncertainty concerning the true price, conditional on the rules and regulations of the trading activity. Harris (1991) and Godek (1996) suggest that the uncertainty about the true price should be modeled using economic fundamentals (e.g., price level, price change volatility, firm size, and trading activity) as instrumental variables. They show that clustering increases with price level and volatility and decreases with capitalization and transaction frequency. Grossman, Miller, Cone, Fischel, and Ross (1997) provide a competitive theory of clustering that emphasizes the effect of price uncertainty, the size of transactions, volatility, and the informational and transactional roles of quotations on the degree of clustering.

Moreover, rounding can be viewed as a means to lower negotiation costs. Ball et al. (1985) introduce the "degree of price resolution" with the implication that rounding leads to coarse choices of prices and thus involves a low degree of resolution. Harris (1991) argues that clustering exists because traders use a discrete grid of prices to simplify their information set to lower negotiation costs. Specifically, a small set of choices limits the amount of information exchanged between negotiating traders and reduces the time it takes to strike a bargain. Angel (1997) indicates that this view is consistent with cognitive research by Miller (1956) and Simon (1974) that human short-term memory is capable of processing only a few bits of information concurrently.

While rounding may reduce negotiation costs in an imperfect information market, it increases the degree of price discreteness. Under fractional trading, the minimum tick size arbitrarily set by the regulator as well as the rounding to multiples of the minimum tick may lead to enlarged bid–ask spreads and thus inflate market makers' profits. As Harris (1994) points out, a high degree of price discreteness due to regulations widens bid–ask spreads. Bessembinder (1997) investigates the relationship between trade execution costs and price-rounding practices for NYSE- and Nasdaq-listed stocks. Execution costs on each exchange are found positively correlated with the proportion of transaction prices and quotations rounded to even eighths of a dollar. In addition, Chung and Chuwonganant (2001) present evidence that the minimum price variation imposes a binding constraint on bid–ask spreads.

The recent decimalization on the NYSE provides an excellent opportunity for us to revisit the issue of price rounding. Harris (1999) predicts that the conversion to decimal trading would lead to lower execution costs. Bessembinder (2003) shows that bid–ask spreads have declined after the decimalization. In this paper, we investigate the pattern of price rounding before and after decimal trading and its effect on bid–ask spreads for NYSE stocks. First, since decimal trading leads to a finer price grid or a set of less discrete prices, we expect to observe a decline in frequencies of rounding on integers, halves, and quarters. Second, although frequencies of rounding on integers, halves, and quarters may decline after decimalization, we expect that cross sectionally, the relationship between rounding and trading variables and the relationship between execution costs and rounding will stay the same. That is, the sensitivity of rounding to trading variables and the sensitivity of execution costs to rounding should remain unchanged because the fundamentals of the market do not change as a result of decimalization. Finally, consistent with the arguments of Harris (1997, 1999), we expect to find a significant relationship between the decrease in execution costs and the decrease in rounding after decimalization when controlling for the changes in stock features. If fractional pricing indeed allows market makers to keep bid–ask spreads artificially high to earn a positive rent, a conversion to decimal trading should reduce price rounding, decrease market makers' rents, and cause a fall in bid–ask spreads.

Our empirical results show that although rounding is pervasive in transaction prices, bids, and asks in both the pre- and postdecimalization periods, it becomes less salient after the decimalization. The cross-sectional relationship between rounding and trading variables is similar before and after the decimalization and so is the relationship between execution costs and rounding when trading variables are held constant for each stock. More importantly, we find that the quoted and effective bid–ask spreads decrease after the decimalization, and this decrease can be ascribed to the decrease in price rounding when we control for the changes in trading variables.

The remainder of the paper is organized as follows. Section 2 discusses the institutional features of decimalization. Section 3 describes data and the empirical method, and Section 4 presents empirical results. Finally, Section 5 summarizes the findings of this paper.

2. Decimalization

The minimum tick varies substantially by market and location. For instance, pricing of stock, bond, and options markets in the United States and Canada had traditionally been denominated in eighths; while in European and Asian markets, decimal prices are more common. During the later half of 1990s, the U.S. and Canadian markets underwent substantial changes. Canadian stocks switched from fractions to decimals in April 1996.[1] In the U.S. markets, the minimum tick size was reduced from one eighth to one sixteenth of a dollar in June 1997. At the beginning of year 2000, the U.S. equity markets were the only major financial markets in the globe that trade in fractional increments. This fractional trading practice puts U.S. markets at a competitive disadvantage with foreign markets trading the same securities. In addition, individual investors may have a difficulty in determining the differences between increasingly smaller fractions.

To make the U.S. securities markets more competitive globally and their prices easier to decipher, the Securities Industry Association and the Securities and Exchange Commission decided to convert the U.S. equity and exchange-traded options markets from fractional to decimal trading. On August 28, 2000, the NYSE selected seven pilot stocks for a decimal pricing test. On September 25, 2000, another 57 securities were added to the pilot program for decimal trading. Finally, on January 29, 2001, all NYSE-listed stocks were switched to decimals.

Since traders often choose to use a larger price increment than the minimum tick, prices tend to cluster on certain fractions or decimals even when the tick is small. See Ball et al. (1985) for gold trading,

[1] Ahn, Cao, and Choe (1998) report that bid–ask spreads decreased after the decimalization on the Toronto Stock Exchange (TSE). Bacidore (1997) studies the effect that TSE decimalization has on market quality and finds that liquidity is not adversely affected by decimalization.

Brown, Laux, and Schachter (1991) for silver, Goodhart and Curcio (1992) for foreign exchange, and Aitken, Brown, Buckland, Izan, and Walter (1995) for Australian stocks.

This paper examines price clustering by using the second pilot sample that includes 57 NYSE securities. Prior to September 25, 2000, these stocks were traded on sixteenths. Since then, they have been traded on pennies.

3. Data and empirical methodology

3.1. Data

We select 39 stocks from the 57 security sample of decimal trading on the NYSE. These 39 stocks meet the following two criteria: they are common stocks and their numbers of shares outstanding do not change between 8/1/2000 and 11/31/2000. We exclude nonequity securities such as closed-end funds as well as stocks that had a split or new issuance during the period of 8/1/2000 to 11/31/2000. Two sample periods are chosen, one before and the other after the pilot decimalization. The predecimalization period is from August 1 to September 22, 2000, whereas the postdecimalization period is from October 1 to November 31, 2000.

We collect intraday data for the 39 stocks from the Trade and Quote (TAQ) database. The data contain trades and quotes. Trade data consist of the transactions coded as regular trades. Trades and quotes outside normal market hours (9:30 a.m. to 4:00 p.m. Eastern Standard Time) are excluded. The first trade in a trading day is deleted. In addition, we bunch small trades transacted at the same price within a second into one big trade. Our empirical analysis is conducted on a transaction by transaction basis for each sample stock.

3.2. Measures of rounding frequencies

Based on intraday records of trades and quotes, we calculate rounding frequencies for each individual security's transaction, bid, and ask prices before and after the decimalization. In the predecimalization period, the minimum tick size is one sixteenth of a dollar, and thus we define F16, F8, F4, and F2 as the frequencies of prices rounded to the nearest integers, halves, quarters, and even sixteenths, respectively. If there is no clustering, we would observe a uniform distribution with mean of 6.25% for prices traded on integers, 12.5% on halves, 25% on quarters, and 50% on even sixteenths. With clustering, we would observe a higher frequency than the mean of uniform distribution for each type of rounding. In the postdecimalization period, the minimum tick size is one penny, and we define F100, F50, F25, F10, and F5 as the frequencies of prices rounded to the nearest 100, 50, 25, 10, and 5 cents, respectively. If clustering does not exist, we would observe a uniform distribution with mean of 1% for prices traded on 100 cents, 2% on 50 cents, 4% on 25 cents, 10% on 10 cents, and 20% on 5 cents. If clustering does exist, we would observe a higher frequency than the mean of uniform distribution for each type of rounding.

The estimates of rounding frequencies (F16, F8, F4, F2, F100, F50, F25, F10, and F5) may be biased due to the time dependence among the fractions or decimals. Better estimates of clustering can be obtained by taking into account the time dependence. This problem is more severe for lower price stocks than for higher price stocks. This is because higher price stocks tend to have larger absolute price changes, causing their domain to be more evenly distributed over various fractions or decimals.

Following Harris (1991), we define the path-adjusted estimators for frequencies of prices rounded on integers, halves, quarters, and even sixteenths in the predecimalization period as:

$$AF16 = F16 + .0625 - D16, \tag{1a}$$

$$AF8 = F8 + .125 - D8, \tag{1b}$$

$$AF4 = F4 + .25 - D4, \tag{1c}$$

$$AF2 = F2 + .5 - D2, \tag{1d}$$

where the probability of .0625 denotes the mean of a uniform distribution for any fraction, given a minimum tick size of one sixteenth of a dollar. The probabilities of .125, .25, and .5 denote the means of uniform distributions for prices reported in fractions of halves, quarters, and even sixteenths, respectively. D16, D8, D4, and D2 denote the frequencies of domain events occurring on integers, halves, quarters, and even sixteenths, respectively. For instance, the domain event frequency of integer prices (D16) is defined as the number of times that a price change passes over or arrives on an integer divided by the number of times that a price change passes over or arrives on any fraction.[2] Eqs. (1a)–(1d) indicate that if prices have visited a given fraction (or some given fractions) less often than others, the frequency for that fraction (or those fractions) may be lower than the frequency for others due to nonrounding factors. Thus, the frequency for that fraction (or those fractions) is adjusted upward to reflect rounding frequency only. If prices have dwelt on a given fraction (or some given fractions) more often than others, the frequency for that fraction (or those fractions) may be higher than the frequency for others due to nonrounding factors. Thus, the frequency for that fraction (or those fractions) is adjusted downward to reflect rounding frequency only.

Similarly, we define the path-adjusted estimators for 100, 50, 25, 10, and 5 cent rounding frequencies in the postdecimalization period as:

$$AF100 = F100 + .01 - D100, \tag{2a}$$

$$AF50 = F50 + .02 - D50, \tag{2b}$$

$$AF25 = F25 + .04 - D25, \tag{2c}$$

$$AF10 = F10 + .1 - D10, \tag{2d}$$

$$AF5 = F5 + .2 - D5, \tag{2e}$$

where the probability of .01 denotes the mean of an uniform distribution for any decimal, and the probabilities of .02, .04, .1, and .2 denote the means of uniform distributions for prices reported in decimals of 50, 25, 10, and 5 cents, respectively. D100, D50, D25, D10, and D5 denote the frequencies of domain events occurring on prices reported in decimals of 100, 50, 25, 10, and 5 cents, respectively. Eqs. (2a)–(2e) indicate that if prices have not often visited a given decimal (or some given decimals), the frequency for that decimal (or those decimals) is adjusted upward. Conversely, if prices have dwelt on a

[2] Please see Harris (1991) for further explanation of the frequency of domain events.

given decimal (or some given decimals) more often than others, the frequency for that decimal (or those decimals) is adjusted downward.

3.3. Regressions of rounding frequencies and bid–ask spreads

First, we test whether the cross-sectional variation in rounding frequency can be explained by some trading variables, and whether the relationship between rounding frequency and trading variables is similar before and after the pilot decimalization. We include transaction price (P), return volatility (VOLA), market capitalization (MV), and the inverse of the square root of daily number of trades (IST) as variables that may influence rounding frequency. Price has a positive effect on price rounding because high-price stocks are more likely to have price clustering at certain fractions. Market capitalization has a similar effect as price. Volatility has a positive effect on price rounding because higher price uncertainty leads to a coarser set of trading prices. In addition, more frequent trading reveals true stock values more quickly and so leads to a lower degree of price clustering.

The following is the regression model for empirical estimation:

$$\begin{aligned} F_i &= \lambda_0 + \lambda_1 P_i + \lambda_2 \mathrm{VOLA}_i + \lambda_3 \mathrm{MV}_i + \lambda_4 \mathrm{IST}_i \\ &\quad + D(\lambda_0' + \lambda_1' P_i + \lambda_2' \mathrm{VOLA}_i + \lambda_3' \mathrm{MV}_i + \lambda_4' \mathrm{IST}_i) + e_i, \end{aligned} \tag{3}$$

where F is the rounding frequency of transaction prices, F can be the frequency of rounding on integers, halves, or quarters, and D is a dummy variable that is equal to 0 for the predecimalization period and 1 for the postdecimalization period. Parameters λ_1, λ_2, λ_3, and λ_4 denote sensitivity coefficients for the predecimalization period. Parameters λ_1', λ_2', λ_3', and λ_4' measure the differences in sensitivity coefficients between the post- and predecimalization periods. For integer rounding, F is equal to F16 (or AF16) for the preperiod and F100 (or AF100) for the postdecimalization period. For rounding on halves, F is equal to F8 (or AF8) for the predecimalization period and F50 (or AF50) for the postperiod. For rounding on quarters, F is equal to F4 (or AF4) for the preperiod and F25 (or AF25) for the postperiod.

Second, we investigate whether the cross-sectional variation in bid–ask spreads can be explained by price rounding after controlling for market making costs and whether the relations between rounding frequency and bid–ask spreads are similar before and after the decimalization. Variations in bid–ask spreads can be explained by several important variables related to liquidity and adverse selection. Market capitalization (MV), inverse of square root of trades (IST), the proportion of primary market volume out

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Notes to Table 1:

This table provides summary statistics on sample characteristics and bid–ask spreads for 39 selected stocks traded in the NYSE. The predecimalization period is from 8/1/2000 to 9/22/2000. The postdecimalization period is from 10/1/2000 to 11/31/2000. P is the average transaction price. VOLA is the volatility of price returns. MV is the average market capitalization. V is the average volume in a day. DV is the average dollar volume in a day. PM is the average proportion of the volume in the primary market out of the consolidated volume. T is the average number of trades in a day. TS is the average trade size (in shares). Q is the average number of quote updates in a day. QS is the average quote size (in rounds) of bids and asks. SPR is the average bid–ask spread in dollar. SPR% is the average bid–ask spread in percentage. ESPR is the average effective bid–ask spread in dollar. ESPR% is the average effective bid–ask spread in percentage. The *t* tests and Wilcoxon sign tests are performed with the null hypotheses that the mean and median values in the postdecimalization period are the same as those in the predecimalization period. All the *t* tests and Wilcoxon sign tests are conducted on variables in log terms.

* A significance level of 5% for a two-tailed test.

Table 1
Summary statistics on sample characteristics and bid–ask spreads

Variable		Preperiod	Postperiod	Mean difference (t value)	Median difference (z score)
Panel A. Sample characteristics					
P (US$)	Mean	53.10	41.36	−0.47	−0.45
	S.D.	79.17	33.44		
	Median	31.77	31.09		
VOLA	Mean	1.63%	2.05%	1.40	1.63
	S.D.	0.67%	1.03%		
	Median	1.72%	1.95%		
MV (US$1000)	Mean	11,174,863	10,577,179	−0.19	−0.31
	S.D.	26,607,814	24,509,237		
	Median	1,101,314	965,794		
V (shares)	Mean	855,745	972,022	0.72	0.64
	S.D.	2,294,216	2,485,012		
	Median	91,411	120,112		
DV (US$)	Mean	37,524,890	43,434,041	0.42	0.40
	S.D.	93,654,616	109,735,358		
	Median	5,041,076	4,294,692		
PM	Mean	84.89%	86.97%	1.03	1.06
	S.D.	9.30%	8.15%		
	Median	87.43%	88.44%		
T	Mean	286	351	0.48	0.59
	S.D.	491	565		
	Median	92	125		
TS (shares)	Mean	1603	1545	−0.06	−0.37
	S.D.	1370	1275		
	Median	1243	1064		
Q	Mean	530	545	0.23	0.37
	S.D.	699	638		
	Median	258	377		
QS (rounds)	Mean	80	28	−2.18*	−2.05*
	S.D.	193	33		
	Median	27	18		
Panel B. Bid–ask spreads					
SPR (US$)	Mean	0.2631	0.1538	−4.54*	−4.57*
	S.D.	0.5817	0.0914		
	Median	0.1600	0.1350		
SPR%	Mean	0.69%	0.61%	−4.12*	−3.84*
	S.D.	0.57%	0.57%		
	Median	0.51%	0.40%		
ESPR (US$)	Mean	0.1706	0.1086	−3.26*	−4.03*
	S.D.	0.3527	0.0648		
	Median	0.1069	0.0913		
ESPR%	Mean	0.48%	0.41%	−3.94*	−3.45*
	S.D.	0.40%	0.38%		
	Median	0.30%	0.26%		

Table 2
Frequencies of price rounding

Predecimalization		Postdecimalization		Mean difference (t value)	Median difference (z score)
Rounding	Frequency (%)	Rounding (cents)	Frequency (%)		
Panel A. Unadjusted rounding frequencies					
Transaction price					
Integers	9.66	100	6.54	−2.89*	−2.91*
Halves	17.08	50	10.94	−4.24*	−4.11*
Quarters	31.45	25	17.09	−7.69*	−6.63*
Even sixteenths	58.63	10	32.89	–	–
		5	54.80	–	–
Bid price					
Integers	12.93	100	5.62	−3.53*	−3.66*
Halves	21.12	50	9.93	−5.50*	−5.46*
Quarters	35.44	25	17.09	−7.72*	−6.48*
Even sixteenths	62.44	10	32.90	–	–
		5	55.38	–	–
Ask price					
Integers	12.92	100	6.15	−2.21*	−2.65*
Halves	20.04	50	10.18	−3.50*	−3.68*
Quarters	34.55	25	16.77	−7.29*	−6.06*
Even sixteenths	61.16	10	31.50	–	–
		5	52.41	–	–
Panel B. Path-adjusted rounding frequencies					
Transaction price					
Integers	9.76	100	6.35	−3.48*	−3.61*
Halves	17.36	50	10.78	−4.98*	−5.09*
Quarters	32.04	25	16.98	−9.10*	−7.33*
Even sixteenths	58.59	10	33.17	–	–
		5	55.86	–	–
Bid price					
Integers	9.56	100	5.54	−3.66*	−4.04*
Halves	17.26	50	9.86	−5.14*	−5.24*
Quarters	32.45	25	17.02	−8.03*	−6.64*
Even sixteenths	60.21	10	33.11	–	–
		5	56.16	–	–
Ask price					
Integers	9.47	100	6.13	−2.92*	−3.65*
Halves	17.02	50	10.14	−4.79*	−4.64*
Quarters	31.63	25	16.18	−8.70*	−6.64*
Even sixteenths	59.31	10	31.44	–	–
		5	52.73	–	–

This table reports frequencies of rounding for 39 selected securities traded in the NYSE. The predecimalization period is from 8/1/2000 to 9/22/2000. The postdecimalization period is from 10/1/2000 to 11/31/2000. Panel A reports the sample average of unadjusted rounding frequencies for transaction, bid, and ask prices, and Panel B reports the sample average of path-adjusted rounding frequencies. For comparable frequencies of rounding on integers, halves, and quarters, two-tailed t tests and Wilcoxon sign tests are performed with the null hypotheses that the mean and median values in the postdecimalization period are the same as those in the predecimalization period.

* A significance level of 5% for a two-tailed test.

of consolidated volume (PM), and dollar volume (DV) are proxies for the liquidity of stocks. Price (P) is included to control for the effects of the minimum tick size. Return volatility (VOLA) is a proxy for the asymmetric information associated with a stock. The following is the regression model used in empirical estimation:

$$Y_i = \lambda_0 + \lambda_1 \mathrm{P}_i + \lambda_2 \mathrm{VOLA}_i + \lambda_3 \mathrm{MV}_i + \lambda_4 \mathrm{IST}_i + \lambda_5 \mathrm{DV}_i + \lambda_6 \mathrm{PM}_i + \lambda_7 \mathrm{F}_i + D(\lambda_0' + \lambda_1' \mathrm{P}_i + \lambda_2' \mathrm{VOLA}_i + \lambda_3' \mathrm{MV}_i + \lambda_4' \mathrm{IST}_i + \lambda_5' \mathrm{DV}_i + \lambda_6' \mathrm{PM}_i + \lambda_7' \mathrm{F}_i) + e_i, \quad (4)$$

where Y can be SPR% or ESPR%, SPR% is the average quoted bid–ask spread in percentage, ESPR% is the average effective bid–ask spread in percentage, F can be the frequency of rounding on integers, halves, or quarters, and D is a dummy variable that is equal to 0 for the preperiod and 1 for the postperiod. Parameter λ_7 denotes the sensitivity coefficient of bid–ask spreads to rounding frequency in the predecimalization period when trading variables are held constant. Parameter λ_7' measures the difference in the sensitivity coefficient of price rounding between the post- and predecimalization periods when trading variables are held constant.

Finally, we investigate whether the change in bid–ask spreads after decimalization can be explained by the change in price rounding frequency when controlling for the changes in trading variables. The following is the regression model:

$$\Delta Y_i = \lambda_0 + \lambda_1 \Delta \mathrm{P}_i + \lambda_2 \Delta \mathrm{VOLA}_i + \lambda_3 \Delta \mathrm{MV}_i + \lambda_4 \Delta \mathrm{IST}_i + \lambda_5 \Delta \mathrm{DV}_i + \lambda_6 \Delta \mathrm{PM}_i + \lambda_7 \Delta \mathrm{F}_i + e_i, \quad (5)$$

where the change in a variable (Δ) is defined as the log of the ratio of the value of the variable before the decimalization to that after the decimalization. Parameter λ_7 denotes the effect of the change in rounding frequency on the change in bid–ask spreads when the changes in trading variables are held constant.

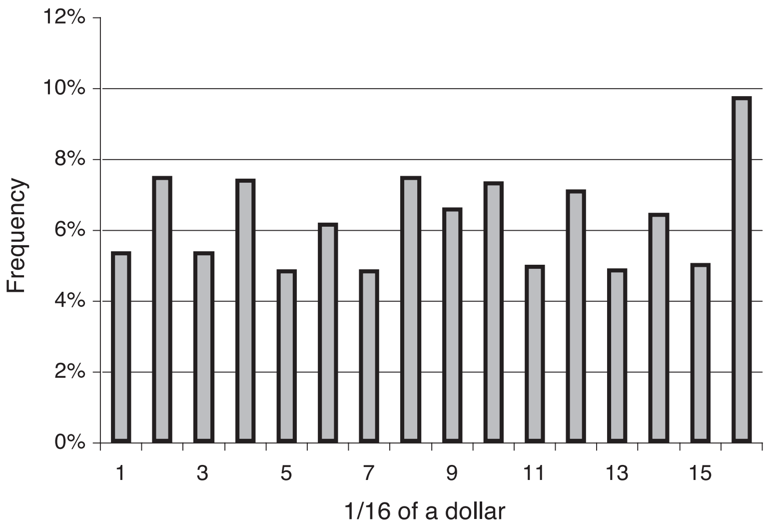

Fig. 1. Frequency of transaction price rounding in the predecimalization period.

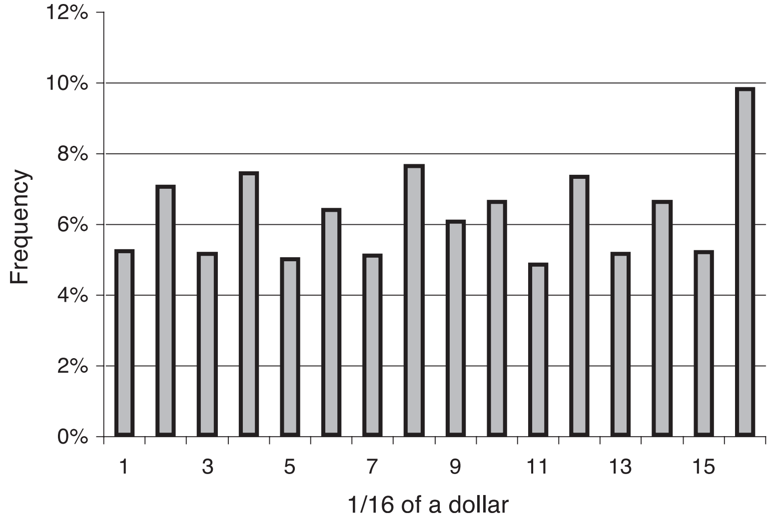

Fig. 2. Frequency of adjusted transaction price rounding in the predecimalization period.

Eqs. (3)–(5) are estimated by the Generalized Method of Moments (GMM) to ensure robustness to heteroscedasticity and autocorrelation.

4. Empirical results

Table 1 provides summary statistics on stock characteristics and bid–ask spreads for 39 selected stocks. We conduct both t tests on mean differences and Wilcoxon sign tests on median differences between the pre- and postdecimalization samples. All the t tests are consistent with the Wilcoxon z tests. First, stock features, such as price (P), return volatility (VOLA), market capitalization (MV), volume (V), dollar volume (DV), the proportion of the primary market volume out of the consolidated volume (PM), daily number of trades (T), trade size (TS), and daily number of quote updates (Q), show insignificant changes over the sample period. This is not surprising given that the sample period is short. Second, the average quote size (QS) declines considerably, indicating that decimal trading lowers market depth. This result is consistent with the finding of Bacidore, Battalio, Jennings, and Farkas (2001) that the NYSE has 70% less depth at the inside quote after decimal trading. Finally, the quoted bid–ask spreads in dollars (SPR), the quoted bid–ask spreads in percentage (SPR%), the effective bid–ask spreads in dollars (ESPR), and the effective bid–ask spreads in percentage (ESPR%) all decrease significantly over the sample period, which is in line with the findings of the NYSE (2001) staff report. Thus, the conversion to decimal trading appears to reduce market makers' rents.[3]

4.1. Rounding frequencies

Table 2 reports the non-path-adjusted and the path-adjusted frequencies of transaction, bid, and ask prices rounded to the nearest integers, halves, quarters, and even sixteenths, respectively, in the

[3] See also Gibson, Singh, and Yerramilli (2002).

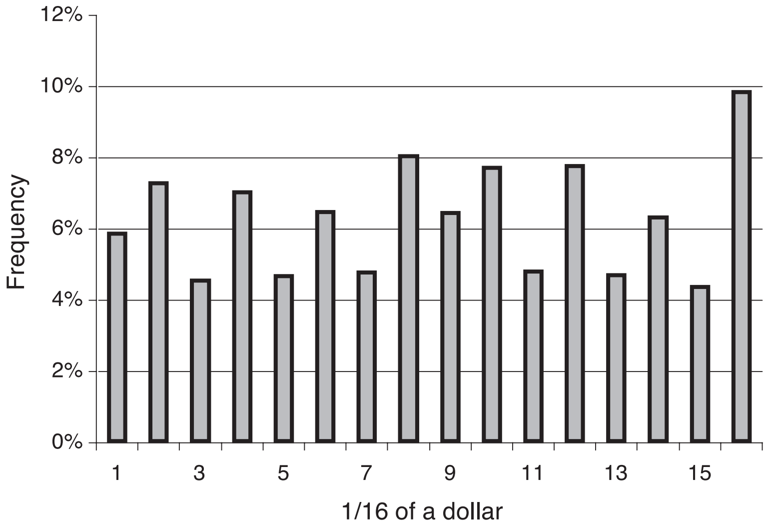

Fig. 3. Frequency of bid price rounding in the predecimalization period.

predecimalization period and to the nearest 100, 50, 25, 10, and 5 cents, respectively, in the postdecimalization period. First, we note that clustering exists in transaction, bid, and ask prices both before and after the decimalization. In the predecimalization period, the frequencies of clustering on integers are larger than 6.25%, the frequencies of rounding on halves are larger than 12.5%, the frequencies of rounding on quarters are larger than 25%, and the frequencies of rounding on even sixteenths are larger than 50%. In the postdecimalization period, the frequencies of 100-cent rounding are larger than 1%, the frequencies of 50-cent rounding are larger than 2%, the frequencies of 25-cent rounding are larger than 4%, the frequencies of 10-cent rounding are larger than 10% and the frequencies

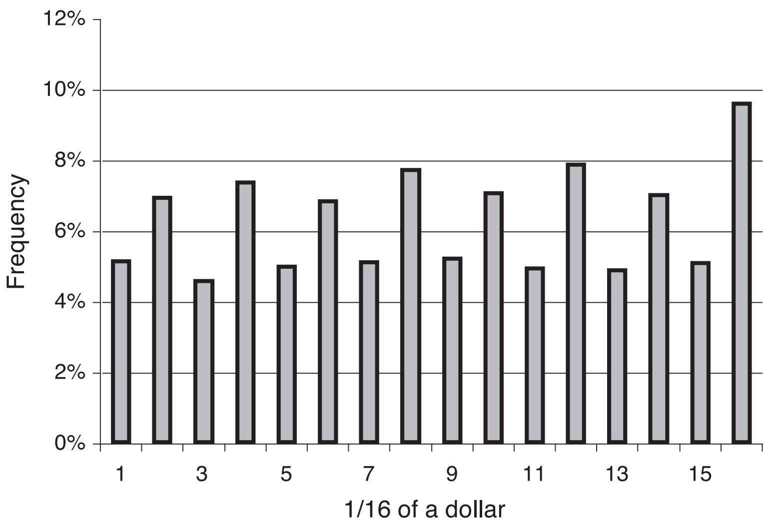

Fig. 4. Frequency of adjusted bid price rounding in the predecimalization period.

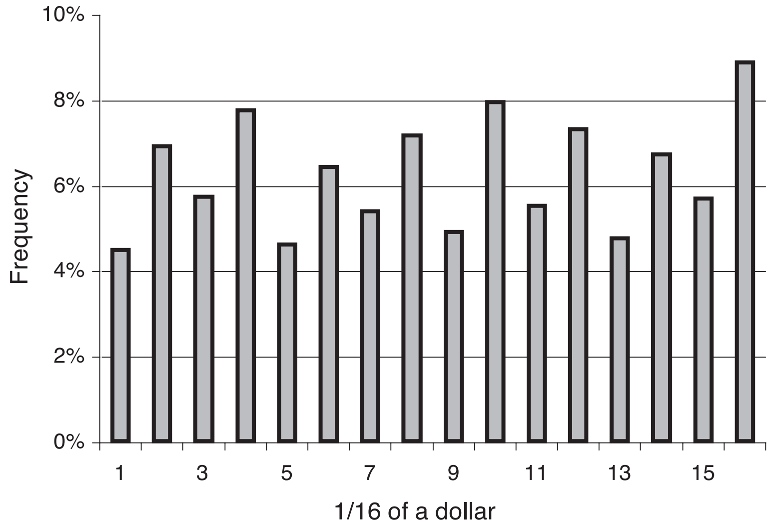

Fig. 5. Frequency of ask price rounding in the predecimalization period.

of 5-cent rounding are larger than 20%. Second, we note that the path-adjusted frequencies show similar patterns as the unadjusted frequencies for transaction, bid, and ask prices. Third, for comparable rounding frequencies (that is, rounding on integers, halves, and quarters), the postdecimalization frequencies are significantly lower than the predecimalization frequencies. All the t values on mean changes and the Wilcoxon z values on median differences are significant at least at the 5% level. Thus, rounding becomes much less salient after the decimalization.

Figs. 1–12 present rounding frequencies for the 39 selected NYSE stocks. Figs. 1–6 show that in the predecimalization period clustering is concentrated on integers, halves, quarters, and even sixteenths for

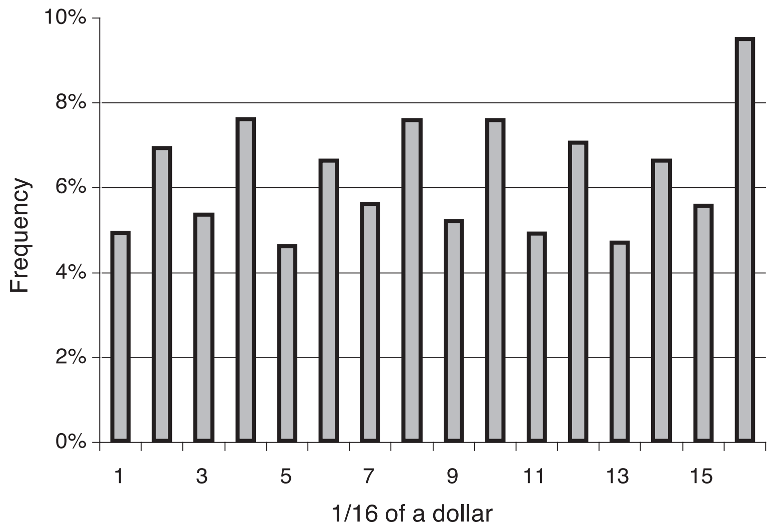

Fig. 6. Frequency of adjusted ask price rounding in the predecimalization period.

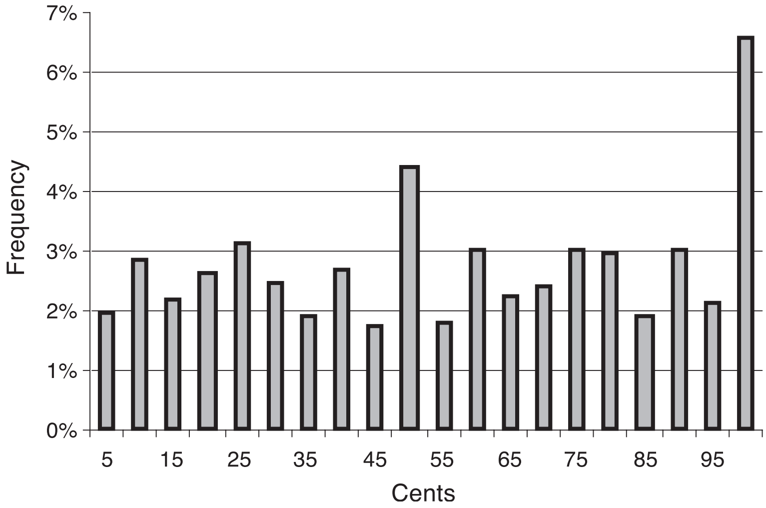

Fig. 7. Frequency of transaction price rounding in the postdecimalization period.

transaction, bid, and ask prices. On the one hand, these figures confirm the presence of clustering; on the other hand, they indicate that the rounding incidence is not uniform. For instance, the rounding frequencies on integers are considerably higher than those on other fractions. Figs. 7–12 show that in the postdecimalization period, clustering is concentrated on 100, 50, 25, 10, and 5 cents for transaction, bid, and ask prices. In addition, the rounding frequencies on 100 cents are considerably higher than those on 50 cents, and the frequencies on 50 cents higher than those on 25 cents.

4.2. Regressions of rounding frequencies and bid–ask spreads

Table 3 provides dummy regression test results of rounding frequencies against trading variables. It is found that the trading variables, including price level, return volatility, and inverse of square root of

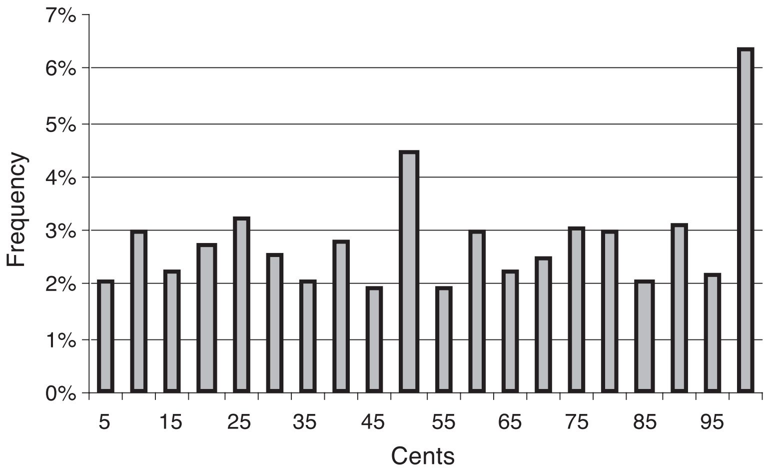

Fig. 8. Frequency of adjusted transaction price rounding in the postdecimalization period.

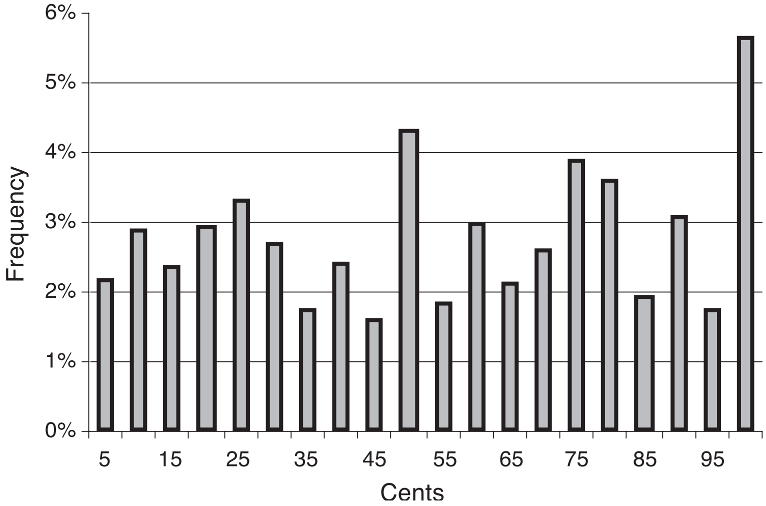

Fig. 9. Frequency of bid price rounding in the postdecimalization period.

trades, are significantly related to rounding frequencies. The price level has a positive effect on rounding because larger price variations (more clustering) are often related to higher price stocks. Volatility has a positive effect on rounding because higher volatility is likely to indicate a less well-known value and hence a coarser set of trading prices. The inverse of square root of trades has a positive effect on rounding because more frequent trading tends to reveal stock values more quickly by aggregating the information possessed by different traders leading to a lower degree of clustering. All the above effects remain similar after decimalization. Our finding supports the price resolution hypothesis of Ball et al. (1985). That is, price clustering depends on how well the underlying value of the security is known. If the value is uncertain, prices will cluster. In addition, we note that the estimates of parameters λ_1', λ_2', λ_3',

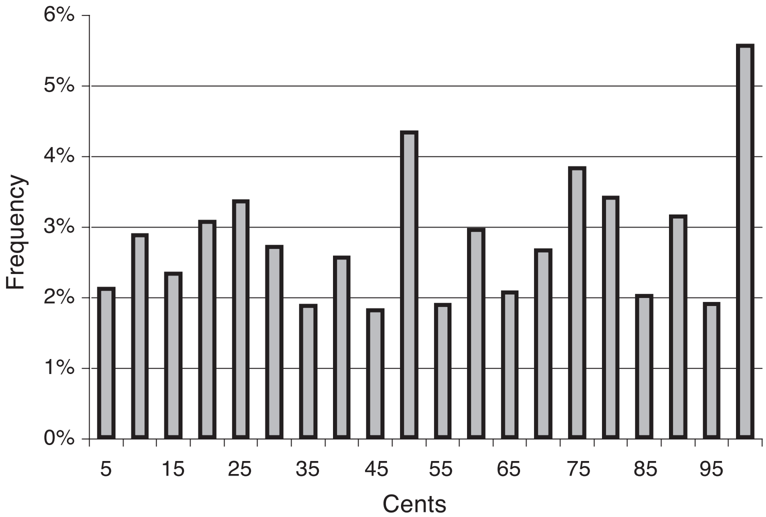

Fig. 10. Frequency of adjusted bid price rounding in the postdecimalization period.

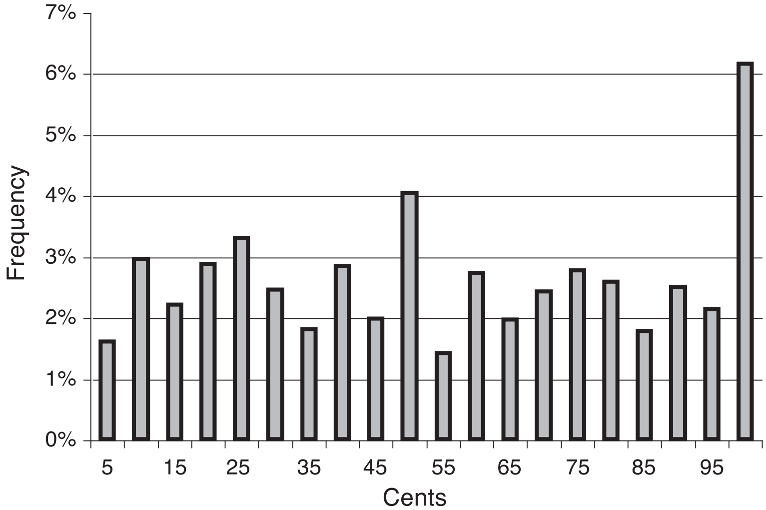

Fig. 11. Frequency of ask price rounding in the postdecimalization period.

and λ_4' are insignificantly different from zero, indicating that the effects of the trading variables on rounding frequencies are similar in the pre- and postdecimalization periods. That is, the sensitivity of price rounding to trading variables does not change as a result of decimalization.

Table 4 reports dummy regression test results of bid–ask spreads against rounding frequencies and trading variables. In Panels A and B, we observe that rounding frequency does not have a significant effect on the quoted or effective bid–ask spreads in most regression tests after controlling for price, volatility, market capitalization, inverse of square root of trades, dollar volume, and proportion of the primary market volume out of the consolidated volume. These results are generally consistent with

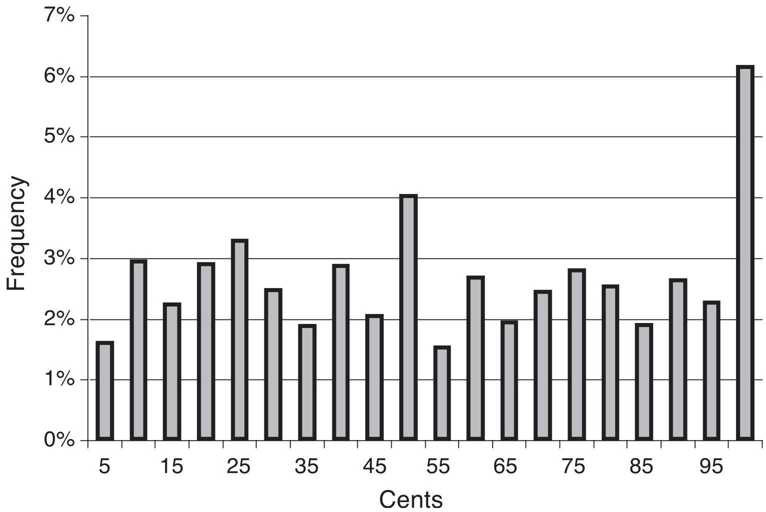

Fig. 12. Frequency of adjusted ask price rounding in the postdecimalization period.

Table 3
Regression of rounding frequency against trading variables

Dependent variable=F		Predecimalization period					Difference (post−pre)					Adjusted R^2 (%)
		CONST λ_0	P λ_1	VOLA λ_2	MV λ_3	IST λ_4	CONST λ_0'	P λ_1'	VOLA λ_2'	MV λ_3'	IST λ_4'	
Rounding on integers												
Nonpath adjusted	Coefficient	0.1055	0.0467	0.0457	0.0139	0.0787	0.0713	−0.0263	−0.0062	−0.0064	−0.0240	57
	t value	1.18	3.17*	3.26*	1.77	2.81*	0.72	−1.71	−0.39	−0.70	−0.77	
Path adjusted	Coefficient	0.0776	0.0421	0.0393	0.0154	0.0804	0.0784	−0.0226	−0.0055	−0.0090	−0.0318	61
	t value	0.96	2.90*	2.84*	2.14*	3.11*	0.89	−1.51	−0.36	−1.10	−1.12	
Rounding on halves												
Nonpath adjusted	Coefficient	0.2753	0.0582	0.0748	0.0171	0.1048	0.0048	−0.0232	−0.0115	−0.0046	−0.0145	65
	t value	2.23*	2.85*	4.82*	1.76	2.99*	0.04	−1.09	−0.64	−0.39	−0.36	
Path adjusted	Coefficient	0.1955	0.0563	0.0604	0.0192	0.1056	0.0512	−0.0232	−0.0075	−0.0088	−0.0259	70
	t value	1.88	3.08*	3.98*	2.17*	3.36*	0.45	−1.22	−0.44	−0.83	−0.73	
Rounding on quarters												
Nonpath adjusted	Coefficient	0.6008	0.0780	0.1157	0.0168	0.1383	−0.2108	−0.0291	−0.0303	0.0018	−0.0077	84
	t value	5.11*	4.42*	7.14*	2.25*	5.35*	−1.49	−1.47	−1.46	0.13	−0.19	
Path adjusted	Coefficient	0.4725	0.0693	0.0786	0.0144	0.1195	−0.1187	−0.0226	−0.0053	0.0012	−0.0046	84
	t value	4.26*	3.81*	4.91*	1.74	4.62*	−0.91	−1.15	−0.28	0.09	−0.12	

This table provides test results of price rounding frequency on trading variables for 39 stocks traded in the NYSE. The predecimalization period is from 8/1/2000 to 9/22/2000. The postdecimalization period is from 10/1/2000 to 11/31/2000. The testing model is

$$\mathrm{F}_i = \lambda_0 + \lambda_1 \mathrm{P}_i + \lambda_2 \mathrm{VOLA}_i + \lambda_3 \mathrm{MV}_i + \lambda_4 \mathrm{IST}_i + D(\lambda_0' + \lambda_1' \mathrm{P}_i + \lambda_2' \mathrm{VOLA}_i + \lambda_3' \mathrm{MV}_i + \lambda_4' \mathrm{IST}_i) + e_i,$$

where F represents the rounding frequency of transaction prices, P is the average transaction price, VOLA is the volatility of price returns, MV is the market capitalization, IST is the inverse of square root of daily number of trades, and D is a dummy variable that is equal to 0 for the preperiod and 1 for the postperiod. All the independent variables are in log term. We employ the GMM to estimate the coefficients and t values to account for heteroskedasticity in the error term.

* Significant at the 5% level for a two-tailed test.

Table 4

Regression of bid–ask spreads against trading variables and rounding frequency

Dependent variable=SPR%		Predecimalization period								Difference (post−pre)								Adjusted R^2 (%)
		CONS (λ_0)	P (λ_1)	VOLA (λ_2)	MV (λ_3)	IST (λ_4)	DV (λ_5)	PM (λ_6)	F (λ_7)	CONS (λ_0')	P (λ_1')	VOLA (λ_2')	MV (λ_3')	IST (λ_4')	DV (λ_5')	PM (λ_6')	F (λ_7')	
Panel A. Quoted bid–ask spreads against all independent variables																		
F=0	Coefficient	0.0410	−0.0016	0.0037	0.0009	0.0025	−0.0015	−0.0108		0.0028	−0.0019	0.0015	−0.0003	0.0042	0.0017	0.0174		75
	t value	4.15*	−1.15	3.91*	1.45	1.08	−1.34	−1.59		0.21	−1.07	1.07	−0.37	1.06	1.08	2.03*		
Rounding on integers																		
Nonpath adjusted	Coefficient	0.0418	−0.0024	0.0030	0.0007	0.0008	−0.0016	−0.0076	0.0132	−0.0058	−0.0019	0.0001	−0.0005	0.0024	0.0016	0.0129	0.0393	76
	t value	4.00*	−1.89	2.23*	1.01	0.23	−1.24	−1.20	0.85	−0.44	−1.06	0.08	−0.56	0.52	0.96	1.54	1.61	
Nonpath adjusted[a]	Coefficient	0.0221	−0.0044	0.0009	−0.0012	0.0053	−0.0015	−0.0108	0.0132	−0.0004	−0.0003	0.0004	−0.0002	0.0012	0.0017	0.0174	0.0393	76
	t value	7.58	−5.44*	1.14	−4.69*	2.85*	−1.17	−1.73	0.85	−0.09	−0.24	0.42	−0.48	0.49	1.08	2.09*	1.61	
Path adjusted	Coefficient	0.0442	−0.0032	0.0023	0.0004	−0.0016	−0.0019	−0.0046	0.0283	−0.0076	−0.0012	0.0010	−0.0001	0.0049	0.0019	0.0104	0.0279	77
	t value	3.85*	−2.51*	1.84	0.52	−0.34	−1.28	−0.72	1.49	−0.54	−0.67	0.62	−0.16	0.87	1.05	1.23	0.97	
Path adjusted[a]	Coefficient	0.0221	−0.0044	0.0009	−0.0012	0.0053	−0.0015	−0.0108	0.0283	−0.0004	−0.0003	0.0004	−0.0002	0.0012	0.0017	0.0174	0.0279	77
	t value	8.10*	−5.85*	1.20	−4.58*	2.85*	−1.06	−1.98	1.49	−0.10	−0.24	0.43	−0.47	0.48	1.01	2.22*	0.97	
Rounding on halves																		
Nonpath adjusted	Coefficient	0.0403	−0.0033	0.0018	0.0004	−0.0015	−0.0019	−0.0045	0.0215	−0.0044	−0.0013	0.0011	−0.0003	0.0041	0.0018	0.0107	0.0142	77
	t value	3.92*	−2.21*	0.99	0.65	−0.29	−1.21	−0.63	1.47	−0.33	−0.65	0.51	−0.34	0.67	0.97	1.19	0.64	
Nonpath adjusted[a]	Coefficient	0.0221	−0.0044	0.0009	−0.0012	0.0053	−0.0015	−0.0108	0.0215	−0.0004	−0.0003	0.0004	−0.0002	0.0012	0.0017	0.0174	0.0142	77
	t value	8.54*	−6.16*	1.08	−4.63*	3.04*	−1.04	−2.10*	1.47	−0.10	−0.25	0.40	−0.47	0.51	1.00	2.30*	0.64	
Path adjusted	Coefficient	0.0427	−0.0033	0.0019	0.0004	−0.0022	−0.0021	−0.0043	0.0237	−0.0053	−0.0012	0.0015	−0.0001	0.0056	0.0020	0.0108	0.0096	76
	t value	3.85*	−2.41*	1.27	0.48	−0.43	−1.33	−0.64	1.45	−0.37	−0.61	0.72	−0.12	0.87	1.08	1.23	0.39	
Path adjusted[a]	Coefficient	0.0221	−0.0044	0.0009	−0.0012	0.0053	−0.0015	−0.0108	0.0237	−0.0004	−0.0003	0.0004	−0.0002	0.0012	0.0017	0.0174	0.0096	76
	t value	8.21*	−5.94*	1.17	−4.62*	2.92*	−1.06	−2.05*	1.45	−0.09	−0.24	0.41	−0.46	0.49	1.00	2.25*	0.39	
Rounding on quarters																		
Nonpath adjusted	Coefficient	0.0326	−0.0042	−0.0001	0.0003	−0.0044	−0.0023	−0.0030	0.0280	0.0001	−0.0009	0.0021	−0.0004	0.0053	0.0021	0.0096	0.0078	79
	t value	3.43*	−2.50*	−0.03	0.44	−0.90	−1.54	−0.44	1.83	0.01	−0.40	0.86	−0.48	0.93	1.23	1.13	0.38	
Nonpath adjusted[a]	Coefficient	0.0221	−0.0044	0.0009	−0.0012	0.0053	−0.0015	−0.0108	0.0280	−0.0004	−0.0003	0.0004	−0.0002	0.0012	0.0017	0.0174	0.0078	79
	t value	8.65*	−6.08*	0.96	−4.39*	2.96*	−1.08	−2.15*	1.83	−0.11	−0.27	0.38	−0.48	0.54	1.07	2.45*	0.38	
Path adjusted	Coefficient	0.0385	−0.0035	0.0014	0.0005	−0.0034	−0.0024	−0.0042	0.0231	−0.0051	−0.0016	0.0011	−0.0005	0.0050	0.0023	0.0114	0.0134	78
	t value	3.79*	−2.22*	0.86	0.63	−0.71	−1.55	−0.61	1.31	−0.39	−0.78	0.55	−0.53	0.87	1.28	1.29	0.59	
Path adjusted[a]	Coefficient	0.0221	−0.0044	0.0009	−0.0012	0.0053	−0.0015	−0.0108	0.0231	−0.0004	−0.0003	0.0004	−0.0002	0.0012	0.0017	0.0174	0.0134	78
	t value	8.02*	−5.66*	1.21	−4.18*	2.72*	−1.05	−1.99	1.31	−0.10	−0.25	0.44	−0.46	0.50	1.03	2.29*	0.59	

(continued on next page)

Table 4 (*continued*)

Dependent variable=SPR%		Predecimalization period								Difference (post−pre)								Adjusted R^2 (%)
		CONS (λ_0)	P (λ_1)	VOLA (λ_2)	MV (λ_3)	IST (λ_4)	DV (λ_5)	PM (λ_6)	F (λ_7)	CONS (λ_0')	P (λ_1')	VOLA (λ_2')	MV (λ_3')	IST (λ_4')	DV (λ_5')	PM (λ_6')	F (λ_7')	
Panel B. Effective bid−ask spreads against all independent variables																		
F=0	Coefficient	0.0265	−0.0012	0.0021	0.0005	0.0015	−0.0009	−0.0095		0.0002	−0.0012	0.0011	−0.0001	0.0033	0.0012	0.0132		74
	t value	3.97*	−1.33	3.24*	1.16	0.91	−1.30	−1.87		0.02	−0.93	1.05	−0.16	1.18	1.15	2.10*		
Rounding on integers																		
Nonpath adjusted	Coefficient	0.0272	−0.0020	0.0015	0.0002	−0.0001	−0.0010	−0.0067	0.0118	−0.0044	−0.0008	0.0007	−0.0001	0.0031	0.0012	0.0097	0.0141	75
	t value	3.87*	−2.32*	1.60	0.58	−0.02	−1.22	−1.45	1.18	−0.47	−0.63	0.58	−0.12	0.98	1.08	1.62	0.82	
Nonpath adjusted[a]	Coefficient	0.0159	−0.0032	0.0004	−0.0008	0.0029	−0.0009	−0.0095	0.0118	−0.0013	0.0001	0.0003	−0.0001	0.0013	0.0012	0.0132	0.0141	75
	t value	8.28	−6.14*	0.62	−4.88*	2.42*	−1.11	−2.08*	1.18	−0.45	0.11	0.35	−0.47	0.81	1.11	2.21*	0.82	
Path adjusted	Coefficient	0.0290	−0.0024	0.0010	0.0000	−0.0017	−0.0013	−0.0047	0.0219	−0.0057	−0.0004	0.0013	0.0002	0.0049	0.0014	0.0080	0.0045	76
	t value	3.79*	−2.98*	1.23	0.09	−0.55	−1.30	−0.98	1.85	−0.57	−0.28	1.10	0.28	1.28	1.18	1.30	0.23	
Path adjusted[a]	Coefficient	0.0159	−0.0032	0.0004	−0.0008	0.0029	−0.0009	−0.0095	0.0219	−0.0013	0.0001	0.0003	−0.0001	0.0013	0.0012	0.0132	0.0045	76
	t value	8.86*	−6.61*	0.69	−4.78*	2.44*	−1.01	−2.28*	1.85	−0.46	0.11	0.37	−0.46	0.80	1.05	2.31*	0.23	
Rounding on halves																		
Nonpath adjusted	Coefficient	0.0259	−0.0026	0.0005	0.0001	−0.0018	−0.0012	−0.0044	0.0175	−0.0028	−0.0003	0.0016	0.0001	0.0048	0.0014	0.0079	−0.0017	76
	t value	3.74*	−2.72*	0.47	0.17	−0.52	−1.23	−0.92	1.88	−0.29	−0.20	1.10	0.18	1.14	1.12	1.29	−0.12	
Nonpath adjusted[a]	Coefficient	0.0159	−0.0032	0.0004	−0.0008	0.0029	−0.0009	−0.0095	0.0175	−0.0013	0.0001	0.0003	−0.0001	0.0013	0.0012	0.0132	−0.0017	76
	t value	9.76*	−7.27*	0.63	−4.87*	2.65*	−0.98	−2.65*	1.88	−0.47	0.11	0.35	−0.46	0.85	1.03	2.51*	−0.12	
Path adjusted	Coefficient	0.0278	−0.0025	0.0007	0.0000	−0.0022	−0.0014	−0.0046	0.0182	−0.0035	−0.0002	0.0018	0.0002	0.0057	0.0016	0.0082	−0.0057	75
	t value	3.77*	−2.84*	0.74	0.06	−0.64	−1.37	−0.94	1.76	−0.35	−0.17	1.22	0.34	1.31	1.24	1.32	−0.36	
Path adjusted[a]	Coefficient	0.0159	−0.0032	0.0004	−0.0008	0.0029	−0.0009	−0.0095	0.0182	−0.0013	0.0001	0.0003	−0.0001	0.0013	0.0012	0.0132	−0.0057	75
	t value	9.02*	−6.74*	0.67	−4.84*	2.51*	−1.02	−2.36*	1.76	−0.45	0.11	0.36	−0.44	0.80	1.04	2.36*	−0.36	
Rounding on quarters																		
Nonpath adjusted	Coefficient	0.0205	−0.0031	−0.0006	0.0000	−0.0035	−0.0015	−0.0039	0.0201	0.0002	−0.0001	0.0021	0.0000	0.0052	0.0016	0.0076	−0.0008	78
	t value	3.08*	−2.91*	−0.43	0.07	−1.15	−1.65	−0.85	2.08*	0.02	−0.10	1.31	−0.04	1.39	1.41	1.29	−0.06	
Nonpath adjusted[a]	Coefficient	0.0159	−0.0032	0.0004	−0.0008	0.0029	−0.0009	−0.0095	0.0201	−0.0013	0.0001	0.0003	−0.0001	0.0013	0.0012	0.0132	−0.0008	78
	t value	9.55*	−6.93*	0.55	−4.61*	2.50*	−1.08	−2.62*	2.08*	−0.50	0.12	0.33	−0.48	0.89	1.14	2.58*	−0.06	
Path adjusted	Coefficient	0.0247	−0.0026	0.0004	0.0001	−0.0030	−0.0016	−0.0047	0.0172	−0.0034	−0.0006	0.0014	−0.0001	0.0051	0.0017	0.0086	0.0017	76
	t value	3.62*	−2.64*	0.37	0.29	−0.96	−1.65	−0.93	1.58	−0.37	−0.42	1.04	−0.11	1.33	1.45	1.37	0.12	
Path adjusted[a]	Coefficient	0.0159	−0.0032	0.0004	−0.0008	0.0029	−0.0009	−0.0095	0.0172	−0.0013	0.0001	0.0003	−0.0001	0.0013	0.0012	0.0132	0.0017	76
	t value	8.69*	−6.33*	0.69	−4.36*	2.29*	−1.01	−2.27*	1.58	−0.46	0.11	0.38	−0.45	0.82	1.08	2.34*	0.12	
Panel C. Quoted bid−ask spreads against selected independent variables																		
F=0	Coefficient	0.0213	−0.0028		0.0001	0.0030		−0.0069		0.0083	−0.0014		−0.0004	−0.0015		0.0166		59
	t value	2.63*	−1.73		0.14	1.70		−0.81		0.74	−0.62		−0.63	−0.72		1.42		
Rounding on integers																		
Nonpath adjusted	Coefficient	0.0263	−0.0050		−0.0003	0.0009		0.0000	0.0361	−0.0026	−0.0003		−0.0001	−0.0010		0.0055	0.0524	72
	t value	4.45*	−3.50*		−0.58	0.63		0.00	2.70*	−0.32	−0.17		−0.18	−0.58		0.62	2.20	
Path adjusted	Coefficient	0.0279	−0.0054		−0.0005	−0.0001		0.0015	0.0477	−0.0042	−0.0001		0.0001	−0.0002		0.0048	0.0519	73
	t value	4.71*	−3.76*		−0.94	−0.06		0.23	2.93*	−0.52	−0.05		0.19	−0.11		0.54	1.84	

Rounding on halves																		
Nonpath adjusted	Coefficient	0.0237	−0.0051		−0.0002	0.0008		0.0002	0.0332	0.0002	−0.0005		−0.0002	−0.0014		0.0065	0.0285	75
	t value	4.51*	−3.71*		−0.39	0.63		0.03	3.22*	0.03	−0.28		−0.38	−0.84		0.79	1.62	
Path adjusted	Coefficient	0.0252	−0.0054		−0.0004	0.0001		0.0009	0.0376	−0.0015	−0.0004		0.0000	−0.0008		0.0064	0.0297	73
	t value	4.51*	−3.76*		−0.75	0.07		0.14	2.98*	−0.19	−0.21		−0.01	−0.43		0.72	1.45	
Rounding on quarters																		
Nonpath adjusted	Coefficient	0.0167	−0.0053		0.0001	0.0011		−0.0021	0.0298	0.0065	−0.0007		−0.0006	−0.0023		0.0092	0.0197	78
	t value	2.96*	−3.94*		0.17	0.85		−0.40	3.43*	0.89	−0.40		−0.99	−1.42		1.27	1.46	
Path adjusted	Coefficient	0.0174	−0.0054		−0.0001	0.0006		−0.0005	0.0320	0.0053	−0.0008		−0.0004	−0.0018		0.0086	0.0229	75
	t value	3.00*	−3.77*		−0.11	0.35		−0.08	2.38*	0.70	−0.43		−0.66	−0.96		1.05	1.27	
Panel D. Effective bid spreads against selected independent variables																		
F=0	Coefficient	0.0148	−0.0019		0.0000	0.0019		−0.0073		0.0044	−0.0008		−0.0001	−0.0007		0.0129		63
	t value	2.71*	−1.87		−0.09	1.60		−1.22		0.57	−0.54		−0.32	−0.52		1.59		
Rounding on integers																		
Nonpath adjusted	Coefficient	0.0181	−0.0033		−0.0002	0.0005		−0.0028	0.0233	−0.0022	0.0000		0.0000	−0.0003		0.0060	0.0272	72
	t value	4.48*	−3.69*		−0.80	0.57		−0.65	2.81*	−0.38	−0.02		0.11	−0.23		0.96	1.58	
Path adjusted	Coefficient	0.0191	−0.0036		−0.0004	−0.0001		−0.0019	0.0308	−0.0032	0.0001		0.0002	0.0003		0.0055	0.0255	73
	t value	4.74*	−3.93*		−1.13	−0.11		−0.42	3.02*	−0.55	0.10		0.45	0.22		0.86	1.28	
Rounding on halves																		
Nonpath adjusted	Coefficient	0.0164	−0.0035		−0.0002	0.0005		−0.0027	0.0217	−0.0004	−0.0001		0.0000	−0.0005		0.0065	0.0133	75
	t value	4.51*	−3.95*		−0.61	0.55		−0.70	3.35*	−0.07	−0.09		−0.06	−0.41		1.13	1.08	
Path adjusted	Coefficient	0.0173	−0.0036		−0.0003	0.0001		−0.0024	0.0238	−0.0014	−0.0001		0.0001	−0.0001		0.0066	0.0135	73
	t value	4.49*	−3.89*		−0.94	0.06		−0.55	3.01*	−0.23	−0.05		0.25	−0.08		1.04	0.98	
Rounding on quarters																		
Nonpath adjusted	Coefficient	0.0120	−0.0034		0.0000	0.0007		−0.0043	0.0184	0.0035	−0.0003		−0.0003	−0.0011		0.0084	0.0107	77
	t value	2.98*	−3.98*		−0.05	0.80		−1.14	3.26*	0.65	−0.26		−0.66	−0.98		1.58	1.09	
Path adjusted	Coefficient	0.0124	−0.0035		−0.0001	0.0004		−0.0033	0.0199	0.0028	−0.0004		−0.0002	−0.0008		0.0079	0.0120	75
	t value	3.03*	−3.90*		−0.30	0.37		−0.77	2.45*	0.51	−0.28		−0.37	−0.63		1.34	1.00	

This table provides test results of bid–ask spreads on trading variables and rounding frequencies for 39 stocks traded in the NYSE. The predecimalization period is from 8/1/2000 to 9/22/2000. The postdecimalization period is from 10/1/2000 to 11/31/2000. The testing model is

$$Y_i = \lambda_0 + \lambda_1 \mathrm{P}_i + \lambda_2 \mathrm{VOLA}_i + \lambda_3 \mathrm{MV}_i + \lambda_4 \mathrm{IST}_i + \lambda_5 \mathrm{DV}_i + \lambda_6 \mathrm{PM}_i + \lambda_7 \mathrm{F}_i + D(\lambda_0' + \lambda_1' \mathrm{P}_i + \lambda_2' \mathrm{VOLA}_i + \lambda_3' \mathrm{MV}_i + \lambda_4' \mathrm{IST}_i + \lambda_5' \mathrm{DV}_i + \lambda_6' \mathrm{PM}_i + \lambda_7' \mathrm{F}_i) + e_i,$$

where Y can be SPR% or ESPR%, SPR% is the average bid–ask spread in percentage, ESPR% is the average effective spread in percentage, P is the average transaction price, VOLA is the volatility of price returns, MV is the market capitalization, IST is the inverse of square root of daily number of trades, DV is the daily dollar volume, PM is the proportion of the volume in the primary market out of the consolidated volume, F is the rounding frequency of transaction prices, and D is a dummy variable that is equal to 0 for the preperiod and 1 for the postperiod. All the control variables (P, VOLA, MV, IST, DV, and PM) are in log term. Panels A and B report regressions of spreads against all independent variables. Panels C and D report regressions of spreads against selected independent variables to avoid collinearity problem. We employ the GMM to estimate the coefficients and t values to account for heteroskedasticity in the error term.

[a] We use orthogonalized regressors of VOLA, MV, IST, DV, PM, and F as the explanatory variables to deal with collinearity problems. The orthogonalized regressor of VOLA is the residual in the regression of VOLA against P. The orthogonalized regressor of MV is the residual in the regression of MV against P and VOLA. The orthogonalized regressor of IST is the residual in the regression of IST against P, VOLA, and MV. The orthogonalized regressor of DV is the residual in the regression of DV against P, VOLA, MV, and IST. The orthogonalized regressor of PM is the residual in the regression of PM against P, VOLA, MV, IST, and DV. The orthogonalized regressor of F is the residual in the regression of F against P, VOLA, MV, IST, DV, and PM.

* Significant at the 5% level for a two-tailed test.

Table 5
Regression of bid–ask spread changes against changes in trading variables and rounding frequency

Dependent variable=ΔSPR%		CONST (λ_0)	ΔP (λ_1)	ΔVOLA (λ_2)	ΔMV (λ_3)	ΔIST (λ_4)	ΔDV (λ_5)	ΔPM (λ_6)	ΔF (λ_7)	Adjusted R^2 (%)
Panel A. Changes in quoted bid–ask spreads against all independent variables										
ΔF=0	Coefficient	−0.0710	3.6261	0.1902	−3.5020	0.8809	0.1420	−2.1518		21
	t value	−1.53	0.78	2.14*	−0.76	2.17*	1.20	−2.85*		
Rounding on integers										
Nonpath adjusted	Coefficient	−0.0507	3.9492	0.1958	−3.8166	0.9672	0.1591	−1.8191	0.0191	26
	t value	−1.10	0.86	2.13*	−0.84	2.36*	1.31	−2.60*	4.27*	
Path adjusted	Coefficient	0.0302	3.1562	0.1843	−3.1465	1.0827	0.1511	−0.8789	0.2669	39
	t value	0.61	0.69	1.87	−0.69	2.80*	1.30	−1.33	3.67*	
Rounding on halves										
Nonpath adjusted	Coefficient	−0.0681	3.5388	0.1902	−3.4043	0.9421	0.1521	−1.3946	0.0140	22
	t value	−1.43	0.77	2.16*	−0.75	2.37*	1.30	−1.31	1.91	
Path adjusted	Coefficient	0.1170	1.7092	0.1350	−1.7601	0.9625	0.1040	0.0876	0.4683	44
	t value	2.12*	0.41	1.39	−0.42	3.00*	1.04	0.13	3.88*	
Rounding on quarters										
Nonpath adjusted	Coefficient	0.0924	2.5422	0.1802	−2.4534	0.8016	0.0936	−1.3407	0.2937	31
	t value	1.00	0.59	1.82	−0.58	2.37*	0.91	−1.16	1.66	
Path adjusted	Coefficient	0.2793	0.8993	0.1803	−0.8637	0.8831	0.0666	0.3943	0.6192	48
	t value	3.59*	0.21	1.80	−0.21	3.13*	0.79	0.65	4.13*	

Panel B. Changes in effective bid–spreads against all independent variables										
ΔF=0	Coefficient	−0.0625	3.1404	0.1967	−3.0458	0.9974	0.1817	−2.2960		21
	t value	−1.31	0.74	1.84	−0.73	2.11*	1.45	−2.39*		
Rounding on integers										
Nonpath adjusted	Coefficient	−0.0455	3.4116	0.2014	−3.3098	1.0698	0.1960	−2.0168	0.0161	24
	t value	−0.93	0.80	1.82	−0.79	2.24*	1.52	−2.27*	2.35*	
Path adjusted	Coefficient	0.0211	2.7526	0.1918	−2.7524	1.1640	0.1892	−1.2453	0.2203	31
	t value	0.37	0.65	1.62	−0.66	2.50*	1.49	−1.48	2.50*	
Rounding on halves										
Nonpath adjusted	Coefficient	−0.0586	3.0221	0.1966	−2.9134	1.0804	0.1955	−1.2697	0.0190	25
	t value	−1.18	0.71	1.83	−0.70	2.36*	1.60	−1.02	2.31*	
Path adjusted	Coefficient	0.0834	1.6529	0.1539	−1.6940	1.0608	0.1522	−0.5581	0.3634	33
	t value	1.21	0.41	1.30	−0.43	2.52*	1.32	−0.65	2.48*	
Rounding on quarters										
Nonpath adjusted	Coefficient	0.0477	2.4093	0.1899	−2.3385	0.9439	0.1490	−1.7489	0.1981	24
	t value	0.41	0.58	1.65	−0.57	2.21*	1.28	−1.41	0.96	
Path adjusted	Coefficient	0.2360	0.8165	0.1882	−0.7973	0.9993	0.1174	−0.1260	0.5277	38
	t value	2.34*	0.20	1.57	−0.20	2.67*	1.22	−0.15	2.90*	

This table provides test results of bid–ask spread changes on changes in trading variables and rounding frequencies for 39 stocks traded in the NYSE. The predecimalization period is from 8/1/2000 to 9/22/2000. The postdecimalization period is from 10/1/2000 to 11/31/2000. The testing model is

$$\Delta Y_i = \lambda_0 + \lambda_1 \Delta \mathrm{P}_i + \lambda_2 \Delta \mathrm{VOLA}_i + \lambda_3 \Delta \mathrm{MV}_i + \lambda_4 \Delta \mathrm{IST}_i + \lambda_5 \Delta \mathrm{DV}_i + \lambda_6 \Delta \mathrm{PM}_i + \lambda_7 \Delta \mathrm{F}_i + e_i,$$

where the change in a variable is defined as the log of the post- to prevariable ratio, *Y* can be SPR% or ESPR%, SPR% is the average bid–ask spread in percentage, ESPR% is the average effective spread in percentage, P is the average transaction price, VOLA is the volatility of price returns, MV is the market capitalization, IST is the inverse of square root of daily number of trades, DV is the daily dollar volume, PM is the proportion of the volume in the primary market out of the consolidated volume, and F is the rounding frequency of transaction prices. We employ the GMM to estimate the coefficients and *t* values to account for heteroskedasticity in the error term.

* Significant at the 5% level for a two-tailed test.

Bessembinder (1997).[4] Additionally, in most regressions, the estimate of λ_7' is insignificantly different from zero, indicating that the effect of rounding frequency on the quoted or effective bid–ask spreads remains similar after the decimalization, with the trading variables held constant. We also provide orthogonal dummy regression test results. For example, in the orthogonal regression, we use the adjusted rounding frequency variable as an explanatory variable where the adjusted variable is the residual in the regression of F against P, VOLA, MV, IST, DV, and PM. The adjusted variable removes the effects of other explanatory variables. We also use the same orthogonal procedure to mitigate the effect of collinearity in other explanatory variables. However, we find that while the orthogonal regression may increase the significance of some explanatory variables, the conclusion stays the same regardless of orthogonalization.

While the orthogonal regression does not lead to significant rounding frequency coefficients, we adopt an alternative method to deal with the collinearity problem. In Panels C and D of Table 4, we drop some independent variables that are highly correlated with other independent variables but have no significant relationship with the dependent variable. The remaining independent variables in the regression are P, MV, IST, PM, and F. It is found that rounding frequency has a significant effect on the quoted or effective bid–ask spreads after controlling for price, market capitalization, the inverse of square root of trades, and the proportion of the primary market volume out of the consolidated volume. Thus, the insignificance of the rounding frequency in Panels A and B of Table 4 appears to be a consequence of collinearity. Additionally, in Panels C and D, most λ_7' estimates are insignificantly different from zero, indicating that the effect of rounding frequency on the quoted or effective bid–ask spreads remains similar after decimal trading.

Table 5 examines changes in bid–ask spreads in relation to changes in rounding frequencies after controlling for changes in trading variables. After differencing the independent variables, the collinearity problem becomes inconsequential. By including the change in rounding frequencies into the regression of quoted spreads, the adjusted R^2 increases from 21% to 39% for rounding on integers, to 44% for rounding on halves, and to 48% for rounding on quarters. By including the change in rounding frequencies into the regression of effective spreads, the adjusted R^2 increases from 21% to 31% for rounding on integers, to 33% for rounding on halves, and to 38% for rounding on quarters. In addition, the estimates of parameter λ_7 are significant in most regression tests, implying that the change in the quoted or effective bid–ask spreads is significantly related to the change in rounding frequencies, with control for the changes in all the trading variables. Thus, the decrease in execution costs after decimalization can be ascribed to the decrease in rounding frequencies when trading variables are held constant. The results support the contention that the decline in price rounding frequency significantly reduces bid–ask spreads in the postdecimalization period.

5. Conclusions

This paper investigates price clustering in the NYSE market before and after the pilot program of decimalization. We find that rounding exists in transaction, bid, and ask prices in both the pre- and

[4] Bessembinder (1997) finds that for NYSE issues, there is no significant relationship between rounding frequencies and execution costs after controlling for market making costs. However, for Nasdaq issues, price-rounding frequencies are strongly related to execution costs even after allowing for variations in market making costs.

postdecimalization periods. In the predecimalization period, prices tend to cluster on integers, halves, quarters, and even sixteenths. In the postdecimalization period, prices tend to cluster on 100, 50, 25, 10, and 5 cents. More importantly, the frequencies of clustering on integers, halves, and quarters reduce considerably in the postdecimalization period, and the decrease in rounding frequencies exerts significant influence on the decrease in execution costs when market making costs are held constant.

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