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The effect of decimalization on the components of the bid-ask spread

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Abstract

Previous empirical studies that decompose the bid-ask spread were done when securities traded in discrete price points equal to one-sixteenth or one-eighth of a dollar. These studies concluded that inventory and adverse-selection costs were economically insignificant compared to order-processing costs. Natural questions arise as to: (i) whether price discreteness allowed market makers to enjoy excess rents, thus reducing the significance of the inventory and adverse selection costs; (ii) whether discreteness decreased the traders' incentives to gather information; or (iii) whether methodologies previously employed mis-estimated the inventory and the adverse-selection costs. We show that the recent conversion to decimal pricing results in significantly tighter spreads. However, the dollar value of spreads attributed to adverse selection and inventory costs do not change significantly. Almost all of the reduction occurs in the order-processing component. As a result, inventory and adverse-selection costs now account for a significantly larger proportion of the traded spreads. A plausible explanation is that the minimum tick size constraint previously in place under fractional pricing allowed market makers to enjoy spreads that were larger than their actual costs.

JEL classification: G14; G19; N20

Keywords: Decimalization; Bid-ask spread components; Market-maker rents

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1. Introduction

Theoretical researchers of market microstructure have made significant strides in understanding the role of adverse-selection costs and inventory-holding costs in determining bid-ask spreads.[1] Recent empirical research, however, calls into question the economic significance of the contribution that adverse-selection and inventory costs make to observed bid-ask spreads.[2] Importantly, these studies were conducted when securities traded in discrete price points equal to one-sixteenth or one-eighth of a dollar. With the well-publicized conversion by the major exchanges and NASDAQ to decimal pricing from fractional pricing, the one-cent minimum tick size now in place has reshaped the trading environment for market makers and investors, creating the potential for systematic changes in spreads. Natural questions arise as to whether price-discreteness was responsible for the observed economic insignificance of the inventory and adverse-selection costs. In this article, we examine how the size of each of the various components that together comprise the traded spread changed with the conversion to decimal pricing. This decomposition allows us to answer questions as to: (i) whether price-discreteness allowed market makers to enjoy excess rents which were relatively large in comparison; (ii) whether discreteness decreased the traders' incentives to gather information; or (iii) whether methodologies previously employed were unable to detect these costs due to discreteness.

Our research complements several recent studies that examine how decimalization affected market quality and trade execution costs. Bessembinder (2002) finds no degradation after conversion in a number of market quality measures (including quote sizes, competitiveness of quotes originating off the listing market, intraday return volatility, and systematic intraday quote changes).[3] Bacidore et al. (2001) report evidence of thinner limit order books after decimalization, but no evidence of this decrease in committed liquidity adversely affecting traditional measures of execution quality. With respect to trade execution costs, the aforementioned studies along with Chung et al. (2001), NASDAQ (2001), and NYSE (2001) all document significant decreases in quoted spreads, effective spreads, and/or realized spreads with the conversion to decimalization. Our contribution to this literature is to examine how the component parts that together comprise traded spreads changed under decimalization.

Our research also complements Bacidore's (1997) study of the Toronto Stock Exchange's (TSE's) conversion to a reduced tick size.[4] Bacidore focuses on the impact of this change on the market quality, specifically market depth and liquidity. He finds that

[1] For example, Kyle (1985), Glosten and Milgrom (1985), Easley and O'Hara (1987), Admati and Pfleiderer (1988) provided pioneering models of adverse selection in securities' trading. For papers studying the inventory holding costs, see Demsetz (1968), Stoll (1978), Ho and Stoll (1981), and Ho and Stoll (1983).

[2] George et al. (1991), for example, report that only 8 to 13 percent of the quoted spread was attributable to adverse-selection costs. In the same vein, Huang and Stoll (1997) find that on average about 38 percent of traded spreads were attributable to inventory and adverse-selection costs. Similar evidence is provided by Madhavan et al. (1997) and Cao et al. (1997).

[3] Bessembinder (2000) obtains similar results when he analyzes spreads for NASDAQ stocks that experienced tick size changes as their share prices passed through the $10 mark.

[4] The TSE converted from a one-eighth-dollar to a five-cent minimum tick size for stocks priced above five dollars and to a decimal tick size for stocks priced below five dollars.

this narrowing of the tick size on the TSE was accompanied by decreases in quoted and effective spreads, and interprets evidence on quoted spreads as being consistent with no adverse consequences for liquidity. Given that trading volume did not increase on the TSE following conversion, Bacidore posits that providers of liquidity may have been adversely affected because the per-share decrease in spreads was not offset by higher volumes. We too focus on how the narrowing of the minimum tick size affected liquidity providers, but take a different approach by explicitly examining how the components of the bid-ask spread changed after decimalization.

Liquidity providers may have been affected in a number of ways by the conversion to decimalization. One potential change stems from the possibility that the minimum tick size under fractional pricing allowed market makers to enjoy spreads that were rounded up from what they would have been without the tick-size constraint (see, for example, Ball and Chordia (2001)). With competition between limit orders and market makers restricted to fractional price points, market makers may have been able to keep spreads artificially high, enabling them to earn a positive rent component. If this were true, then the conversion to decimal pricing ought to increase competition, dramatically reducing the ability of market makers to capture rents. The extent to which market maker rents decreased (if at all) is, we believe, an empirical question that we attempt to answer through spread-decomposition analysis.

Another potential change is the effect on informed trading. It is unclear ex ante whether the incentives for gathering information will increase or decrease under decimal pricing. A bid-ask spread that is too large, which is more likely under fractional pricing, not only imposes a greater fixed cost on informed traders but also increases the probability of the spread straddling the efficient price, thus reducing traders' incentives for obtaining information. Hence, any decrease in the spread owing to decreased market maker rents under decimal pricing ought to increase informed trading. On the other hand, a large minimum tick size protects informed traders from front running and order jumping[5] by floor traders and/or market makers. Decimal pricing benefits floor traders and market makers by reducing the cost of such order jumping.[6] Decimalization can thus reduce the profits from informed trading, decreasing traders' incentive for obtaining information. In summary, arguments exist which suggest the possibility of an increase or a decrease in the level of informed trading with the inception of decimal trading. Whether informed trading increased or decreased after decimalization is, we believe, an empirical question that we attempt to answer through spread-decomposition analysis. A net increase (decrease) in the

[5] Front-running by the broker, with whom the order has been placed, is illegal. However, order jumping, where floor traders make an offer slightly better than the existing limit order or the order being shopped by another floor broker is legal.

[6] As far back as April 1997, Lawrence Harris in his testimony to Congress said that, "If the tick is too small, front-runners will exploit investors who offer to trade. ... Estimates of the benefits to the public from decimalization are grossly overstated. ... They do not estimate the increased costs that large traders will have to pay to avoid front-runners." Testimony on H.R. 1053: The Common Cents Stock Pricing Act of 1997 (Lawrence Harris, April 17, 1997). Similar sentiments have been expressed in the popular press. See for example, 'Decimals point the way,' Tom Geck, February 2000, *Red Herring*, and 'Stock prices switch to decimals from fractions, raising concerns,' Greg Ip, August 28, 2000, *Wall Street Journal*.

incentives of traders to get privately informed post-decimalization, we hypothesize, will increase (decrease) the dollar value of the adverse-selection component.

Citing a desire to lower transaction costs for investors, the NYSE was a leader in the conversion to decimal pricing. The conversion began on July 25, 2000 with seven stocks and then successively larger numbers of stocks were phased in over a period that culminated on January 29, 2001, with all listed stocks. (See Appendix A for a timeline of the NYSE conversion to decimal pricing.) This phase-in approach taken by the NYSE creates an experimental setting that allows us to make a contemporaneous comparison of spreads for stocks that went to decimalization early with those that did not. Studying all NYSE-listed S&P 500 stocks from December 11, 2000, to March 23, 2001, we split the sample based on whether the stock began decimal pricing before January 29, 2001. We thus have a 'control sample' of stocks which traded under the decimal pricing over the entire sample period and a 'test sample' of stocks which underwent a pricing regime shift on January 29, 2001, from a one-sixteenth-dollar pricing to one-cent pricing. Aiding our empirical design, the NYSE selected a cross section of stocks for the early adoption of decimal pricing that were representative of the population.

In the period before full conversion to decimal trading, when the control and test sample stocks traded under different pricing regimes, we find that the quoted spread was on average a statistically significant 3.74 cents lower for stocks in the control sample as compared to the stocks in the test sample. Estimating what investors actually paid once price improvement is taken into consideration, we find that these lower quoted spreads translated into traded spreads that were on average a significant 3.17 cents lower for stocks in the control sample. Corroborating this evidence of the spread-tightening effect of decimalization, the stocks in the test sample, which shifted from fractional to decimal trading, experienced significant declines in both quoted and traded spreads at the time of conversion. Results are also robust when we separately examine small trades (shares $\leqslant 1000$), medium trades ($1000 < \text{shares} < 10{,}000$) and large trades (shares $\geqslant 10{,}000$).

Our finding of tighter spreads under decimal pricing might not seem too surprising. The interesting question, we believe, is: how did the components that together comprise the spread change to affect this tightening? We employ a methodology proposed by Huang and Stoll (1997) to decompose the traded spread into an inventory plus adverse-selection component and an order-processing component. As we later describe, the method accounts for the adverse selection and inventory costs, with the residual attributable to order processing costs. In the context of the discussion above, it is important to recognize that any market maker rents would be included in the residual order-processing component.

Our empirical results show that almost all of the decline in traded spreads resulted from a reduction in the order-processing component. In the period before full conversion to decimal trading, we find that the order-processing component was a significant 3.14 cents lower in the control sample than in the test sample. The inventory plus adverse-selection component, in contrast, was an insignificant 0.03 cents lower. Confirmation is provided by our examination of the test sample before and after conversion, which also shows that almost all of the decline in traded spreads resulted from a decrease in the order-processing component. Once again results are robust when trades of different size categories are examined separately. Interpreting the results in the context of the questions posed above, we find evidence consistent with no *net* change in informed trading. Not only are the estimates of the inventory plus adverse-selection component for the test and control samples similar before and after conversion, they are also similar to the estimates obtained in earlier studies. This similarity suggests that the methodologies used in previous work were sound in spite of the fractional tick size. Faulty methodologies do not appear to be the reason for the relatively low empirical estimates of the proportion of the traded spread attributable to inventory plus adverse-selection costs. An alternative explanation for the tighter traded spreads under decimal pricing is that the fractional minimum tick size requirements in place during these earlier studies restricted competition between limit orders and market makers, contributing to spreads that were larger than market makers' actual costs, thus allowing market makers to enjoy excess profits. The smaller order-processing estimates under the decimal pricing regime produced by our spread-decomposition analysis are consistent with increased competition between limit orders and market makers at decimal price points narrowing spreads, thus reducing these market maker profits.

We also examine realized spreads, a short-term measure of the potential profit or loss realized by the limit order book, floor trader, or market maker who takes the other side of market orders. We find that realized spreads for all trades averaged together regardless of size are significantly lower under decimal pricing, which is consistent with liquidity suppliers' revenues declining overall on a per trade basis under decimal pricing. As we find with traded spreads, the greatest decreases in realized spreads are exhibited by small trades, followed by medium trades.

We gain additional insights by analyzing the cross-sectional relationship between proportional traded spreads and stock characteristics. Consistent with earlier work,[7] we find that proportional traded spreads for the test sample prior to conversion are negatively related to a stock's daily dollar volume, number of daily trades and market capitalization, but are positively related to its price volatility. Interestingly, these cross-sectional regression coefficient estimates for the test sample exhibit insignificant changes after conversion. Test sample coefficients also differ insignificantly from those of the control sample prior to conversion. In contrast, the sensitivity of proportional traded spreads to share prices shows significant changes under decimal pricing. The price coefficient for the test sample shows a significant decrease in magnitude, becoming less negative, after conversion. A similar pattern is found prior to conversion for the price coefficient of the control sample relative to that of the test sample. The observed flatter sensitivity of proportional spreads to share prices is once again consistent with the theory that the minimum tick size under the fractional pricing regime allowed market makers to enjoy spreads that were rounded up from what they would have been without the tick-size constraint.

As a final test of this possibility, we examine the cross-sectional properties of dollar spreads (as opposed to proportional spreads). We again find evidence consistent with a sharp reduction in market maker profits after conversion. Moreover, our cross-sectional dollar-spread analysis produces estimates of the decline in market maker profits that are similar to the estimates of the decline in the order-processing component obtained in our decomposition analysis.

[7] See, for example, Demsetz (1968), Tinic (1972), Tinic and West (1974), Benston and Hagerman (1974), Branch and Freed (1977), Stoll (1978), and Stoll (2000).

Taken together, our results suggest that the fractional minimum tick size requirements in place during earlier studies contributed to spreads that were larger than market makers' actual costs, thus allowing market makers to enjoy excess profits. Numerous reports in the financial press provide anecdotal evidence bolstering this interpretation that market maker profits declined with the conversion to decimal pricing. Major trading firms such as Merrill Lynch & Co., Morgan Stanley, Goldman Sachs Group Inc., Credit Suisse First Boston, and Lehman Brothers Holdings Inc. all cited tighter spreads after conversion as causing substantial declines in trading revenues (*Wall Street Journal*, May 25, 2001). Additional evidence is found in the sharp decrease in payment-for-order-flow following conversion (*Wall Street Journal*, April 18, 2001).

The remainder of the paper is organized as follows: In Section 2, we describe our data and sample composition. In Section 3, we explain the methodology which we use to decompose spreads. Empirical results from our spread-decomposition analysis are also presented and interpreted. In Section 4, we describe the models employed in our cross-sectional analysis, and then present and interpret results. We make our concluding remarks in Section 5.

2. Data and sample composition

We conduct our study on S&P 500 stocks that are listed on the NYSE. Of the 500 stocks in the index, 424 are listed on the NYSE.[8] Of these 424 stocks, we exclude six that underwent splits and three that were dropped from the S&P 500 during the period of our study. After these exclusions, the total number of stocks in our final sample is 415.

The key events associated with the phase-in of decimal pricing on the NYSE are detailed in Appendix A. The conversion began on July 25, 2000 with seven stocks and then successively larger numbers of stocks were phased in over a period that culminated on January 29, 2001 with all listed stocks. We consider two time periods of seven trading weeks each:

- Period 1, from December 11, 2000 to January 26, 2001, is characterized by 29 stocks in our sample trading under decimal pricing and the remaining 386 stocks trading under fractional pricing.
- Period 2, from February 5, 2001, to March 23, 2001, is characterized by all sample stocks trading under decimal pricing.

We exclude the trading week of January 29 to February 2 to allow markets to adjust after the commencement of decimalized trading. We thus have a 'test sample' of 386 stocks which underwent a pricing regime shift on January 29, 2001, from a one-sixteenth-dollar pricing to one-cent pricing and a 'control sample' of 29 stocks which traded under the decimal pricing over the entire sample period.

In the empirical tests that follow, we compare the spreads of the test and control samples in periods 1 and 2. Aiding our empirical design, the NYSE selected a cross section of

[8] S&P 500 has the following breakdown by exchanges: the NYSE lists 424, the NASDAQ lists 74, and the AMEX lists 2.

Table 1
Comparative statistics for stocks in the test and control samples

Variable	Mean			Median		
	Test	Control	Diff.	Test	Control	Diff.
Panel A: Comparative statistics for period 1						
Daily trades	743	820	−77	553	695	−142
Daily volume (in million shares)	1.85	2.18	−0.33	0.96	1.12	−0.16
Daily volume (in million $)	79.69	82.65	−2.96	36.41	43.47	-7.06
Market value (in billion $)	22.53	17.58	4.95	7.60	9.46	−1.86
Average price (in $)	41.2	42.2	−1.0	39.1	34.8	4.3
σ^2	9.83%	11.13%	−1.30%	7.94%	9.47%	−1.53%
Panel B: Comparative statistics for period 2						
Daily trades	865	927	−62	674	814	−140
Daily volume (in million shares)	1.80	2.09	−0.29	0.93	0.99	−0.06
Daily volume (in million $)	75.25	77.69	−2.44	34.78	47.56	−12.78
Market value (in billion $)	21.46	17.65	3.81	7.85	10.15	−2.30
Average price (in $)	41.0	41.8	−0.8	40.1	38.4	1.7
σ^2	9.83%	11.13%	−1.30%	7.94%	9.47%	−1.53%

The table summarizes the comparative statistics for stocks in the test and control samples in periods 1 and 2. The first three items in the panel are average daily statistics for the number of trades, transaction volume in number of shares, and transaction volume in $ amount traded, respectively. 'Average market value' and 'average price' are averages for the entire period. σ^2 is the variance of daily returns from December 1, 1999, to November 30, 2000.

stocks for the early adoption of decimal pricing that were representative of the population. Table 1 presents statistics for the test and control samples on the number of daily trades, total shares traded daily, dollar volume of daily trades, equity market capitalization, price per share, and variance of daily returns. Attesting to the similarity of the test and control samples, Panels A and B show that the mean and median values for all six variables are insignificantly different from one another in periods 1 and 2, respectively.

Trade and quotes data for these stocks are obtained from the TAQ data set distributed by the NYSE. Following are the filter rules which we applied to the data:

(1) We only consider trades and quotes pertaining to the principal stock exchange, namely the NYSE.
(2) We exclude trades or quotes time stamped outside the normal trading hours.
(3) We exclude opening batch trades because the trading mechanism at the open is different from that during the rest of the day.
(4) We exclude trades reported out of sequence, and quotes that do not correspond to a normal trading environment.[9]
(5) We exclude quotes in which the bid exceeds the ask, the spread exceeds 10 percent of the average of the bid and ask, and the bid or ask equals zero.

[9] For those familiar with the TAQ database, we exclude a trade if its correction indicator CORR is greater than one, and only include quotes coded MODE = 12.

The number of shares outstanding and daily returns are obtained from the CRSP dataset. In the analysis to follow, we use the number of shares outstanding as of December 31, 2000. We calculate the variance of daily returns for each stock using daily closing returns between December 1, 1999, and November 30, 2000.

3. Spread decomposition

3.1. All trades regardless of size

3.1.1. Empirical design

We employ a modified version of the methodology proposed by Huang and Stoll (1997) to estimate traded spreads and to decompose traded spreads into an order-processing component and an inventory plus adverse-selection component. The variables used in the analysis include:

- V_t the unobservable fundamental value of the stock at time t in the absence of transaction costs;
- M_t quote mid-point at time t, computed as the average of the bid and ask;
- P_t actual observed transaction price at time t;
- Q_t buy–sell indicator at time t. Q_t equals 1 if the transaction is buyer-initiated and -1 if the transaction is seller-initiated;
- S the traded spread for the stock;
- α the percentage of S attributable to adverse-selection costs;
- β the percentage of S attributable to inventory costs;
- λ the percentage of S attributable to adverse-selection and inventory costs.

The modification we make to the Huang and Stoll (1997) methodology has to do with the way we determine Q_t. We use the trade classification rule proposed in Ellis et al. (2000), which they show to be more accurate in classifying within-the-quote trades than earlier trade classification rules. The trade classification rule is as follows:

Rule	Classification
Trade executed at or above the ask	$Q_t = 1$
Trade executed at or below the bid	$Q_t = -1$
Trade executed inside quoted spread and $P_t > P_{t-1}$	$Q_t = 1$
Trade executed inside quoted spread and $P_t < P_{t-1}$	$Q_t = -1$
Trade executed inside quoted spread and $P_t = P_{t-1}$	$Q_t = Q_{t-1}$

The market maker has to bear the adverse-selection costs and the inventory costs, which depend on the direction of the trade. Thus, for a unit positive buyer-initiated trade, the market maker revised his estimate of V_t upwards by an amount αS. The buyer initiated trade on average reduces his inventory, thus, making him less anxious to trade in that direction. This effect is captured by his adjusting the midpoint of the spread upwards by an amount βS. Combining the two, we can write:

$$M_t = M_{t-1} + (\alpha + \beta)SQ_{t-1} + \varepsilon_t,$$

or

$$\Delta M_t = (\alpha + \beta)SQ_{t-1} + \varepsilon_t. \tag{1}$$

The observed transaction price depends on the direction of the trade. A buyer-motivated trade occurs at the tradeable ask ($M_t + S/2$) while the seller-motivated trade occurs at the tradeable bid ($M_t - S/2$). Thus,

$$P_t = M_t + \frac{S}{2}Q_t + \eta_t,$$

where η_t captures the deviation of the observed half-spread, $P_t - M_t$, from the constant half-spread, $S/2$, and includes rounding errors associated with the minimum tick size. The first difference of the above equation yields

$$\Delta P_t = \Delta M_t + \frac{S}{2}(Q_t - Q_{t-1}) + \Delta\eta_t.$$

Substituting from (1) we obtain the model to be estimated,

$$\begin{aligned}\Delta P_t &= (\alpha + \beta)SQ_t + \frac{S}{2}(Q_t - Q_{t-1}) + e_t \\ &= \lambda SQ_{t-1} + \frac{S}{2}(Q_t - Q_{t-1}) + e_t,\end{aligned} \tag{2}$$

where $e_t = \varepsilon_t + \Delta\eta_t$.

Equation (2) can be used to estimate S, the traded spread, and λ, the percentage of traded spread that is attributable to adverse-selection and inventory costs. Earlier in the paper we put forward arguments suggesting that it is unclear ex ante whether informed trading would increase or decrease under decimal pricing. Traders with superior information can only make expected profits if the value of the security conditional on their information is outside the spread. If the spread is too large, which is more likely under fractional pricing, the probability of the informed traders' conditional valuation being straddled by the spread is high. Hence, any decrease in the spread ought to increase the incentives to gather information for trading. On the other hand, a large minimum tick size protects informed traders from front running and order jumping by floor traders and/or market makers. Decimalization reduces the cost of such order jumping and can, thus, reduce the profits from informed trading, decreasing traders' incentive for obtaining information. We can test these hypotheses by examining whether the test sample exhibits a significant change in λS after conversion to decimal pricing. Given the natural experimental setting created by the phased-in approach taken by the NYSE, we can also test these hypotheses by directly comparing λS for the stocks in the control sample which were already trading under decimal pricing vis-a-vis stocks in the test sample which were still trading under fractional pricing.

Earlier in the paper we also put forward the argument that fractional price points may have allowed market makers to keep spreads artificially high (i.e., higher than their actual costs), thus enabling them to earn a positive rent component. The conversion to decimal pricing may have created increased competition between the limit order book and market maker, reducing these market maker rents, in turn narrowing traded spreads. We construct a test of this hypothesis based on the residual in the spread decomposition analysis, $(1 - \lambda)S$. This residual, referred to in the literature as the order processing component, is a measure of the compensation demanded by the market maker for the fixed costs of providing liquidity and the other variable costs not associated with inventory or adverse selection. This residual component would also contain excess profits (if any) that would accrue to the market maker from an ability to exert market power. We conjecture that a change in the tick size should have no impact on the real fixed and variable costs, but might have an impact on the market maker's ability to extract excess profits. Given our conjecture, we interpret a change in the order processing component as a change in the rents that accrue to the market maker.

3.1.2. Results

Table 2 reports the results of the spread decomposition for all trades regardless of size. Panels A, B, and C present results for stocks in the test and control samples in period 1, test sample in periods 1 and 2, and control sample in periods 1 and 2, respectively. In descending order, the rows in each panel report statistics on the quoted spread (measured in cents), traded spread (cents), order-processing component (cents), inventory plus adverse-selection component (cents), and ratio of the inventory plus adverse-selection component to traded spreads (percent). Significance levels reported for the differenced medians were calculated using the median-score test, which is a non-parametric test for the equality of medians. Significance levels reported for the differenced means were calculated using a t-test for the equality of means.

Examining Panel A of Table 2, we find that quoted spreads were on average a significant 3.73 cents lower (8.02 cents versus 11.76 cents) for stocks in the control sample which were already trading under decimal pricing vis-a-vis stocks in the test sample which were still trading under fractional pricing. Estimating what investors actually paid once price improvement is taken into consideration, we find that these lower quoted spreads translated into traded spreads that were on average a significant 3.17 cents lower (4.36 cents versus 7.53 cents) for stocks in the control sample. Importantly, almost all of this 3.17 cent difference was attributable to lower order-processing component estimates. In the period before full conversion to decimal trading, we find that the order-processing component was a significant 3.14 cents lower in the control sample than in the test sample, whereas inventory plus adverse-selection component was an insignificant 0.03 cents lower in the control sample. The sharply lower order-processing component translates into a significant increase in the proportion, 58.6 percent versus 33.2 percent, of the traded spread attributable to the inventory plus adverse-selection component. The results do not appear to be driven by outliers, as an examination of the median changes also indicate decreasing traded spreads due almost entirely to decreases in the order-processing component. Our finding of narrower spreads is consistent with the results reported in Bessembinder (2002), Bacidore et al. (2001), Chung et al. (2001), NASDAQ (2001), and NYSE (2001) for stocks after decimalization; with Bacidore (1997) for TSE-listed stocks after a narrowing of tick

Table 2
Summary statistics for 'all' trades

Variable	Minimum		Maximum		Median			Mean		
	Test	Control	Test	Control	Test	Control	Diff.	Test	Control	Diff.
					Panel A: Test versus control sample in period 1					
Quoted spread	6.72	2.99	31.17	22.24	11.20	7.11	4.09**	11.76	8.02	3.73**
Traded spread	5.55	2.02	16.69	13.32	7.25	3.93	3.32**	7.53	4.36	3.17**
$(1-\lambda)S$	2.58	0.92	6.38	6.17	4.97	1.50	3.47**	4.92	1.78	3.14**
λS	0.24	0.98	10.47	7.15	2.39	2.32	0.07	2.61	2.58	0.03
λ (in %)	4.01	32.81	69.29	77.56	33.21	59.09	−25.88**	33.19	58.56	−25.37**
Variable	Minimum		Maximum		Median			Mean		
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2	Diff.	Period 1	Period 2	Diff.
					Panel B: Test sample in period 1 versus period 2					
Quoted spread	6.72	2.51	31.17	19.08	11.20	6.79	4.40**	11.76	7.14	4.61**
Traded spread	5.55	1.64	16.69	10.05	7.25	3.65	3.60**	7.53	3.76	3.77**
$(1-\lambda)S$	2.58	0.65	6.38	3.72	4.97	1.42	3.55**	4.92	1.49	3.43**
λS	0.24	0.41	10.47	6.42	2.39	2.15	0.24	2.61	2.28	0.33**
λ (in %)	4.01	23.42	69.29	84.70	33.21	59.08	−25.87**	33.19	59.04	−25.85**
					Panel C: Control sample in period 1 versus period 2					
Quoted spread	2.99	2.95	22.24	17.79	7.11	6.67	0.44	8.02	7.32	0.70
Traded spread	2.02	1.20	13.32	9.74	3.93	3.56	0.42	4.36	3.87	0.49
$(1-\lambda)S$	0.92	0.99	6.17	3.88	1.50	1.53	−0.03	1.78	1.66	0.12
λS	0.98	0.84	7.15	5.86	2.32	2.02	0.30	2.58	2.21	0.37
λ (in %)	32.81	29.84	77.56	71.60	59.09	57.08	2.01	58.56	55.80	2.76

The summary statistics for the test and control samples in periods 1 and 2 pertain to 'all' trades (i.e., 'small', 'medium' and 'large' sized trades combined). Quoted spread is the difference between the bid and offer prices. S is the traded spread and λ is the percentage of traded spread due to inventory and adverse selection costs. S and λ are estimated using the modified Huang and Stoll (1997) methodology as described in the article. λS is the inventory plus adverse selection cost component of the traded spread and $(1-\lambda)S$ is the order processing cost plus rents component. All numbers, except λ, are in cents.

** P-value $< 0.01\%$.

sizes; and Bessembinder (2000) for NASDAQ stocks experiencing tick size changes after crossing through the ten-dollar price threshold.

Reinforcing evidence of the spread-tightening effect of decimalization is found when we consider the evidence reported in Panels B and C of Table 2. Examining Panel B, we see that stocks in the test sample which shifted from fractional to decimal trading experienced significant declines in both the quoted and traded spreads after conversion. The average quoted spread fell by 4.61 cents from 11.76 cents to 7.14 cents and the average traded spread fell by 3.77 cents from 7.53 cents to 3.76 cents. Interestingly, similar to the pattern described above, the vast majority of this 3.77 cent decrease was attributable to lower order-processing component estimates. The order-processing component was a significant 3.43 cents lower on average after conversion, whereas the inventory plus adverse-selection component was a significant 0.33 cents lower on average. An examination of the median changes for the test sample at the time of conversion once again suggests that the spread tightening pattern is not driven by outliers. Turning to Panel C, we do not find a similar pattern of decreasing spreads for stocks in the control sample which traded under decimal pricing over both periods. The control sample exhibits insignificant changes in the mean and median quoted spread, traded spread, order-processing component, and inventory plus adverse-selection component.

To summarize the results so far, our evidence suggests that the NYSE's hoped-for result of tighter spreads was achieved by the conversion to decimal pricing. The spread tightening does not appear to be related to a change in informed trading, as the inventory plus adverse-selection component of the spread did not experience significant changes with the conversion to decimal pricing. Rather, the tightening of traded spreads post-decimalization appears to be largely the result of decreases in the order-processing component of the spread. A potential explanation for the tighter traded spreads under decimal pricing, which we later pursue further by analyzing the cross-section of traded spreads, is that the minimum tick size requirements in place during the fractional pricing regime contributed to spreads that were larger than market makers' actual costs, thus allowing market makers to enjoy excess profits. Bacidore (1997) also makes a similar argument based on his calculation of the liquidity premium. The smaller order-processing estimates under the decimal pricing regime produced by our spread-decomposition analysis are consistent increased competition between limit orders and market makers, resulting in a reduction in these market maker profits.

3.2. Trades conditional on size

3.2.1. Empirical design

In this section, we investigate the robustness of the above results across trades of different sizes. Harris (1999) points out that institutional investors, who typically execute large trades, may not benefit from decimalization given that the lower cost of front running could inhibit incentives to post limit orders, thus decreasing the liquidity for large orders. Recent studies of the effects of the NYSE decrease in the minimum tick size from one-eighth dollar to one-sixteenth dollar supports this argument. Goldstein and Kavajecz (2000) find that the cumulative impact of tighter spreads and a thinner limit order book was a net benefit to investors who submitted small orders, but was not a net benefit to those who submitted large orders. Jones and Lipson (2001) find that realized execution costs for institutions actually increased with the change from eights to sixteenths. Given that large market orders are more likely to be placed by institutions, we can provide indirect evidence by examining how the traded spread and its component parts changed with decimalization across trades of different sizes.

We separately estimate the traded spread and its components for trades that are classified as small (shares traded $\leqslant 1000$), medium ($1000 <$ shares traded $< 10{,}000$) and large (shares traded $\geqslant 10{,}000$) trades. We estimate a general form of Eq. (2) suggested in Huang and Stoll (1997):

$$\Delta P_t = \lambda^{\mathrm{s}} S^{\mathrm{s}} D^{\mathrm{s}}_{t-1} + \frac{S^{\mathrm{s}}}{2}\left(D^{\mathrm{s}}_t - D^{\mathrm{s}}_{t-1}\right) + \lambda^{\mathrm{m}} S^{\mathrm{m}} D^{\mathrm{m}}_{t-1} + \frac{S^{\mathrm{m}}}{2}\left(D^{\mathrm{m}}_t - D^{\mathrm{m}}_{t-1}\right) + \lambda^{\mathrm{l}} S^{\mathrm{l}} D^{\mathrm{l}}_{t-1} + \frac{S^{\mathrm{l}}}{2}\left(D^{\mathrm{l}}_t - D^{\mathrm{l}}_{t-1}\right) + \varepsilon_t, \tag{3}$$

where D^{s}_t, D^{m}_t and D^{l}_t are indicator variables for small, medium and large sized trades, respectively. Thus, for each stock in each time period, we estimate the following six parameters: S^{s}, λ^{s}, S^{m}, λ^{m}, S^{l} and λ^{l}.

Under fractional pricing, large trades exhibited wider traded spreads than small trades (see, e.g., Huang and Stoll, 1997). Previous researchers found that these wider spreads were primarily attributable to higher adverse selection and inventory components, perhaps unsurprising given that the large trades are more often executed by institutional investors who are better informed than individual investors. Under decimal pricing, we again expect traded spreads to be wider for large trades than small trades. As Harris (1999) points out, though, individual investors may benefit more than institutional investors, causing the disparity to widen further. Also unclear is the extent to which the order-processing component changed across trade size categories. These are empirical questions that we take up now.

3.2.2. Results

The results for the small, medium, and large trades are presented in Tables 3, 4, and 5, respectively. The same qualitative pattern of spread changes that was exhibited by the entire sample of trades is found in each of the three trade-size categories. Regardless of trade size in period 1, quoted and traded spreads were significantly lower for stocks in the control sample which were already trading under decimal pricing relative to stocks in the test sample which were still trading under fractional pricing. In each case, the vast majority of the spread decreases were attributable to lower order-processing component estimates. Again, regardless of trade size, stocks in the test sample which shifted from fractional to decimal trading experienced significant declines in both the quoted and traded spreads at the time of conversion, with almost all of the decrease attributable to decreased order-processing component estimates. Finally, regardless of trade size, stocks in the control sample which traded under decimal pricing over both periods show insignificant changes in the quoted spread, traded spread, order-processing component, and inventory plus adverse-selection component.

Consistent with the prediction made by Harris (1999), individual investors appear to benefit more than institutional investors. While the direction of spread changes are similar across trade-size categories, the magnitude of changes are greater for smaller trades. The

Table 3
Summary statistics for ‘small’ trades

Variable	Minimum		Maximum		Median			Mean		
	Test	Control	Test	Control	Test	Control	Diff.	Test	Control	Diff.
Panel A: Test versus control sample in period 1										
Quoted spread	6.66	2.93	29.60	20.72	11.02	6.74	4.28**	11.48	7.54	3.94**
Traded spread	5.39	1.79	16.04	12.48	6.67	3.20	3.47**	6.94	3.68	3.26**
$(1-\lambda)S$	2.65	0.82	6.12	6.05	5.11	1.31	3.80**	5.03	1.64	3.39**
λS	0.09	0.51	10.11	6.44	1.63	1.89	−0.26	1.91	2.04	−0.13
λ (in %)	1.47	20.16	66.53	78.11	24.64	54.77	−30.13**	26.00	53.76	−27.76**
Variable	Minimum		Maximum		Median			Mean		
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2	Diff.	Period 1	Period 2	Diff.
Panel B: Test sample in period 1 versus period 2										
Quoted spread	6.66	2.47	29.60	17.55	11.02	6.48	4.54**	11.48	6.79	4.69**
Traded spread	5.39	1.44	16.04	9.65	6.67	3.11	3.56**	6.94	3.22	3.72**
$(1-\lambda)S$	2.65	0.54	6.12	3.32	5.11	1.34	3.77**	5.03	1.40	3.63**
λS	0.09	0.03	10.11	6.34	1.63	1.78	−0.15	1.91	1.82	0.09
λ (in %)	1.47	1.79	66.53	86.12	24.64	55.18	−30.54**	26.00	54.66	−28.66**
Panel C: Control sample in period 1 versus period 2										
Quoted spread	2.93	2.89	20.72	16.49	6.74	6.49	0.25	7.54	7.01	0.53
Traded spread	1.79	1.76	12.48	8.91	3.20	3.13	0.07	3.68	3.37	0.31
$(1-\lambda)S$	0.82	0.95	6.05	3.77	1.31	1.46	−0.15	1.64	1.58	0.06
λS	0.51	0.63	6.44	5.14	1.89	1.72	0.17	2.04	1.79	0.25
λ (in %)	20.16	23.99	78.11	69.39	54.77	53.84	0.93	53.76	51.00	2.76

The summary statistics for the test and control samples in periods 1 and 2 pertain to ‘small’ sized trades, i.e., trades involving less than 1000 shares. Quoted spread is the difference between the bid and offer prices. S is the traded spread and λ is the percentage of traded spread due to inventory and adverse selection costs. S and λ are estimated using the modified Huang and Stoll (1997) methodology as described in the article. λS is the inventory plus adverse selection cost component of the traded spread and $(1-\lambda)S$ is the order processing cost plus rents component. All numbers, except λ, are in cents.

** P-value $< 0.01\%$.

Table 4
Summary statistics for 'medium' trades

Variable	Minimum		Maximum		Median			Mean		
	Test	Control	Test	Control	Test	Control	Diff.	Test	Control	Diff.
Panel A: Test versus control sample in period 1										
Quoted spread	6.78	3.01	33.85	27.73	11.36	7.39	3.97**	11.98	8.65	3.33*
Traded spread	5.36	2.25	19.97	16.56	8.03	4.69	3.34**	8.39	5.51	2.88**
$(1-\lambda)S$	2.38	0.97	8.16	7.29	4.73	1.79	2.94**	4.75	2.14	2.61**
λS	0.17	1.13	12.07	9.98	3.51	2.75	0.76	3.65	3.37	0.28
λ (in %)	3.01	37.28	75.81	73.84	42.72	60.47	−27.75**	41.42	60.30	−18.88**
Variable	Minimum		Maximum		Median			Mean		
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2	Diff.	Period 1	Period 2	Diff.
Panel B: Test sample in period 1 versus period 2										
Quoted spread	6.78	2.48	33.85	21.40	11.36	7.09	4.27**	11.98	7.55	4.43**
Traded spread	5.36	1.70	19.97	13.05	8.03	4.51	3.52**	8.39	4.80	3.59**
$(1-\lambda)S$	2.38	0.58	8.16	5.24	4.73	1.64	3.09**	4.75	1.74	3.01**
λS	0.17	0.55	12.07	9.65	3.51	2.88	0.63**	3.65	3.06	0.59**
λ (in %)	3.01	30.14	75.81	88.01	42.72	62.09	−19.37**	41.42	62.17	−20.75**
Panel C: Control sample in period 1 versus period 2										
Quoted spread	3.01	3.01	27.73	22.06	7.39	7.00	0.39	8.65	7.75	0.90
Traded spread	2.25	2.27	16.56	12.81	4.69	4.26	0.43	5.51	4.84	0.67
$(1-\lambda)S$	0.97	1.05	7.29	4.84	1.79	1.68	0.11	2.14	1.88	0.26
λS	1.13	1.21	9.98	8.10	2.75	2.53	0.22	3.37	2.97	0.40
λ (in %)	37.28	41.73	73.84	75.56	60.47	59.84	0.63	60.30	59.66	0.64

The summary statistics for the test and control samples in periods 1 and 2 pertain to 'medium' sized trades, i.e., trades involving 1000–10,000 shares. Quoted spread is the difference between the bid and offer prices. S is the traded spread and λ is the percentage of traded spread due to inventory and adverse selection costs. S and λ are estimated using the modified Huang and Stoll (1997) methodology as described in the article. λS is the inventory plus adverse selection cost component of the traded spread and $(1-\lambda)S$ is the order processing cost plus rents component. All numbers, except λ, are in cents.

* $0.01\% < P$-value $< 5\%$.

** P-value $< 0.01\%$.

Table 5
Summary statistics for 'large' trades

Variable	Minimum		Maximum		Median			Mean		
	Test	Control	Test	Control	Test	Control	Diff.	Test	Control	Diff.
Panel A: Test versus control sample in period 1										
Quoted spread	6.91	3.95	46.42	34.99	13.20	10.61	2.59*	14.22	12.23	1.99
Traded spread	5.88	3.30	35.18	24.54	9.75	7.39	2.36*	10.63	8.43	2.20*
$(1-\lambda)S$	0.89	0.98	14.02	9.58	5.43	3.14	2.29**	5.58	3.36	2.22**
λS	0.78	1.67	29.78	15.51	4.38	4.33	0.05	5.05	5.07	−0.02
λ (in %)	13.23	42.70	91.86	75.97	44.54	59.84	−15.34**	44.95	59.62	−14.67**
Variable	Minimum		Maximum		Median			Mean		
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2	Diff.	Period 1	Period 2	Diff.
Panel B: Test sample in period 1 versus period 2										
Quoted spread	6.91	2.64	46.42	46.93	13.20	9.79	3.41**	14.22	10.57	3.65**
Traded spread	5.88	2.02	35.18	67.82	9.75	6.61	3.14**	10.63	7.38	3.25**
$(1-\lambda)S$	0.89	0.22	14.02	10.45	5.43	2.54	2.89**	5.58	2.76	2.82**
λS	0.78	0.56	29.78	66.81	4.38	3.82	0.56*	5.05	4.62	0.43
λ (in %)	13.23	19.84	91.86	98.51	44.54	59.51	−14.97**	44.95	59.37	−14.42**
Panel C: Control sample in period 1 versus period 2										
Quoted spread	3.95	3.65	34.99	33.60	10.61	9.16	1.45*	12.23	10.56	1.67
Traded spread	3.30	3.36	24.54	27.10	7.39	6.05	1.34*	8.43	7.42	1.01
$(1-\lambda)S$	0.98	1.04	9.58	7.53	3.14	2.51	0.63	3.36	2.75	0.61
λS	1.67	1.45	15.51	20.86	4.33	3.29	1.04	5.07	4.67	0.40
λ (in %)	42.70	41.05	75.97	93.65	59.84	56.26	3.58	59.62	58.77	0.85

The summary statistics for the test and control samples in periods 1 and 2 pertain to 'large' sized trades, i.e., trades involving 10,000 shares or more. Quoted spread is the difference between the bid and offer prices. S is the traded spread and λ is the percentage of traded spread due to inventory and adverse selection costs. S and λ are estimated using the modified Huang and Stoll (1997) methodology as described in the article. λS is the inventory plus adverse selection cost component of the traded spread and $(1-\lambda)S$ is the order processing cost plus rents component. All numbers, except λ, in cents.

* $0.01\% < P$-value $< 5\%$.

** P-value $< 0.01\%$.

mean and median changes in the quoted spread, traded spread, and the order-processing component are all monotonically decreasing in trade size. Before conversion, for example, the control sample relative to the test sample shows mean traded spreads for small, medium, and large trades that are 3.26, 2.88, and 2.20 cents lower, respectively. Making the same comparison for order-processing component, we observe differences for small, medium, and large trades of 3.39, 2.61, and 2.22 cents, respectively. Further confirmation is provided by examining the test sample before versus after conversion, as the same monotonic relationship is found with respect to trade size.

The pattern of traded spread changes that we document across trade size categories is qualitatively similar to the those for effective spreads reported in concurrent studies by Bessembinder (2002) and Bacidore et al. (2001). Taken together, the evidence points to all investors benefiting from lower spreads, with individual investors who typically make smaller trades, enjoying the largest decreases.

Finally, the consistency of our qualitative results across trade size categories provides a robustness check to our finding that the spread tightening does not appear to be primarily the result of a change in informed trading. Rather, the evidence points to the tightening of traded spreads under decimalization being largely the result of decreases in the order-processing component of the spread.

3.3. Realized spreads

Our results so far suggest that the per trade revenues of liquidity suppliers declined with the conversion to decimal pricing. To better understand how these revenues were affected, we examine the realized spread, a short-term measure of the potential profit or loss realized by the limit order book, floor trader, or market maker who takes the other side of the order.[10] For buy orders, the realized spread is calculated as twice the difference between the transaction price and the post-trade value. For sell orders, the reverse price differential is calculated. Given that buy (sell) orders tend to result in price increases (decreases), realized spreads ought to be less than traded spreads.

We calculate realized spreads by replicating the methodology used by Bessembinder (2002), setting the post-trade value equal to the mid-point of quoted spreads thirty minutes after each trade. Results are presented in Table 6. Overall, realized spread levels are very low. In fact, some estimates are slightly negative. This suggests that once we control for the information content of market orders, the net gains to liquidity providers as a group are close to zero. Bessembinder (2002), who also finds very low realized spreads, suggests that uninformed liquidity traders may be submitting limit orders despite narrow spreads, given that their alternative is to pay the spread by submitting market orders.

Turning to the key issue of realized spread changes, we find evidence consistent with liquidity suppliers' revenues declining overall on a per trade basis under decimal pricing. Like Bessembinder (2002), we find that realized spreads for all trades averaged together regardless of size are significantly lower under decimal pricing. Panel A shows that prior to conversion, test sample realized spreads were a significant 1.37 cents lower than those for

[10] We thank the referee for pointing out the insights that could be gained by examining realized spreads.

Table 6
Realized spread in cents (30 min interval)

Sample	Minimum		Maximum		Median			Mean		
	Test	Control	Test	Control	Test	Control	Diff.	Test	Control	Diff.
Panel A: Test versus control sample in period 1										
All	−8.0	−4.2	5.41	3.01	1.27	−0.16	1.43^{**}	0.97	−0.40	1.37^{**}
Small	−7.9	−4.2	6.67	3.04	2.15	0.17	1.98^{**}	1.78	−0.09	1.87^{**}
Medium	−17.0	−6.2	4.67	3.39	0.17	−0.90	1.07^{*}	−0.31	−1.02	0.71
Large	−18.9	−31.2	40.50	23.15	0.49	0.59	−0.10	0.52	0.30	0.22
Sample	Minimum		Maximum		Median			Mean		
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2	Diff.	Period 1	Period 2	Diff.
Panel B: Test sample in period 1 versus period 2										
All	−8.0	−4.8	5.41	7.78	1.27	0.09	1.18^{**}	0.97	0.00	0.97^{**}
Small	−7.9	−4.5	6.67	7.04	2.15	0.28	1.87^{**}	1.78	0.13	1.65^{**}
Medium	−17.0	−9.3	4.67	11.93	0.17	−0.29	0.46^{*}	−0.31	−0.60	0.29
Large	−18.9	−19.9	40.50	42.17	0.49	1.97	-1.48^{**}	0.52	2.47	-1.95^{**}
Panel C: Control sample in period 1 versus period 2										
All	−4.2	−3.1	3.01	3.59	−0.16	−0.15	−0.01	−0.40	0.18	−0.58
Small	−4.2	−3.5	3.04	4.06	0.18	0.09	0.09	−0.09	0.25	−0.34
Medium	−6.2	−3.7	3.39	3.45	−0.90	0.07	−0.97	−1.02	0.08	-1.10^{*}
Large	−31.2	−4.2	23.15	12.79	0.59	1.17	−0.58	0.31	2.11	−1.80

The table presents the realized spreads for the test and control samples before and after decimalization. The realized spreads are presented for ‘all,’ ‘small,’ ‘medium,’ and ‘large’ trades. Realized spread is defined as twice the amount by which prices for market buy orders exceed, or prices for market sell orders fall short of, the estimated post-trade value. For the table, we use the mid-point of the quote in effect 30 min after the trade as a proxy for the post-trade value. For trades that occur after 3:30 PM, we use the quote mid-point in effect at 4:00 PM.

* $0.01\% < P$-value $< 5\%$.

** P-value $< 0.01\%$.

Table 7
Realized spread in cents (5 min interval)

Sample	Minimum		Maximum		Median			Mean		
	Test	Control	Test	Control	Test	Control	Diff.	Test	Control	Diff.
Panel A: Test versus control sample in period 1										
All	−3.4	−2.9	5.24	2.80	1.42	0.07	1.35^{**}	1.32	−0.20	1.49^{**}
Small	−2.9	−2.7	5.54	2.88	2.19	0.32	1.87^{**}	2.04	0.12	1.92^{**}
Medium	−6.0	−4.3	4.75	2.80	0.43	−0.23	0.66^{*}	0.18	−0.70	0.88^{*}
Large	−9.2	−11.1	37.40	14.28	0.89	0.77	0.12	1.04	0.74	0.29
Sample	Minimum		Maximum		Median			Mean		
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2	Diff.	Period 1	Period 2	Diff.
Panel B: Test sample in period 1 versus period 2										
All	−3.4	−4.0	5.24	7.80	1.42	0.11	1.31^{**}	1.32	0.00	1.32^{**}
Small	−2.9	−3.8	5.56	7.08	2.19	0.28	1.91^{**}	2.04	0.19	1.85^{**}
Medium	−6.0	−5.5	4.75	8.03	0.43	−0.37	0.80^{**}	0.18	−0.55	0.73^{**}
Large	−9.2	−6.9	37.40	21.31	0.89	1.41	-0.52^{*}	1.04	1.74	-0.70^{*}
Panel C: Control sample in period 1 versus period 2										
All	−2.9	−2.4	2.80	3.90	0.07	0.19	−0.12	−0.20	0.24	−0.44
Small	−2.7	−2.6	2.90	4.00	0.32	0.51	−0.19	0.12	0.43	−0.31
Medium	−4.3	−2.1	2.80	3.70	−0.23	−0.28	0.05	−0.70	−0.20	−0.50
Large	−11.1	−3.3	14.28	5.17	0.77	0.82	−0.05	0.74	1.32	−0.58

The table presents the realized spreads for the test and control samples before and after decimalization. The realized spreads are presented for 'all,' 'small,' 'medium,' and 'large' trades. Realized spread is defined as twice the amount by which prices for market buy orders exceed, or prices for market sell orders fall short of, the estimated post-trade value. For the table, we use the mid-point of the quote in effect 5 min after the trade as a proxy for the post-trade value. For trades that occur after 3:55 PM, we use the quote mid-point in effect at 4:00 PM.

* $0.01\% < P$-value $< 5\%$.

** P-value $< 0.01\%$.

the control sample. Confirming evidence is found in Panel B, with the test sample experiencing a significant 0.97 cent decrease in realized spreads after conversion. As we find with traded spreads, the greatest decreases in realized spreads are exhibited by small trades, followed by medium trades. The pre-conversion differential between trade and control sample realized spreads was 1.87 cents and 0.73 cents for small and medium trades, respectively. The test sample shows 1.65 cent and 0.29 cent decreases for small and medium trades, respectively, after conversion. Only the small-trade differences, however, are significant. Large trades, in contrast, do not show clear evidence of lower realized spreads under decimal pricing. The pre-conversion realized spread differential between the trade and control samples is an insignificant 0.22 cents for large trades. Moreover, the test sample shows a significant increase in realized spreads for large trades after conversion.

For robustness, we also calculate spreads using the mid-point of quoted spreads five minutes after each trade.[11] Results are presented in Table 7. The pattern of evidence is again consistent with an overall decline in per trade revenues for liquidity suppliers under decimal pricing. The realized spread changes calculated using the five-minute interval are all in the same direction as those found using the thirty-minute interval. The five-minute results can be interpreted as stronger evidence of decreased liquidity supplier revenues, in that the magnitudes of the realized spread changes are all greater. For all trades regardless of size, the average pre-conversion differential between the test and control samples is a significant 1.49 cents, and the average pre- versus post-conversion decrease for the test sample is a significant 1.32 cents. The small-trade and medium-trade differentials are also larger, with the medium-trade differentials now significant. The large-trade evidence is again mixed.

4. Cross-sectional analysis

4.1. Proportional traded spreads

4.1.1. Empirical design

In this section, we study how the cross-sectional relationship between traded spreads and stock characteristics changed with the conversion to decimal pricing. Previous research under the fractional pricing regime (e.g., Demsetz, 1968; Tinic, 1972; Tinic and West, 1974; Benston and Hagerman, 1974; Branch and Freed, 1977; Stoll, 1978; Stoll, 2000) documented that proportional spreads were related to characteristics often thought of as proxies for liquidity and asymmetric information. Stoll (2000), for example, runs a cross-sectional regression of proportional spreads containing five independent variables:

$$\frac{S}{P} = a_0 + a_1 \ln(V) + a_2\sigma^2 + a_3 \ln(MV) + a_4 \ln(P) + a_5 \ln(N) + \varepsilon, \qquad (4)$$

where V is the average daily dollar volume, σ^2 is the return variance, MV is the equity market capitalization, P is the price level, and N is the average number of daily trades.

[11] Some other previous studies (e.g., Office of Economic Analysis, 2001) set the post-trade value equal to the mid-point of quoted spreads five minutes after each trade.

Given that high pairwise correlations exist among independent variables $\ln(V)$, $\ln(MV)$, and $\ln(N)$ in our data, we use a specification more parsimonious than Eq. (4):[12]

$$\frac{S}{P} = a_0 + a_1 \ln(V) + a_2\sigma^2 + a_3 \ln(P) + \varepsilon. \tag{5}$$

We estimate Eq. (5) for the test and control samples before and after the conversion in a seemingly unrelated regression (SUR) framework. Given that the SUR model specifically assumes that disturbance variances differ across equations and that the disturbance covariances are non-zero across equations, we can test the hypothesis that a particular coefficient is equal across the test and control samples in a given period, and to test whether a particular coefficient changes for either sample after conversion.

Of particular interest given our focus on the effects of the minimum tick size on spreads is the price level at which a stock trades. The minimum tick size constraint is clearly more restrictive the lower a stock is priced. This tick size restriction ought to manifest itself in Eq. (4) as a negative coefficient on price. In other words, if S is fixed at the lower bound of the minimum allowable tick size, then we ought to observe an inverse relation between S/P and $\ln(P)$ that is driven by the common effect of changes in P. For the test sample, this relationship should be more pronounced in the fractional trading regime when the minimum tick size was one-sixteenth of a dollar than in the decimal trading regime. Moreover, before conversion, this relationship should be more pronounced for the test sample than for the control sample.

4.1.2. Results

Table 8 presents the estimates of Eq. (5). Panel A reports results for all trades, while Panels B, C, and D report results for small, medium, and large trades, respectively. Consistent with evidence from earlier studies that examine stocks trading under fractional pricing (e.g., Demsetz, 1968; Tinic, 1972; Tinic and West, 1974; Benston and Hagerman, 1974; Branch and Freed, 1977; Stoll, 1978; Harris, 1994; Stoll, 2000), we find that traded proportional spreads are decreasing in average daily dollar volume, increasing in return variance, and decreasing in share prices. The magnitude of the volume and return variance coefficients are not significantly different for the test sample after conversion regardless of trade size. Moreover, the magnitude of the volume and return variance coefficients are not significantly different between the test and control samples before conversion regardless of trade size. The new insight suggested by our findings is that the inverse relationship between proportional spreads and prices appears to have been driven in large part by the minimum tick size requirement. That is, with S sticky at the lower bound of the minimum allowable tick size, changes to P caused S/P and $\ln(P)$ to move inversely. With the less restrictive minimum tick size requirement under decimal pricing, this inverse relationship became much less pronounced as we observe a significant decrease in the magnitude of the price coefficient. When all trades for the test sample are examined together, the magnitude changes from -0.23 percent to -0.06 percent. This means that after conversion a one

[12] Unreported results show that these high pairwise correlations lead to regression estimates of Eq. (4) that are plagued by multicollinearity problems. Results are qualitatively similar if we include $\ln(MV)$ or $\ln(N)$ in place of $\ln(V)$ in Eq. (5).

Table 8
Proportional-spread regression results for all trade size categories

Dependent variable	Intercept			ln V coefficient			σ^2 coefficient			ln P coefficient			R^2	
	Period			Period			Period			Period			Period	
	1	2	Diff.	1	2	Diff.	1	2	Diff.	1	2	Diff.	1	2
Panel A: Regression results for 'all' trades														
$(S/P)_{\text{Test}}$	1.2**	0.5**	0.7**	−0.01*	−0.01**	0.00	14.0*	9.7**	4.3	−0.23**	−0.06**	−0.17**	79%	76%
	(0.1)	(0.0)		(0.00)	(0.00)		(5.8)	(1.9)		(0.01)	(0.00)			
$(S/P)_{\text{Control}}$	0.4**	0.4**	0.02	−0.01*	−0.01*	0.00	22.4*	20.7*	1.7	−0.03*	−0.03*	0.00	75%	76%
	(0.1)	(0.1)		(0.00)	(0.00)		(6.0)	(5.7)		(0.01)	(0.01)			
Difference	0.8**	0.2**		0.00	0.00		−8.4	−11.0**		−0.20**	−0.03**			
Panel B: Regression results for 'small' sized trades														
$(S/P)_{\text{Test}}$	1.1**	0.6**	0.5**	−0.00	−0.02**	−0.02*	8.0	5.8*	2.2	−0.23**	−0.03**	−0.20**	78%	75%
	(0.1)	(0.0)		(0.01)	(0.00)		(5.9)	(1.8)		(0.01)	(0.00)			
$(S/P)_{\text{Control}}$	0.3*	0.3*	0.0	−0.01	−0.01	−0.00	16.4*	13.4*	3.0	−0.02	−0.02	0.00	63%	66%
	(0.1)	(0.1)		(0.01)	(0.01)		(6.6)	(6.2)		(0.01)	(0.01)			
Difference	0.8**	0.2**		0.01	−0.01**		−8.5	−7.6*		−0.21**	−0.01			
Panel C: Regression results for 'medium' sized trades														
$(S/P)_{\text{Test}}$	1.3**	0.7**	0.7**	−0.02**	−0.02**	0.00	20.2*	15.9**	4.3	−0.21**	−0.05**	−0.16**	78%	72%
	(0.1)	(0.0)		(0.01)	(0.00)		(6.0)	(2.5)		(0.01)	(0.00)			
$(S/P)_{\text{Control}}$	0.5**	0.5**	0.0	−0.02*	−0.02*	0.00	26.2*	25.3*	0.9	−0.02	−0.02	0.00	59%	61%
	(0.1)	(0.1)		(0.01)	(0.01)		(9.0)	(8.6)		(0.01)	(0.01)			
Difference	0.8**	0.2**		0.00	0.01*		−6.0	−9.4*		−0.19**	−0.03**			
Panel D: Regression results for 'large' sized trades														
$(S/P)_{\text{Test}}$	1.9**	1.2**	0.6**	−0.04**	−0.05**	0.00	28.4*	21.2*	7.2	−0.24**	−0.09**	−0.15**	70%	43%
	(0.1)	(0.1)		(0.01)	(0.00)		(9.1)	(8.5)		(0.01)	(0.01)			
$(S/P)_{\text{Control}}$	1.1**	0.8**	0.3	−0.03*	−0.03*	0.00	24.3	48.9*	−24.7	−0.10*	−0.02	−0.08*	75%	76%
	(0.2)	(0.2)		(0.01)	(0.01)		(26.8)	(19.0)		(0.04)	(0.03)			
Difference	0.7**	0.5**		−0.01	−0.02*		4.1	−27.7*		−0.14**	−0.07**			

The table presents the results of the following regression: $S/P = \alpha_0 + \alpha_1 \ln V + \alpha_2 \sigma^2 + \alpha_3 \ln P$. Panel A presents the results when the regression is run on 'all' trades cumulated. Panels B, C, and D presents the results separately for 'small,' 'medium,' and 'large' size trades, respectively. The numbers in parentheses are the standard errors. $(S/P)_{\text{Test}}$ and $(S/P)_{\text{Control}}$ denote the dependent variable for the test and control samples, respectively. All numbers are in %.

* $0.01\% < P$-value $< 5\%$.

** P-value $< 0.01\%$.

percent increase in share price results in only a 0.06 percent decrease in the proportional spread, a decrease approximately one quarter of what would have been expected in the fractional pricing regime. When we examine trades of different sizes, we observe the same pattern found in our earlier decomposition analysis of effects that are monotonically decreasing in trade size. Reinforcing evidence is found prior to conversion when we compare the price coefficient for the test sample to that of the control sample. Regardless of trade size, the magnitude for the control sample is significantly lower. Again, the difference is monotonically decreasing in trade size.

4.2. Dollar spreads

4.2.1. Empirical design

A possible explanation for the observed flatter sensitivity of proportional spreads to price, as Ball and Chordia (2001) posit, is that the minimum tick size under the fractional pricing regime restricted competition from limit orders and allowed market makers to enjoy spreads that were rounded up from what they would have been without the tick-size constraint. To investigate this possibility, we recast Eq. (5) such that the dependent variable is in dollar terms by multiplying through by P. To control for any portion of dollar spreads that varies linearly with price, we make a further modification replacing $\ln(P)$ such that we estimate the following equation using weighted-least-squares regression with price as the weight:

$$S = a_0 + a_1 P + a_2(P * V) + a_3\bigl(P * \sigma^2\bigr) + \varepsilon. \tag{6}$$

In Eq. (6), a_0 can be interpreted as the average per share component of spreads, expressed in dollar terms, that is unexplained by the independent variables; and a_1 can be interpreted as the variable component of spreads measured as a percentage of price. As in the proportional spread analysis above, we estimate Eq. (6) for the test and control samples before and after the conversion in a SUR framework so that we can test whether a particular coefficient is equal across the test and control samples in a given period and whether a particular coefficient changes for either sample after conversion. The focal coefficient in Eq. (6) is a_0, which captures any market maker rents that are present. If indeed market maker rents decreased under decimal pricing, then the test sample should show a smaller intercept post conversion. In addition, prior to conversion, the intercept for the test sample should be significantly less than the control sample.

4.2.2. Results

Table 9 presents the estimates of Eq. (6). Panel A reports results for all trades, while Panels B, C, and D report results for small, medium, and large trades, respectively. As in the above analysis of proportional spreads, dollar spreads exhibit algebraic signs on average daily dollar volume and return variance coefficients that generally conform to earlier research. The one exception is for small sized trades, which show a positive, but insignificant, estimate for the volume coefficient. Also generally consistent with earlier results, volume and return variance coefficients do not appear to have changed for the test sample with the move to decimal pricing. The only exception is the volume coefficient for small sized trades. Comparing the test and control samples before conversion, we also observe

Table 9
Dollar-spread regression results for all trade-size categories (in ¢)

Dependent variable	Intercept			Coefficient of P			Coefficient of $(P \ln V)$			Coefficient of $(P\sigma^2)$			R^2	
	Period			Period			Period			Period			Period	
	1	2	Diff.	1	2	Diff.	1	2	Diff.	1	2	Diff.	1	2
Panel A: Regression results for 'all' trades														
S_{Test}	5.27^{**}	1.64^{**}	3.63^{**}	0.20^{**}	0.22^{**}	-0.02	-0.009^{**}	-0.010^{**}	0.001	14.84^{**}	12.01^{**}	2.83	66%	58%
	(0.08)	(0.09)		(0.02)	(0.02)		(0.001)	(0.001)		(1.48)	(1.61)			
$S_{Control}$	0.73^{*}	1.03^{*}	-0.30	0.22^{*}	0.20^{*}	0.020	-0.009^{*}	-0.008^{*}	-0.000	24.30^{*}	21.34^{*}	2.96	82%	71%
	(0.38)	(0.40)		(0.08)	(0.08)		(0.004)	(0.005)		(8.85)	(9.14)			
Difference	4.54^{**}	0.61^{**}		-0.02	0.02		0.000	-0.002		-9.46^{*}	-9.33^{*}			
Panel B: Regression results for 'small' sized trades														
S_{Test}	5.13^{**}	0.98^{**}	4.15^{**}	0.16^{**}	0.35^{**}	-0.19^{**}	-0.008^{**}	-0.019^{**}	0.011^{**}	9.28^{**}	7.27^{**}	2.01	47%	49%
	(0.12)	(0.12)		(0.03)	(0.03)		(0.002)	(0.002)		(1.59)	(1.60)			
$S_{Control}$	1.10	1.30^{*}	-0.20	-0.01	0.04	-0.04	0.00	0.00	0.00	12.87	8.67	4.20	72%	62%
	(0.59)	(0.56)		(0.12)	(0.11)		(0.007)	(0.007)		(10.07)	(9.35)			
Difference	4.03^{**}	-0.32		0.17^{**}	0.31^{**}		-0.011^{**}	-0.019^{**}		-3.59	-1.40			
Panel C: Regression results for 'medium' sized trades														
S_{Test}	4.73^{**}	1.33^{**}	3.40^{**}	0.38^{**}	0.39^{**}	0.00	-0.018^{**}	-0.019^{**}	0.001	21.11^{**}	19.12^{**}	1.99	71%	66%
	(0.12)	(0.13)		(0.02)	(0.02)		(0.001)	(0.001)		(2.00)	(2.14)			
$S_{Control}$	0.48	0.77	-0.29	0.28^{*}	0.25	0.03	-0.010	-0.010	-0.000	18.59	19.02	-0.43	80%	71%
	(0.62)	(0.63)		(0.13)	(0.13)		(0.007)	(0.007)		(13.65)	(14.16)			
Difference	4.25^{**}	0.56^{*}		0.10^{*}	0.14^{*}		-0.008^{*}	-0.009^{**}		2.52	0.10			
Panel D: Regression results for 'large' sized trades														
S_{Test}	5.57^{**}	2.89^{**}	2.68^{**}	0.62^{**}	0.66^{**}	-0.04	-0.031^{**}	-0.035^{**}	0.004	26.33^{**}	23.05^{*}	3.28	55%	26%
	(0.25)	(0.46)		(0.04)	(0.07)		(0.002)	(0.004)		(4.61)	(8.71)			
$S_{Control}$	2.81^{*}	-0.28	3.09^{*}	0.52^{*}	0.89^{**}	-0.37^{*}	-0.024^{*}	-0.046^{*}	0.022^{*}	26.22	75.88^{*}	-49.66	56%	70%
	(1.09)	(1.11)		(0.18)	(0.18)		(0.011)	(0.010)		(27.98)	(28.48)			
Difference	2.76^{**}	3.17^{**}		0.10	-0.23^{*}		-0.007	0.011^{*}		0.11	-52.83^{**}			

The table presents the results of the following weighted least squares (WLS) regression, with price P as the weight: $S = \alpha_0 + \alpha_1 P + \alpha_2 (P \ln(V)) + \alpha_3 (P\sigma^2)$. Panel A presents the results when the regression is run on 'all' trades cumulated. Panels B, C, and D presents the results separately for 'small,' 'medium,' and 'large' size trades, respectively. The numbers in parentheses are the standard errors. S_{Test} and $S_{Control}$ denote the dependent variable for the test and control samples, respectively.

* $0.01\% < P$-value $< 5\%$.

** P-value $< 0.01\%$.

no difference in magnitude except for the volume coefficient for small and medium sized trades. Recall that Table 8 shows an inverse relation between proportional spreads and prices, consistent with dollar spreads being sticky because of the minimum tick size tick size requirement. With the minimum tick size requirement relaxed under decimalization, dollar spreads were more readily able to adjust to price changes and the inverse relation between proportional spreads and prices became less pronounced. This ability of dollar spreads to more readily adjust to prices is also evident in Table 9, which shows a positive relation between dollar spreads and prices that does not change, or increases slightly, under decimalization.

The key result in Table 9 is that the test sample exhibits significant declines in the intercept after the conversion to decimalization, which is consistent with a reduction in market maker profits. Panel A shows that stocks in the test sample exhibit a 3.63 cent decline in the intercept after conversion. Panels B, C, and D show that the magnitude of the declines are decreasing in the size of the trade, with small, medium, and large trades exhibiting declines of 4.15 cents, 3.40 cents, and 2.68 cents, respectively. These results from our cross-sectional examination of dollar spreads provide a robustness check to the decomposition results reported above as the estimates of the decline in market maker profits are similar under the two alternative methodologies.

As a further robustness check, we can also compare the test sample to the control sample before conversion. The control sample which had already begun trading under decimal pricing exhibits an intercept that is 4.54 cents lower than the test sample which was still trading under fractional pricing. When trades of different sizes are examined separately, we once more find a similar pattern to our earlier results. Before conversion, the control sample intercept is 4.03 cents, 4.25 cents, and 2.76 cents lower, respectively, than the test sample intercept. Once more the similarity of the estimates to the results cited above serve as a robustness check.

5. Conclusion

Examining all S&P 500 stocks listed on the NYSE, we estimate how the size of the various components that together comprise traded spreads changed with the conversion to decimal pricing. Taking advantage in our empirical design of the phased-in manner in which the NYSE converted, we split our sample into a control group that traded under decimal pricing over the entire sample period and a test group that converted from fractional to decimal pricing.

We find that traded spreads were significantly lower in the control sample relative to the test sample prior to conversion. Reinforcing this evidence of the spread-tightening effect of decimalization, the stocks in the test sample experienced significant declines in traded spreads at the time of conversion. The tighter spreads under decimal pricing prove to hold when trades of different sizes are examined separately, with small trades exhibiting the greatest declines.

We decompose the bid-ask spread to show that inventory and adverse-selection costs display insignificant net changes after decimalization. Thus, either the effect of the larger discrete grid on traders' incentive to gather information is small or the various effects discussed in the introduction offset each other. Resolution of this question is left for future research. In contrast, the decomposition analysis points to a reduction in the order-processing component of the spread, which is consistent with increased competition between the limit order book and the market maker. Additional evidence from our examination of realized spreads suggests that liquidity suppliers' revenues declined overall on a per trade basis under decimal pricing. Final evidence from the cross-sectional analysis is once again consistent with the minimum tick size constraint previously in place under fractional pricing restricting competition, allowing market makers to enjoy spreads than were larger than their actual costs. Our evidence is consistent with a reduction in these market maker profits under decimal pricing. Taken together, the pattern of evidence suggests that the NYSE's hoped-for result of tighter spreads for all investors, especially retail investors, was achieved by the conversion.[13]

Our findings help answer questions about the economic significance of the contribution made by inventory and adverse-selection costs to the spread. We show that these components are economically significant in the decimalized pricing regime. Our estimates show that, post conversion, the average proportion of the inventory plus adverse-selection component under decimal trading ranges from approximately 55 percent for small trades to 59 percent for large trades. Our findings also help answer questions about extant methodologies for spread decomposition. By not accounting explicitly for the rounding effect present with the fractional minimum tick size, the possibility existed that these methodologies underestimated the contributions of inventory and adverse-selection costs to the traded spread. We show that this is not the case. Instead high order-processing component of the spread, and not flaws in the spread decomposition methodologies resulted in previous researchers finding relatively low percentages of the traded spread being attributed to inventory and adverse-selection costs. Our evidence points to the need to understand, now more than ever, the inventory and adverse-selection costs of market making and the means by which they can be mitigated.

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[13] Representing this hoped-for result, NYSE Chairman and CEO Richard A. Grasso conjectured that "the switch to decimals creates a much more customer-friendly environment for the average investor and reduces investor costs." Source: NYSE website attributes quote to NYSE Chairman and CEO Richard A. Grasso speaking at the November 2000 Security Industry Association's annual meeting.

Appendix A. NYSE decimalization conversion timeline

June 5, 1997: The NYSE Board of Directors approves conversion to decimal pricing from fractions with the goal of making prices more easily understood by investors, reducing spreads and bringing the United States into conformity with international practices.

January 28, 2000: The SEC establishes July 3, 2000 as the deadline for all US stock exchanges to begin quoting share prices in decimals.

April 11, 2000: The SEC postpones deadline for switch to decimals, citing Nasdaq's "lack of readiness." The NYSE reiterates readiness in response to SEC's decision to postpone decimalization deadline.

May 16, 2000: In a letter to the SEC, the NYSE notes that it is ready for decimal trading and proposes a pilot involving a few stocks to be traded in penny increments followed by a larger pilot involving about 50 stocks.

June 13, 2000: The SEC mandates that all securities be priced in decimals no later than April 9, 2001. The NYSE announces it will begin a pilot program by September 5, 2000 to trade certain stocks in decimals, which will be gradually expanded over time until all stocks trade in decimal quotes.

July 25, 2000: The NYSE proposes August 28, 2000 as start date for decimal pricing pilot in seven listed stocks and expanding the pilot on September 25 to include approximately 50 more stocks.

August 28, 2000: NYSE initiates decimal pricing pilot begins with seven stocks and reports the conversion "went smoothly."

September 25, 2000: The NYSE adds 57 securities (representing 52 issuing companies) to the pilot program for decimal trading. Reports second phase of conversion also proceeds efficiently.

November 7, 2000: The NYSE announced it will expand the decimalization pilot program to the 64 securities already trading in decimals. NYSE reports that the pilot program is "progressing very smoothly so far."

November 9, 2000: At industry conference in Boca Raton, NYSE Chairman and CEO Richard A. Grasso announce the Exchange will complete full conversion to decimals on January 29, 2001.

December 4, 2000: The NYSE adds 94 stocks to decimal pricing pilot, bringing the total number of securities trading in decimals to 158.

December 7, 2000: The iShares S&P Global 100 begins trading on the NYSE as its first exchange traded fund and trades in decimals, raising the number of stocks traded in decimals to 159.

January 29, 2001: All NYSE listed to begin trading in decimals.

Source: NYSE web site.

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