Penny Pricing and the Components of Spread and Depth Changes

Kee H. Chung[*]
State University of New York (SUNY) at Buffalo, Buffalo, NY 14260, USA

Charlie Charoenwong and David K. Ding
Nanyang Technological University, Singapore 639798, SINGAPORE

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The usual disclaimer applies.

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[*]Corresponding Author: Kee H. Chung, The M&T Chair in Banking and Finance, Department of Finance and Managerial Economics, School of Management, SUNY at Buffalo, Buffalo, NY 14260. (e-mail) keechung@acsu.buffalo.edu (phone) 716-645-3262.

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Abstract

Numerous recent studies show that decimal pricing led to significant reductions in the spread and depth on the NYSE. In this paper, we show how much of the observed changes in the spread and depth can be attributed to different factors. Our results show that stocks with higher proportions of one-tick spreads and odd-sixteenth quotes and more frequent trading before decimalization experienced larger declines in the spread and depth after decimalization. We interpret this result as evidence of reduced binding constraints and increased front running/price competition under decimal pricing. We also find that decimal pricing led to nontrivial changes in select stock attributes, and that these changes exerted an additional impact on spreads and depths. Our results suggest that sub-penny pricing may further reduce the spreads of high-volume, low-risk, or low-price stocks.

1.   Introduction

The New York Stock Exchange (NYSE) moved from fractional pricing to dollars-and-cents pricing with the goal of making prices more easily understood by investors, reducing spreads, and bringing the U.S. securities markets into conformity with international practices. It initiated a pilot program on August 28, 2000 with seven listed issues trading in dollars and cents, followed by 57 issues on September 25, 2000, and 94 issues on December 4, 2000. The NYSE completed the conversion on January 29, 2001 by trading all remaining issues in decimals.

Numerous studies analyse the impact of decimalization on trading costs and market quality. Chakravarty, Harris, and Wood (2001a, 2001b) show that decimal pricing resulted in lower quoted and effective spreads. They find that the available depths at the best bid and ask prices are significantly smaller after decimalization. The authors conclude that their findings deliver a mixed verdict on the net effect of decimal pricing on market quality. Similarly, Bacidore, Battalio, Jennings, and Farkas (2001) and NYSE (2001a, 2001b) show that NYSE stocks exhibit smaller spreads and depths after decimalization. Nasdaq (2001a), Chung, Van Ness, and Van Ness (2002), and Bessembinder (2002b) compare trading costs between the NYSE and Nasdaq after decimalization.

Although prior studies show that both spreads and depths declined after decimalization, they provide little evidence on why such changes occurred and thus the main causes of these declines have not been well understood. Most studies [see, e.g., Bacidore et al. (2001) and Bessembinder (2002b)] find larger declines in spreads for large-capitalization or high-volume stocks and interpret the result as evidence that the pre-decimalization tick size ($1/16) was more likely a binding constraint on spread widths for these stocks. None of these studies, however, provide evidence regarding how much of the observed decline in the spread and depth can actually be attributed to the reduced binding constraint, and how much to other factors such as front running, quote rounding, and changes in stock attributes.

In the present study, we provide analyses of the factors that led to the observed decreases in the spread and depth. Specifically, we address the following research questions: (1) how much of the inter-stock differences in spread and depth changes after decimalization can be explained by the inter-stock differences in these factors; (2) how much of the observed changes in the spread and depth in aggregate can be attributed to these factors. Empirical evidence on these issues would reveal which stocks benefited most from decimalization as well as the components of total (i.e., market-wide) spread and depth changes.

Theory suggests at least four possible causes of spread and depth changes that are associated with decimalization [see Harris (1994, 1997, 1999) and Ronen and Weaver (2001)]. First, decimal pricing is likely to narrow the spread because a smaller tick size reduces the probability that the minimum price variation is a binding constraint on spread widths. The relaxation of the binding constraint is also likely to reduce the depth because liquidity providers can slide down the liquidity supply schedule along with the smaller spread. Although prior studies provide indirect evidence on this issue by showing that decimal pricing has a greater impact on high-volume and/or large-capitalization stocks, no direct evidence exists in support of this hypothesis.

Second, decimal pricing may reduce the depth because of the higher risk of front running imposed upon public liquidity suppliers by professional traders and specialists. The smaller cost of stepping in front of existing orders and greater price competition may also lead to narrower spreads even when the minimum price variation is not the binding constraint. Third, decimal pricing may narrow spreads because the smaller tick size reduces the size of quote rounding. Finally, decimal pricing is likely to change the spread and depth because the smaller tick size can alter the factors that influence the spread and depth. For example, the smaller tick size may lead to higher trading activity and, consequently, narrower spreads. Similarly, it may result in lower return volatility and thus narrower spreads.[1]

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[1] For example, Ronen and Weaver (2001) use the American Stock Exchange's May 1997 market-wide adoption of $1/16 ticks to examine several hypotheses relating to tick size reduction and find significant decreases in both daily and transitory volatility after the tick size reduction.

The spread and depth reduction due to the relaxation of the binding constraint is expected to be a positive function of the probability that the minimum price variation was a binding constraint before decimal pricing. In contrast, the spread and depth changes triggered by the increased risk of front running and price competition are likely to be related to the probability of stepping in front of existing quotes after decimal pricing. In this study, we measure the binding-constraint probability by the proportion of spread quotes that are equal to the minimum price variation ($1/16) before decimalization. We measure the front-running probability and price competition by the proportion of odd-sixteenth quotes and the intensity of trading before decimalization. We consider changes in five stock attributes–share price, number of trades, trade size, return volatility, and market capitalization–as additional sources of spread and depth changes after decimal pricing.[2]

Our results show that the observed reductions in the spread and depth are positively correlated with the pre-decimalization proportions of one-tick spreads and odd-sixteenth quotes, indicating that stocks with the most one-tick spreads and the least quote clustering benefited the most from decimal pricing. We also find that stocks with greater number of trades before decimalization exhibited larger reductions in the spread and depth after decimal pricing. These results are consistent with the notion that relaxation of the binding constraint and the increased front running and price competition led to smaller spreads and depths after decimal pricing. Decimal pricing led to nontrivial changes in select stock attributes and these changes exerted an additional impact on spreads and depths. The intraday pattern of the observed changes in spreads and depths is highly correlated with intraday variation in the proportion of one-tick spreads, suggesting that the extent to which the pre-decimalization tick size was a binding constraint varied across different times of the day. Finally, our results suggest that sub-penny pricing may further reduce the spreads of high-volume, low-risk, or low-price stocks.

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[2] Prior studies suggest these variables as determinants of spreads and depths. See, e.g., Stoll (1978), McInish and Wood (1992), Harris (1994), and Bessembinder (1999).

The paper is organized as follows. In Section 2, we discuss the likely effects of decimal pricing on the spread and depth and establish our hypotheses. Section 3 explains our data source, the measurement of key variables, and sample characteristics. Section 4 presents the empirical results. Section 5 addresses the question of whether the penny tick size is a binding constraint for certain stocks. Section 6 provides a brief summary and concluding remarks.

2.   The effects of decimal pricing on the spread and depth of NYSE stocks

In this section, we describe how decimal pricing can affect the spread and depth in four different ways.

2.1.   Probability that the minimum price variation is a binding constraint on spread widths

The minimum price variation limits the prices that liquidity providers can quote. Liquidity providers cannot narrow the bid-ask spread when the spread is equal to one tick. Decimal pricing will narrow spreads when the minimum price variation was a binding constraint on spread widths before decimalization. Because liquidity providers are likely to quote larger depths at better prices (i.e., the liquidity-supply schedule is positively sloped), decimal pricing will also lower the depth through its effect on the spread.

The probability that the minimum price variation is a binding constraint on spread widths is likely to be positively related to the proportion of spreads equal to one tick. This is because the observed spread will be one tick whenever the equilibrium spread (i.e., the spread that liquidity providers would have quoted had there been no binding constraint) is less than one tick. Hence, we employ the proportion of spread quotes that are equal to the pre-decimal tick size ($1/16) as our empirical proxy for the probability that the tick size was a binding constraint on spread widths. This leads to the following hypothesis:

Hypothesis 1:   Decimal pricing leads to larger declines in spreads and depths for stocks with higher proportions of spread quotes that are equal to $1/16 before decimal pricing.

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2.2.   Price competition and front running

The NYSE uses price and time priority rules to determine which orders will be filled first. The price priority rule requires that orders with the highest bid and lowest ask prices must be filled before those with inferior prices. The time priority rule requires that, among public orders, the first order at a given price must be filled before other orders are filled.[3] The time priority rule is meaningful only if the minimum price variation is nontrivial. The minimum price increment determines the cost of obtaining precedence through price priority when a trader does not have time precedence at a given price. If the increment is very small, the cost of obtaining precedence is negligible because traders can obtain precedence simply by bettering the existing quotes by insignificant amounts. Hence, the minimum price variation determines the probability (and also profitability) of stepping in front of existing orders.

Decimal pricing greatly reduces the cost of stepping in front of existing orders, and thus professional traders and specialists are more likely to engage in front running at the expense of public traders. In turn, public traders are likely to defend themselves from front runners by using floor brokers to hide their orders, breaking up their orders, and switching from limit order strategies to market order strategies (Harris, 1999). As a result, decimal pricing is likely to lead to lower displayed depths.

The effect of the reduced cost of front running on spreads is less obvious. The reduced cost of front running may result in wider spreads because of an increase in the adverse selection risk faced by limit order traders. If limit orders are disadvantaged frequently enough, investors may alter order submission strategies and reduce their use of limit orders, resulting in wider spreads. Alternatively, the smaller tick size may narrow spreads because both professional traders and specialists are more likely to improve existing quotes. Traders are more able and willing to improve the quote when it costs only one

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[3] On the NYSE, Rule 2072 requires that the time priority rule be strictly enforced for the first public bid (or offer) at a given price. The NYSE enforces price priority and uses a combination of order size and order placement time to determine priority for limit orders that are tied on price. Price and time priority rules are not enforced, however, across the markets that trade NYSE-listed stocks. For example, limit orders left with Boston, Pacific, or Cincinnati Exchanges do not have time priority over limit orders left with the NYSE. In the present study, we exclude off-NYSE quotes and trades from the study sample.

penny instead of 6.25 cents to do so. Some public limit order traders may also step in front of existing limit orders, causing greater price competition among public traders. Hence, the net effect of the reduced cost of front running on spreads is likely to be determined by the relative strengths of these forces.

Bacidore et al. (2001) find a significant decrease in the distance between limit order prices and the contemporaneous spread midpoint after decimalization and conclude that limit order traders are more aggressive under penny pricing. In a similar vein, Jennings (2001) finds that the proportion of one-tick quote updates that improved both sides of the National Best Bid or Offer increased from 1% of the quote updates before decimalization to 5% after decimalization, indicating the increased competitiveness of the quoting environment.[4] Hence, it appears that traders use the increased flexibility of decimals to compete more intensely on price. These considerations suggest that decimal pricing is likely to reduce spreads even when the pre-decimalization tick size was not a binding constraint on spread widths (i.e., spreads were larger than $1/16).

Professional traders are more likely to engage in front running when there is less uncertainty about asset value because the profitability of front running depends on the accuracy of their prediction of future price movements. Similarly, public limit order traders are more likely to improve existing quotes when asset value uncertainty is lower. Harris (1991) and Grossman, Miller, Cone, Fischel, and Ross (1997) show that coarser price grids are used more frequently when underlying asset values are uncertain. As a result, the extent of front running and price competition under decimal pricing is likely to be higher (lower) for stocks that exhibited finer (coarser) price grids before decimalization. Hence, finer price grids that resulted from decimal pricing are likely to have greater front-running and price competition effects on stocks that exhibited lower quote clustering around even-sixteenths before decimalization. These considerations lead to our next hypothesis:

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[4] Consistent with Harris' (1997, 1999) conjecture, Jennings (2001) also finds that the primary source of one-tick quote improvements changed from agency orders to principal orders in the months following decimal pricing, indicating that the smaller tick size plays into the hands of professional traders.

Hypothesis 2:   Decimal pricing leads to larger declines in spreads and depths for stocks with higher proportions of odd-sixteenth quotes before decimal pricing.

2.3.   Quote rounding

Bid-ask spreads in markets with small tick sizes would be narrower than those in markets with large tick sizes (even when the equilibrium spread is greater than the minimum price variation) if liquidity providers tend to round up their quotes. For example, suppose that the equilibrium spread is ten cents. If the tick size were $1/16 and the spread were rounded up to the next available level, the observed spread would be $2/16 (12.5 cents). However, the observed spread would be ten cents if the tick size were only one penny. Hence, we expect bid-ask spreads to decline after decimal pricing even when the tick size was not a binding constraint on spread widths before decimalization. Because quote rounding is equally likely to occur across stocks with different attributes, we expect to observe a decline in the spread that is independent of stock attributes (such as the proportion of spread quotes that are equal to $1/16 and the proportion of odd-sixteenth quotes).

2.4.   Changes in stock attributes and their impact on the spread and depth

To the extent that decimal pricing accompanied changes in stock attributes which have an effect on the spread and depth, the observed changes in the spread and depth may be attributed, at least in part, to the changes in stock attributes. Prior studies suggest that a decrease in tick size generally results in a greater number of trades, smaller trade sizes, and lower return volatility. For example, NYSE (2001b) reports a significant increase in the number of trades and a decrease in trade size after decimalization. The study also finds that the degree of price change associated with executing a given number of shares is considerably lower after decimalization. Bessembinder (2002b) shows that intraday return volatility declined after decimalization. He finds that the median return volatility declined from 2.04% in the pre-decimalization sample to 1.56% in the post-decimalization sample using a sample of NYSE stocks.

Our study design involves a "before and after" comparison and uses data during two time periods: 30 trading days immediately before and after the implementation of decimal pricing. To the extent that there are any changes in stock attributes between these two time periods, they are likely to have an effect on the spread and depth. For example, the spread as a percentage of share price will be affected by changes in share price as well as changes in the dollar spread. In addition, there may be some exogenously determined shifts in market volatility between the two periods.

In our study, we include the changes in five stock attributes (i.e., share price, number of trades, trade size, return volatility, and market capitalization) in the regression model to determine how much of the observed changes in the spread and depth can be attributed to changes in these stock attributes.

3.   Data source, variable measurement, and descriptive statistics

We obtain data used in this study from the NYSE's Trade and Quote (TAQ) database. Our initial sample consists of 2,629 NYSE-traded common stocks available in the TAQ database. From the initial sample, we omit 19 stocks that have a minimum price variation smaller than $1/16 before decimalization. In addition, we drop seven stocks that do not have sufficient data during either the pre- or post-decimalization period. This leaves us with the final study sample of 2,603 stocks–seven stocks from the first pilot (August 28, 2000), 49 stocks from the second pilot (September 25, 2000), 81 stocks from the third pilot (December 4, 2000), and 2,466 stocks from the full implementation (January 29, 2001) of decimal pricing.

To examine the effects of decimalization on the spread and depth, we use trade and quote data during 30 trading days immediately before and after the date on which each implementation group was subject to decimal pricing. We omit the following to minimize data errors: (1) quotes if either the ask price or the bid price is less than or equal to zero; (2) quotes if either the ask size or the bid size is less than or equal to zero; (3) quotes if the bid price is greater than or equal to the ask price; (3) quotes if the

bid-ask spread is greater than \$5; (4) before-the-open and after-the-close trades and quotes; (5) trades if the price or volume is less than or equal to zero; and (6) out-of-sequence trades and quotes.

Table 1 shows select attributes of our study sample of 2,603 stocks during the pre- and post-decimalization study periods for each pilot as well as the full implementation. We measure share price by the average daily closing quote midpoint and return volatility by the standard deviation of daily returns calculated from the daily closing quote midpoints. The table also reports the results of paired comparison t-tests on the mean absolute and mean relative differences in stock attributes between the pre- and post-decimalization study periods. The mean absolute difference is the mean difference in the stock attribute between the pre- and post-decimalization study periods. The mean relative difference is the cross-sectional mean of the ratio of the absolute difference to the pre-decimalization value of the stock attribute.

Consistent with the results reported in prior studies [e.g., NYSE (2001b) and Bessembinder (2002b)], we find that decimal pricing led to an increase in the number of trades for all three pilots and the full implementation group. We find mixed results, however, for other stock attributes. Decimal pricing led to a significant decrease in return volatility for the full implementation group. In contrast, return volatility is higher after decimalization for the second and third pilots and remains the same for the first pilot. Similarly, trade size is smaller after decimal pricing for the full implementation group but larger for the first pilot. We observe significant increases in both share price and market capitalization after decimalization for the full implementation group. On the whole, these results indicate that at least some part of the observed changes in the spread and depth after decimal pricing may be due to concurrent changes in stock attributes.

3.1. Execution costs

We employ four measures of execution cost in this study: the quoted spread in dollars [$(A_{i,t} - B_{i,t})$], the quoted spread as a proportion of share price [$(A_{i,t} - B_{i,t})/M_{i,t}$], the effective spread in dollars [$2 \cdot D_{i,t} \cdot (P_{i,t} - M_{i,t})$], and the effective spread as a proportion of share price [$2 \cdot D_{i,t} \cdot (P_{i,t} - M_{i,t})/M_{i,t}$], where $A_{i,t}$

is the quoted ask price for stock i at time t, $B_{i,t}$ is the quoted bid price for stock i at time t, $M_{i,t}$ is the midpoint of $A_{i,t}$ and $B_{i,t}$, $P_{i,t}$ is the transaction price for stock i at time t, and $D_{i,t}$ is a binary variable which equals +1 for buyer-initiated trades and −1 for seller-initiated trades. Bessembinder (2002a) suggests that making no allowance for trade reporting lags is optimal when assessing whether trades are buyer or seller initiated, but comparing trade prices with earlier quotations is optimal when assessing trade execution costs. In this study, we estimate $D_{i,t}$ using the algorithm suggested by Lee and Ready (1991) and modified by Bessembinder (2002a). The effective spread measures the actual cost paid by the trader. We measure the quoted depth in both dollars and round lots.[5]

For each stock, we first calculate the time-weighted quoted spread, the trade-weighted effective spread, and the time-weighted quoted depth during the pre- and post-decimalization study periods, respectively. We then calculate the cross-sectional means of these variables during each period. The results (see Table 2) show that decimal pricing led to a significant decrease in both the quoted and effective spreads across all four implementation groups. For example, the quoted dollar spread declined by 3.2 to 7.1 cents after decimalization across different groups. These are equivalent to a decline of about 24% to 31% in relative terms. Similarly, the effective dollar spread declined by 2.8 to 5 cents across different groups, which are equivalent to 29% to 40% declines in relative terms. The results show that decimal pricing led to 30% to 36% declines in the quoted depth, except for the first pilot. Overall, these results are qualitatively identical to those reported in Chakravarty, Harris, and Wood (2001a, 2001b), Bacidore et al. (2001), NYSE (2001a, 2001b), Nasdaq (2001b), and Bessembinder (2002b).

3.2.   Binding constraint on spread widths

We measure the probability that the minimum price variation is a binding constraint on spread widths by the proportion of quoted spreads that are equal to $1/16 (PQMIN_QS hereafter) before decimalization. To assess the sensitivity of our results to different measurement methods, we also

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[5] The share depth is measured by the sum of bid and ask sizes. The dollar depth is the product of the share depth and

calculate the proportion of trading time during which the quoted spread is equal to $1/16 (PTMIN_QS). In addition, we calculate the proportion of effective spreads that are equal to one tick (PQMIN_ES). Both PQMIN_QS and PTMIN_QS measure the probability that liquidity providers could not have narrowed existing quotes due to the binding constraint.

Panel A of Table 3 shows that the mean (median) values of PQMIN_QS, PTMIN_QS, and PQMIN_ES are 0.31 (0.30), 0.32 (0.31), and 0.44 (0.45), respectively, with standard deviations of 0.20, 0.21, and 0.18. More than 50% of our sample stocks have PQMIN_QS, PTMIN_QS, and PQMIN_ES values that are greater than 30%. Figure 1 shows the proportion of our sample of stocks that belong to each decile of PQMIN_QS, PTMIN_QS, and PQMIN_ES, respectively. Figure 1A shows that about 15% of our study sample have $0 \leq$ PQMIN_QS < 0.10, and about 17% of the sample have $0.10 \leq$ PQMIN_QS < 0.20, and so on. Figure 1B shows similar results for the distribution of stocks by PTMIN_QS. Overall, these results indicate that the minimum price variation is a significant binding constraint on liquidity providers' quote decisions for some stocks.

Figure 1 shows wide variation in PQMIN_QS, PTMIN_QS, and PQMIN_ES across stocks. We expect the probability that the minimum price variation is a binding constraint on spread widths to be negatively related to the equilibrium spread–the spread that liquidity providers would have quoted had there been no binding constraint (i.e., when the minimum price variation is infinitesimally small). To the extent that the equilibrium spread is a function of stock attributes, we expect PQMIN_QS, PTMIN_QS, and PQMIN_ES to be related to the stock attributes. In particular, because high-volume, low-risk, or low-price stocks are likely to have smaller equilibrium spreads, we expect PQMIN_QS, PTMIN_QS, and PQMIN_ES to be positively related to the number of trades and trade size, and negatively to share price and return volatility.

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the quote midpoint.

Indeed, when we regress PQMIN_QS, PTMIN_QS, and PQMIN_ES against a common set of explanatory variables (i.e., log of share price, number of trades, trade size, return volatility, market capitalization, and three dummy variables for the decimal pricing pilots), we find that the results are consistent with our expectation (see Table 3). We also find that these explanatory variables account for more than 70% of the cross-sectional variation in PQMIN_QS, PTMIN_QS, and PQMIN_ES.

4.   Empirical findings

In the previous section, we show that decimal pricing led to significant reductions in the spread and depth. We also find evidence that the minimum price variation was a binding constraint on spreads before decimal pricing. In addition, we find significant differences in stock attributes between the pre- and post-decimalization study periods. In this section, we first examine how the observed changes in the spread and depth are related to the proportion of one-tick spreads, the proportion of odd-sixteenth quotes, and the changes in stock attributes. We then show how much of the observed changes in the spread and depth can be attributed to these three factors.

4.1.   Spread and depth changes as a function of the binding probability and quote clustering

To assess how the relaxation of the binding constraint affected the spread and depth, we first cluster our study sample of 2,603 stocks into ten portfolios (each with an approximately equal number of stocks) according to the proportion of one-tick quoted spreads before decimalization (PQMIN_QS).[6] We then calculate the percentage changes in the quoted spread and depth within each portfolio. Similarly, we cluster our sample into ten portfolios according to the proportion of one-tick effective spreads (PQMIN_ES) and calculate the percentage changes in the effective spread within each portfolio.

We show the results in Panel A of Table 4 and Figure 2. Notice that there is a strong positive correlation between the observed reduction in the spread and depth and PQMIN_QS. For example, stocks

that belong to decile 1 experienced on average a 7.78% (11.66%) decline in the quoted dollar (proportional) spread whereas the corresponding figure for stocks that belong to decile 10 is 40.68% (44.45%). Similarly, stocks that belong to decile 1 experienced a 12.93% (16.19%) decline in the effective dollar (proportional) spread whereas the corresponding figure for stocks that belong to decile 10 is 50.65% (54.22%). For the quoted depth in dollars (round lots), we find a 3.65% (0.71%) increase (decline) for decile 1 and a 68.10% (70.20%) decline for decile 10. The magnitudes of spread and depth reductions increase almost linearly across portfolios (see Figure 2). Overall, these results are consistent with hypothesis 1.

Earlier we showed (see Section 3.2) that both PQMIN_QS and PQMIN_ES are positively related to the number of trades and trade size, and negatively to share price and return volatility. Hence, the above results suggest that high-volume, low-risk, or low-price stocks benefited most from decimal pricing.

To assess how the pre-decimalization quote coarseness affected spread and depth changes, we cluster our study sample into ten portfolios according to the proportion of odd-sixteenth quotes (PODD). We then calculate the percentage changes in the spread and depth within each portfolio. We show the results in Panel B of Table 4 and Figure 2. As in Panel A, we find a strong positive correlation between the observed reduction in the spread and depth and PODD. For example, stocks that belong to decile 1 experienced on average an 8.59% (13.15%) decline in the quoted dollar (proportional) spread whereas the corresponding figure for stocks that belong to decile 10 is 34.65% (37.62%). For the quoted depth in dollars (round lots), we find a 2.78% (7.27%) decline for decile 1 and a 49.76% (52.14%) decline for decile 10. These results indicate that stocks with coarser price grids before decimalization experienced smaller declines in the spread and depth after decimal pricing, supporting hypothesis 2.

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[6] We obtain qualitatively identical results when portfolios are formed based on PTMIN_QS. Hence we report only the results from the PQMIN_QS-based portfolios for brevity.

4.2. Regression results

Although the previous section shows that the proportions of one-tick spreads and odd-sixteenth quotes are highly correlated with spread and depth changes, there are other factors that are likely to have an impact on the spread and depth. It is also possible that the observed correlations in Table 4 may be spurious. For example, if stocks with higher quote clustering have wider spreads, the observed correlation between spread changes and PODD may simply reflect the fact that stocks with larger spreads before decimal pricing experienced greater reductions in spreads after decimalization.

To examine how the observed changes in the spread and depth can be explained by the binding constraint and quote clustering after controlling for the effects of other factors, we estimate the following regression models:

$$\Delta SPREAD_i = \alpha_0 + \sum_{k=1}^{3} \alpha_k D_k + \sum_{k=4}^{8} \alpha_k \left\{ Log\left(A_{k,i}^{Post}\right) - Log\left(A_{k,i}^{Pre}\right) \right\} + \alpha_9 PQMIN_i + \alpha_{10} SPREAD_i + \alpha_{11} PODD_i + \varepsilon_{1i}$$

$$\Delta DEPTH_i = \beta_0 + \sum_{k=1}^{3} \beta_k D_k + \sum_{k=4}^{8} \beta_k \left\{ Log\left(A_{k,i}^{Post}\right) - Log\left(A_{k,i}^{Pre}\right) \right\} + \beta_9 PQMIN_i + \beta_{10} DEPTH_i + \beta_{11} PODD_i + \varepsilon_{2i}$$

where $\Delta SPREAD_i$ and $\Delta DEPTH_i$ denote the percentage changes in the spread and depth, respectively, between the pre- and post-decimalization periods, (post value – pre value)/pre value; D_k (k = 1 to 3) is the dummy variable for each decimalization pilot; $A_{k,i}$ (k = 4 to 8) represents one of the five stock attributes– share price, the number of trades, trade size, the standard deviation of daily stock returns, and the market value of equity; $PQMIN_i$, $SPREAD_i$, $DEPTH_i$, and $PODD_i$ are the pre-decimalization values of the proportion of spreads that are equal to the minimum price variation, the spread, the depth, and the proportion of odd-sixteenth quotes, respectively; αs and βs are the regression coefficients; and ε_{1i} and ε_{2i} are the error terms. We calculate $\Delta SPREAD_i$ and $\Delta DEPTH_i$ using the proportional spread and dollar depth. Likewise, $SPREAD_i$ and $DEPTH_i$ are the pre-decimal proportional spread and dollar depth, respectively.[7]

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[7] The results using the dollar spread and share depth are qualitatively identical to those presented here.

We include $SPREAD_i$ and $DEPTH_i$ in the model to determine whether stocks with larger spreads or depths before decimalization experienced greater reductions in these variables. We include the dummy variables D_k (k = 1 to 3) in the model to determine whether decimal pricing exerted different impacts between the first three pilots and the full implementation group. According to hypothesis 1, we expect α_9 and β_9 to be significantly negative. Similarly, we expect α_{11} and β_{11} to be negative according to hypothesis 2.

We show the regression results in Table 5. The first three columns show the results when the dependent variable is the change in the quoted spread, the next three columns show the results when the dependent variable is the change in the effective spread, and the last three columns show the results when the dependent variable is the change in the quoted depth. For each dependent variable, we report the results of the three regression models.

The first model uses only the changes in the five stock attributes and three dummy variables for pilots as the explanatory variables. In this case, the estimates of α_0 measure the changes in the spread and depth that cannot be explained by concurrent changes in the five stock attributes for the full implementation group of 2,466 stocks. Similarly, $\alpha_0 + \alpha_1$, $\alpha_0 + \alpha_2$, and $\alpha_0 + \alpha_3$ measure the changes in the spread and depth that cannot be explained by the changes in the stock attributes for decimal pilots 1, 2, and 3, respectively. Because the majority (94.7%) of our sample stocks belong to the full implementation group and also because the majority of α_1, α_2, and α_3 estimates are not significantly different from zero (see below), we focus our discussion on the results of the full implementation group.[8]

In the second model, we add the proportion of spreads that are equal to the minimum price variation in the regression. In this case, the estimates of α_0 measure the changes in the spread and depth that cannot be explained by either PQMIN or the changes in stock attributes for the full implementation group. The third regression model incorporates two additional variables: the pre-decimal spread (or depth)

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[8] The signs and significance of α_1, α_2, and α_3 estimates tell us whether the effects of decimal pricing on spreads and depths differ between the full implementation and respective pilot samples.

and the proportion of odd-sixteenth quotes. In this case, the estimates of α_0 measure the changes in the spread and depth that cannot be explained by PQMIN, changes in stock attributes, the pre-decimal spread (or depth), or the proportion of odd-sixteenth quotes. We expect α_0 to be significant and negative according to the quote-rounding hypothesis.

The regression results show that a majority of the estimated coefficients for the pilot dummy variables are not significant, suggesting that decimal pricing has similar effects on the spread and depth between the pilots and the full implementation group. The results of regression model (1) indicate that a significant portion of the cross-sectional variation in spread and depth changes can be explained by the cross-sectional differences in the changes in stock attributes. For example, these stock attributes (together with pilot dummies) explain about 26% and 22% of the cross-sectional variation in the quoted and effective spread changes, respectively.

The results of regression model (2) show that the estimated coefficients for PQMIN are significant and negative in all three regressions, indicating that stocks with higher proportions of one-tick spreads experienced larger reductions in the quoted and effective spreads as well as in the quoted depth. These results are consistent with our hypothesis 1. The inclusion of PQMIN alone increased the adjusted R^2 value by 18.70%, 21.96%, and 22.28%, respectively, in each of the three regression models, reflecting the importance of the binding constraint as a possible source of larger (smaller) spreads and depths before (after) decimal pricing.

The estimated coefficients for the proportion of odd-sixteenth quotes are significant and negative in the quoted and effective spread models, respectively, indicating that stocks with higher proportions of odd-sixteenth quotes experienced larger reductions in the quoted and effective spreads.[9] The result is in line with hypothesis 2 and supports the notion that finer price grids, which became available as a result of decimal pricing, may have a greater front-running effect on stocks whose liquidity providers did not avoid

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[9] Because we include the pre-decimalization spread in the regression models, the proportion of odd-sixteenths is not likely to serve as a proxy for the pre-decimalization spread.

odd-sixteenth quotes before decimal pricing.[10] The estimated coefficient for the proportion of odd-sixteenth quotes is negative but not significant in the depth model. Hence, although decimal pricing led to greater reductions in quote depths for stocks that are likely to have a greater front-running effect, the results are not as strong as we anticipated. The estimated intercepts in regression model (3) are negative but not significant for both the quoted and effective spreads, suggesting that liquidity providers may not always round up their quotes.

The estimated coefficient for SPREAD in the quoted spread model and the estimated coefficient for DEPTH in the quoted depth model are not statistically significant, indicating that stocks with larger quoted spreads and depths before decimal pricing do not exhibit greater reduction in quoted spreads and depths after decimal pricing. We find however that the estimated coefficient for SPREAD in the effective spread model is positive and statistically significant, indicating that stocks with larger effective spreads before decimal pricing experienced smaller reductions in effective spreads after decimal pricing.

4.3.   Decomposition of the observed changes in spreads and depths

The primary focus of the previous section was how much of the inter-stock differences in spread and depth changes after decimalization can be explained by inter-stock differences in the proportion of one-tick spreads, the proportion of odd-sixteenth quotes, and changes in stock attributes. In this section, we analyse how much of the observed changes in the spread and depth *in aggregate* can be attributed to the different factors.

Table 5 shows that the estimated intercept in the quoted spread model is -0.2080 when we include only pilot dummies and changes in stock attributes in the regression model. Because the mean percentage change in the quoted spread is -0.2781 for the full implementation group, the spread change that can be attributed to the changes in stocks attributes is -0.0701 [i.e., -0.2781 – (-0.2080)].   Hence, about 25.21%

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[10] This result differs from the finding of Bessembinder (2000) for Nasdaq stocks that a smaller tick size led to the largest spread reductions for stocks whose market makers avoided odd-eighth quotes.

(-0.0701/-0.2781) of the observed change in the quoted spread can be attributed to the changes in stock attributes for the full implementation group.

Next, note that the estimated intercept is -0.0914 when we add the proportion of one-tick spreads to the regression model. Using the same logic, we find that about 41.93% [i.e., {-0.2080 – (-0.0914)}/-0.2781] of the observed change in the quoted spread can be attributed to the relaxation of the binding constraint. Finally, note that the intercept is not significantly different from zero when the spread and the proportion of odd-sixteenth quotes are added to the regression model. Because the coefficient for the spread is also not significantly different from zero, we conclude that about 32.87% [i.e., -0.0914/-0.2781] of the observed change in the quoted spread can be attributed to greater front running and price competition after decimal pricing. We summarize these results in Table 6.

Table 6 also shows the decomposition of the observed changes in the effective spread and quoted depth using the same approach. For expositional clarity, we put zero rather than report the estimated figures whenever the estimated intercept is not statistically different from zero. The results show that 18.43% and 56.11% of the observed reduction in the effective spread can be attributed to changes in stock attributes and the relaxation of the binding constraint, respectively. The remaining 25.46% of the observed decline can be attributed to the pre-decimal spread and the proportion of odd-sixteenth quotes. Similarly, 16.63% and 83.37% of the observed decline in the quoted depth can be attributed to the changes in stock attributes and the relaxation of the binding constraint. Because the intercepts in depth models 2 and 3 are not significantly different from zero (see Table 5), a further breakdown of the observed change in the depth is not meaningful.

4.4.   Sensitivity analysis: alternative measures of front running and price competition

Although our empirical proxy (PODD) for front running and price competition has an expected effect on both quoted and effective spreads, PODD is likely to be an imperfect proxy for the extent of

front running and price competition. To assess the sensitivity of our results to different empirical proxies, we employ alternative measures of front running and price competition. Harris and Panchapagesan (1999) and Ronen and Weaver (2001) suggest that active stocks and higher-price stocks are expected to experience larger decreases in spreads following the tick size reduction, especially if the level of price competition among traders is inversely related to the tick size. To test this conjecture with our data, we replicate Table 5 with the pre-decimal share price (PRICE) and number of trades (NT) in the regression models and show the results in Table 7. In regression model (1), we employ PRICE as our empirical proxy for front running and price competition. Regression model (2) employs PRICE and NT, while regression model (3) employs all three variables (PRICE, NT, and PODD) as empirical proxies for front running and price competition.

Table 7 shows that changes in quoted spreads are negatively related to PRICE, NT, and PODD, although the coefficient for PRICE becomes insignificant when the other two variables are also included in the regression. Hence, stocks with higher activity and/or coarser price grids before decimal pricing experienced larger reductions in quoted spreads after decimalization. These results are in line with the idea that decimal pricing exerted a greater impact on price competition and front running for stocks with more active trading and coarser price grids before decimalization. Similarly, we find that changes in effective spreads are negatively and significantly related to PRICE, NT, and PODD. Finally, the results show that decimal pricing led to larger reductions in quoted depths for more active stocks. Overall, these results support the view that the effect of the tick size reduction on front running and price competition is greater for stocks where the competition between specialists and limit order traders is more intense.

4.5.   Intraday variation in spread and depth reductions

In this section, we provide further evidence regarding the effect of the binding constraint on the spread and depth using intraday data. In so far as the proportion of one-tick spreads varies across different

times of the day, the spread and depth changes that resulted from decimal pricing are also likely to vary over time. That is, we anticipate larger reductions in the spread and depth when the proportion of one-tick spreads was higher before decimal pricing.

We partition each trading day into thirteen 30-minute intervals and calculate the proportion of one-tick spreads for each stock based on both the quoted and effective spreads during each time interval. Similarly, we calculate percentage changes in the spread and depth during each time interval. We then compute the mean values of these variables across stocks during each 30-minute interval. Table 8 shows the mean values of the proportion of one-tick spreads and the changes in the spread and depth for each time interval.

The results show that proportions of one-tick quoted and effective spreads are smallest during the first 30-minutes of trading and then increase steadily throughout the trading day. Similarly, we find that percentage declines in the spread and depth are largest during the first interval, increase steadily until midday, and then level off thereafter. The smallest spread and depth reductions and the least use of one-tick spreads near the open suggest that the tick size is least likely to be the binding constraint on spread widths during this period and, consequently, the reduced tick size yields a smaller impact on the spread and depth. This result is consistent with the well known empirical regularity reported in previous studies that the spread is widest near the open on the NYSE (see, e.g., McInish and Wood, 1992; Chung, Van Ness, and Van Ness, 1999). As time elapses and the spread narrows, the minimum price variation becomes a binding constraint more frequently, and thus the reduced tick size exerts a greater impact on the spread and depth.

To assess the strength of the inter-temporal correlation between the proportion of one-tick spreads and the magnitudes of spread and depth changes, we produce the plots between the two variables (see Figure 3). Plot A shows the relation between the proportion of one-tick quoted spreads and the change in the quoted spread, plot B shows the relation between the proportion of one-tick quoted spreads and the

change in the quoted depth, and plot C shows the relation between the proportion of one-tick effective spreads and the change in the effective spread. In all three plots, we find a strong correlation between the two metrics. Indeed, when we regress the changes in the spread and depth against the proportion of one-tick spreads using the 30-minute mean values of these variables, we find that the adjusted R^2 ranges from 0.6635 (in the effective spread model) to 0.95 (in the quoted spread model). Overall, these results confirm our earlier finding that the pre-decimal pricing tick size was indeed a significant binding constraint on liquidity providers' quote decisions.

5.   Is the penny tick size a binding constraint for some stocks?

In light of a recent debate among regulatory authorities and the investment community on whether decimal pricing provides liquidity suppliers with sufficient freedom in the quote-setting process, this section assesses the extent of the binding constraint under the penny-tick environment. In its response to the Securities and Exchange Commission (SEC)'s Concept Release on Sub-penny Trading, Island–an Electronic Communications Network (ECN) currently operating within the Nasdaq market–casts serious doubt on the adequacy of penny tick increments.[11]

Island accounts for more than one of every five trades on Nasdaq and approximately 40% of the orders submitted and 35% of the executions on Island occur in sub-penny increments. Island currently accepts orders priced out to three decimal places.[12] Island argues that its continued growth casts significant doubt on the claims that sub-penny increments would cause investor confusion and harm transparency. Island holds that sub-penny increments provide an opportunity to lower transaction costs and bring further efficiencies to the market. Island advocates that the SEC should not only continue to

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[11] Source: A letter addressed to Jonathan Katz, Secretary, U.S. Securities and Exchange Commissions by Cameron Smith, General Counsel, December 18, 2001.

[12] ECNs have been offering sub-penny trading even before decimalization. Prior to decimalization, ECNs traded in increments of 1/256th or $0.0039. In Singapore, small-priced stocks currently trade in ticks of S$0.005, which is equivalent to US$0.0028. On a 1,000 share order, the third decimal place can be worth anywhere from $1 to $9.

permit sub-penny trading but should also move forward expeditiously in requiring quotations of at least three decimal places in the publicly disseminated quotation. In the present section, we shed some light on this debate by examining whether the penny tick size is a binding constraint on spread widths using our sample of NYSE stocks.

To assess whether the penny tick size is a binding constraint after full implementation of decimal pricing, we calculate the proportions of quoted and effective spreads that are equal to one penny (PQMIN_QS and PQMIN_ES) as well as the proportion of trading time during which the quoted spread is one penny (PTMIN_QS). Panel A of Table 9 shows the descriptive statistics of these metrics. Not surprisingly, the mean values (6.98%, 6.73%, and 13.79%) of these variables are much smaller than the corresponding figures (31.40%, 32.3%, and 44.16%) for the pre-decimalization study period, indicating that the penny tick is much less a binding constraint than the $1/16 tick on spread widths. Nevertheless, the results suggest that the penny tick may still be a binding constraint for a certain group of stocks. Notice that about 10% of our study sample (260 stocks) have PQMIN_QS, PQMIN_ES, and PTMIN_QS values that are greater than 0.14.[13]

To determine which stocks are more likely to find the penny tick size a binding constraint, we regress PQMIN_QS, PTMIN_QS, and PQMIN_ES on a common set of stock attributes and report the results in Panel B of Table 9. As in Table 3 with the pre-decimalization data, we find that these variables are significantly and positively related to the number of trades and trade size, and negatively to share price and return volatility. These results suggest that sub-penny pricing may further reduce the spreads of high-volume, low-risk, or low-price stocks.

Although we find some evidence of a penny-tick binding constraint, it is unclear whether sub-penny pricing would lead to an unambiguous increase in market quality and investor welfare due to its

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Given that investors change on-line brokers to save a few dollars on a trade, it is doubtful that $9 is irrelevant to investors.
[13] These stocks are likely to account for a much larger (than 10%) proportion of the total market trading volume because they are (as shown below) typically large-volume stocks.

possible costs. For example, sub-penny increments may lead to investor confusion, smaller displayed depths due to front running concerns, higher administrative costs due to multiple executions at multiple prices for a given trade, and technological backlog.[14] The accurate quantification of the costs and benefits of sub-penny pricing is likely to be difficult and well beyond the scope of this paper. Suffice it to say that the results of this study should alert regulators and the investment community that the desirability of a further reduction in tick size deserves careful and full consideration.

6.   Summary and concluding remarks

Extant theories put forward several inferences on how decimal pricing may affect market quality and execution costs. Theory predicts that the smaller tick size lowers the likelihood that the tick size is the binding constraint on spread widths and thus reduces the bid-ask spread. The narrower spread in turn leads to a smaller depth because liquidity providers are less willing to commit large depths when trading profits are lower. The market depth may further drop because the increased probability of front running discourages public traders to display their interests. As more traders are likely to step in front of existing orders due to the lower cost of front running, the spread may also further decline. In this study, we provide empirical evidence on how much of the observed changes in the spread and depth after decimal pricing can be attributed to these different factors.

We show that stocks with higher proportions of one-tick spreads before decimal pricing experienced larger reductions in the spread and depth. In addition, we find that stocks with higher proportions of odd-sixteenth quotes and greater trading frequency before decimalization exhibited larger reductions in the spread and depth after decimal pricing. We interpret these results as evidence that both the relaxation of the binding constraint and the increased front running and price competition exerted a significant impact on the spread and depth. Our results also indicate that a significant portion of the

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[14] Some commentators have expressed concerns that sub-penny trading would strain capacity limits of both market participants and market data vendors.

observed changes in the spread and depth can be attributed to the concurrent changes in stock attributes after decimal pricing.

Some caveats are in order. In this study, we measure the binding-constraint and front-running probabilities by the pre-decimalization proportions of one-tick spreads and odd-sixteenth quotes (and number of trades), respectively. In so far as these are imperfect proxies of respective probabilities, our empirical results are open to alternative interpretations. Our study utilizes trade and quote data during 30 trading days before and after decimal pricing. Hence, the results of our study do not capture any long-term effects of decimal pricing. To the extent that market participants need some adjustment time to fully assimilate themselves to decimal environments, our results may not capture the full impact of decimal pricing. For example, although our results suggest that spreads became narrower as a result of the increased front running, they might become wider in the long term if traders reduce the use of limit orders. Due to limited data availability, our study relied on the quoted depth only at the inside market. Because decimal pricing can affect the entire limit order book, a more accurate account of the effect of decimal pricing on liquidity would require an analysis of how the depth has been affected throughout the limit order book. Further investigations of these issues may be a fruitful area for future research.

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Table 1
Descriptive statistics before and after decimalization
This table shows select attributes of the study sample of stocks during the pre- and post-decimalization study periods for each pilot as well as the full implementation group. We measure share price by the average daily closing quote midpoint and return volatility by the standard deviation of daily returns calculated from the daily closing quote midpoints. The table also reports the results of paired comparison t-tests on the mean absolute and mean relative differences in stock attributes between the pre- and post-decimalization study periods. The mean absolute difference is simply the mean difference in the stock attribute between the pre- and post-decimalization study periods. The mean relative difference is the cross-sectional mean of the ratio of the absolute difference to the pre-decimalization value of the stock attribute. N denotes the sample size.

	Before decimalization			After decimalization			Mean difference			
	Mean	Median	S.D.	Mean	Median	S.D.	Absolute	t-statistic	Relative	t-statistic
Panel A: August 28, 2000 Pilot (N = 7)										
Number of trades	229	39	270	274	42	319	45	2.32	0.3538	2.93[*]
Trade size ($1,000)	53.63	14.93	60.30	62.43	18.90	68.58	8.80	2.73[*]	0.2129	3.29[*]
Share price	36.50	37.32	17.56	38.19	37.11	19.3528	1.69	0.92	0.0389	1.15
Return volatility	0.0193	0.0184	0.0058	0.0240	0.0218	0.0163	0.0047	1.02	0.1592	0.77
Market value of equity ($ million)	6,056	689	7,664	6,954	705	8,339	898	0.90	0.1112	1.06
Panel B: September 25, 2000 Pilot (N = 49)										
Number of trades	245	69	439	302	99	511	58	3.30[**]	0.3104	5.74[**]
Trade size ($1,000)	52.48	35.73	46.77	50.94	32.85	52.44	−1.536	−0.53	−0.0430	−1.11
Share price	48.51	28.86	72.35	39.76	29.13	36.85	−8.75	−1.39	−0.0660	−3.35[**]
Return volatility	0.0212	0.0184	0.0141	0.0328	0.0278	0.0277	0.0116	2.88[**]	0.7261	3.34[**]
Market value of equity ($ million)	9,318	1,020	24,442	8,902	901	22,899	−415	−1.47	−0.0479	−3.30[**]
Panel C: December 4, 2000 Pilot (N = 81)										
Number of trades	161	35	312	198	53	337	37	5.96[**]	0.4587	10.35[**]
Trade size ($1,000)	30.42	17.64	33.03	30.16	16.72	35.68	−0.263	−0.16	0.0154	0.42
Share price	18.49	13.48	14.15	18.94	14.07	14.69	0.45	1.84	0.0070	0.49
Return volatility	0.0267	0.0231	0.0165	0.0292	0.0268	0.0169	0.0025	1.95	0.2341	4.24[**]
Market value of equity ($ million)	3,529	368	11,042	3,483	396	10,703	−46	−0.58	−0.0040	−0.25
Panel D: January 29, 2001 Full (N = 2,466)										
Number of trades	195	59	360	210	61	369	15	11.34[**]	0.0664	8.71[**]
Trade size ($1,000)	35.18	22.24	37.06	30.87	19.27	35.09	−4.310	−10.61[**]	−0.0530	−3.03[**]
Share price	23.99	17.87	23.35	24.55	19.02	23.14	0.56	8.58[**]	0.0602	13.55[**]
Return volatility	0.0321	0.0272	0.0249	0.0243	0.0203	0.0350	−0.0078	−10.53[**]	−0.1912	−13.50[**]
Market value of equity ($ million)	4,578	518	20,825	4,533	549	20,421	−45	−0.92	0.0650	13.01[**]

[**] and [*] Statistically significant at the 1% and 5% levels, respectively.

Table 2
Spreads and depths before and after decimalization
For each stock we first calculate the time-weighted quoted spread, the trade-weighted effective spread, and the time-weighted quoted depth during the pre- and post-decimalization study periods, respectively. We calculate both the dollar and proportional quoted and effective spreads and the depth in dollars and in round lots. We then calculate the cross-sectional means of these variables during each period. The table also reports the results of paired t-tests on the equality of the mean between the two periods. N denotes the sample size.

	Before decimalization			After decimalization			Mean difference			
	Mean	Median	S.D.	Mean	Median	S.D.	Absolute	t-statistic	Relative	t-statistic
Panel A: August 28, 2000 Pilot (N = 7)										
Quoted spread ($)	0.2071	0.1646	0.1126	0.1360	0.1215	0.0548	−0.0712	−3.13*	−0.3081	−7.39**
Quoted spread (%)	0.0078	0.0084	0.0059	0.0050	0.0054	0.0038	−0.0028	−3.29*	−0.3320	−7.50**
Effective spread ($)	0.1244	0.0884	0.0811	0.0741	0.0475	0.0460	−0.0503	−3.69*	−0.3998	−15.93**
Effective spread (%)	0.0047	0.0045	0.0039	0.0028	0.0023	0.0025	−0.0019	−3.55*	−0.4191	−15.28**
Quoted depth ($1,000)	212	63	241	138	66	132	−74	−1.76	−0.0107	−0.07
Quoted depth (round lots)	49	39	41	33	39	18	−16	−1.63	−0.0309	−0.19
Panel B: September 25, 2000 Pilot (N = 49)										
Quoted spread ($)	0.2007	0.1460	0.2789	0.1485	0.1204	0.1205	−0.0522	−2.13*	−0.1968	−7.47**
Quoted spread (%)	0.0068	0.0051	0.0052	0.0059	0.0042	0.0048	−0.0009	−2.96**	−0.1271	−4.59**
Effective spread ($)	0.1163	0.0839	0.1220	0.0808	0.0719	0.0587	−0.0355	−3.30**	−0.2872	−9.65**
Effective spread (%)	0.0044	0.0029	0.0036	0.0035	0.0020	0.0031	−0.0009	−3.81**	−0.2261	−7.22**
Quoted depth ($1,000)	376	186	578	186	122	247	−189	−3.53**	−0.3604	−9.74**
Quoted depth (round lots)	138	59	257	61	37	79	−77	−2.94**	−0.3075	−7.73**
Panel C: December 4, 2000 Pilot (N = 82)										
Quoted spread ($)	0.1523	0.1321	0.0717	0.1177	0.1028	0.0681	−0.0346	−13.29**	−0.2452	−13.39**
Quoted spread (%)	0.0163	0.0101	0.0199	0.0125	0.0080	0.0139	−0.0038	−4.09**	−0.2385	−11.06**
Effective spread ($)	0.0926	0.0825	0.0355	0.0644	0.0534	0.0425	−0.0283	−15.38**	−0.3440	−15.91**
Effective spread (%)	0.0104	0.0064	0.0130	0.0072	0.0045	0.0083	−0.0033	−4.95**	−0.3380	−14.24**
Quoted depth ($1,000)	187	91	234	86	70	73	−100	−4.83**	−0.3174	−8.32**
Quoted depth (round lots)	135	70	243	56	48	37	−79	−3.26**	−0.3141	−8.05**
Panel D: January 29, 2001 Full (N = 2,466)										
Quoted spread ($)	0.1621	0.1339	0.1445	0.1301	0.1001	0.1480	−0.0320	−26.30**	−0.2412	−62.79**
Quoted spread (%)	0.0132	0.0081	0.0168	0.0097	0.0055	0.0134	−0.0034	−26.25**	−0.2781	−74.46**
Effective spread ($)	0.0979	0.0784	0.0935	0.0688	0.0490	0.0909	−0.0290	−38.10**	−0.3529	−83.94**
Effective spread (%)	0.0084	0.0051	0.0111	0.0054	0.0029	0.0078	−0.0029	−27.72**	−0.3846	−94.97**
Quoted depth ($1,000)	223	114	614	104	71	140	−118	−11.79**	−0.3138	−41.35**
Quoted depth (round lots)	140	64	510	55	39	94	−85	−9.83**	−0.3490	−49.78**

** and * Statistically significant at the 1% and 5% levels, respectively.

Table 3
Determinants of the proportion of one-tick spreads during the pre-decimalization period
We measure the probability that the minimum price variation is a binding constraint on spread widths by the proportion of quoted spreads that are equal to $1/16 (PQMIN_QS) during the pre-decimalization study period. To assess the sensitivity of our results to different measurement methods, we also calculate the proportion of trading time during which the quoted spread is equal to $1/16 (PTMIN_QS). In addition, we calculate the proportion of effective spreads that are equal to one tick (PQMIN_ES). Panel A reports the descriptive statistics of the three measures of the binding constraints. Panel B presents the regression results showing how these variables are related to stock attributes (share price, number of trades, trade size, return volatility, and market value of equity). To determine whether the relation between the proportion of one-tick spreads and stock attributes differs across decimalization implementation groups, we include three pilot dummy variables in the regressions. Numbers in parenthesis are t-statistics. N denotes the sample size.

Panel A: Descriptive statistics				Panel B: Regression results			
	PQMIN_QS	PTMIN_QS	PQMIN_ES	Variable	PQMIN_QS	PTMIN_QS	PQMIN_ES
				Intercept	−0.3289	−0.3536	−0.1797
Mean	0.3140	0.3230	0.4416		(−21.31)**	(−22.19)**	(−12.11)*
Standard deviation	0.1959	0.2094	0.1839	Pilot 1 dummy	−0.0186	−0.0257	−0.0279
					(−0.47)	(−0.59)	(−0.74)
Minimum	0.0000	0.0000	0.0000	Pilot 2 dummy	0.0287	0.0268	0.0058
1st percentile	0.0030	0.0002	0.0243		(1.90)	(1.61)	(0.40)
5th percentile	0.0310	0.0241	0.1142	Pilot 3 dummy	−0.0218	−0.0208	−0.0243
10th percentile	0.0654	0.0585	0.1852		(−1.85)	(−1.60)	(−2.15)*
25th percentile	0.1614	0.1535	0.3178	Log(share price)	−0.2323	−0.2416	−0.2038
50th percentile	0.3005	0.3053	0.4523		(−63.42)**	(−59.79)**	(−57.87)**
75th percentile	0.4358	0.4602	0.5619	Log(number of trades)	0.1231	0.1339	0.1239
90th percentile	0.5780	0.6141	0.6630		(35.69)**	(35.19)**	(37.37)**
95th percentile	0.6737	0.7142	0.7398	Log(trade size)	0.0639	0.0678	0.0328
99th percentile	0.8462	0.8606	0.8779		(13.91)**	(13.39)**	(7.43)**
Maximum	0.9744	0.9729	0.9840	Log(return volatility)	−0.1747	−0.1891	−0.1695
					(−42.75)**	(−41.96)**	(−43.16)**
N	2603	2603	2603	Log(market value of equity)	−0.0070	−0.0110	−0.0052
					(−2.43)*	(−3.46)**	(−1.88)
				F–statistic	831.02**	760.28**	777.42**
				Adjusted R^2	0.7185	0.7001	0.7048

** and * Statistically significant at the 1% and 5% levels, respectively.

Table 4
Changes in the spread and depth and the proportions of one-tick spreads and odd-sixteenth quotes
To assess how the relaxation of the binding constraint affected spreads and depth, we first cluster our study sample of 2,603 stocks into ten portfolios according to PQMIN (PQMIN_QS for the quoted spread and depth and PQMIN_ES for the effective spread). We then calculate the mean percentage changes in the quoted spread, effective spread, and depth within each portfolio. To assess how the pre-decimalization quote coarseness affected spread and depth changes, we also cluster our study sample into ten portfolios according to the proportion of odd-sixteenth quotes (PODD) and calculate mean percentage spread and depth changes within each portfolio. In each cell, we report the mean percentage change in the variable (Δvariable) and the corresponding t-statistic. Each portfolio contains 260 or 261 stocks.

Deciles	1 (Smallest)	2	3	4	5	6	7	8	9	10 (Largest)
Panel A: Deciles are based on the proportion of one-tick spreads (PQMIN_QS or PQMIN_ES)										
ΔQuoted spread ($)	−0.0778	−0.1601	−0.1828	−0.2215	−0.2238	−0.2613	−0.2709	−0.2863	−0.3149	−0.4068
	(−5.10)**	(−14.08)**	(−15.66)**	(−23.94)**	(−27.10)**	(−30.98)**	(−30.79)**	(−31.66)**	(−28.94)**	(−39.95)**
ΔQuoted spread (%)	−0.1166	−0.1786	−0.2183	−0.2401	−0.2531	−0.2900	−0.3108	−0.3234	−0.3659	−0.4445
	(−8.66)**	(−14.97)**	(−20.09)**	(−24.72)**	(−29.69)**	(−32.78)**	(−33.76)**	(−34.63)**	(−42.02)**	(−43.67)**
ΔEffective spread ($)	−0.1293	−0.2366	−0.2753	−0.3320	−0.3468	−0.4079	−0.4210	−0.4251	−0.4350	−0.5065
	(−8.02)**	(−17.60)**	(−23.40)**	(−32.04)**	(−32.64)**	(−43.99)**	(−48.66)**	(−47.89)**	(−41.70)**	(−53.75)**
ΔEffective spread (%)	−0.1619	−0.2651	−0.3004	−0.3513	−0.3712	−0.4302	−0.4547	−0.4520	−0.4736	−0.5422
	(−10.83)**	(−20.91)**	(−26.13)**	(−33.36)**	(−37.22)**	(−47.44)**	(−52.14)**	(−49.07)**	(−54.12)**	(−56.94)**
ΔQuoted depth ($)	0.0365	−0.0934	−0.1639	−0.2536	−0.2888	−0.3486	−0.3974	−0.4379	−0.5113	−0.6810
	(1.45)	(−3.72)**	(−4.54)**	(−16.52)**	(−19.75)**	(−22.99)**	(−31.68)**	(−30.44)**	(−38.72)**	(−72.08)**
ΔQuoted depth (#)	−0.0071	−0.1171	−0.2035	−0.2763	−0.3200	−0.3806	−0.4378	−0.4721	−0.5465	−0.7020
	(−0.30)	(−5.00)**	(−6.49)**	(−20.01)**	(−23.39)**	(−27.57)**	(−42.01)**	(−35.60)**	(−44.83)**	(−78.72)**
Panel B: Deciles are based on the proportion of odd-sixteenth quotes (PODD)										
ΔQuoted spread ($)	−0.0859	−0.1375	−0.1810	−0.2273	−0.2175	−0.2717	−0.2855	−0.3113	−0.3419	−0.3465
	(−5.64)**	(−12.25)**	(−16.50)**	(−22.81)**	(−19.20)**	(−30.90)**	(−34.93)**	(−36.48)**	(−39.75)**	(−30.58)**
ΔQuoted spread (%)	−0.1315	−0.1741	−0.2072	−0.2628	−0.2579	−0.3004	−0.3144	−0.3405	−0.3764	−0.3762
	(−10.00)**	(−14.62)**	(−18.36)**	(−25.11)**	(−26.01)**	(−32.76)**	(−34.63)**	(−40.12)**	(−40.57)**	(−32.88)**
ΔEffective spread ($)	−0.1329	−0.2297	−0.2819	−0.3411	−0.3504	−0.3939	−0.4217	−0.4438	−0.4777	−0.4423
	(−8.37)**	(−19.38)**	(−23.18)**	(−32.22)**	(−29.43)**	(−44.61)**	(−41.38)**	(−50.44)**	(−57.43)**	(−37.75)**
ΔEffective spread (%)	−0.1754	−0.2638	−0.3067	−0.3724	−0.3840	−0.4165	−0.4453	−0.4672	−0.5046	−0.4668
	(−11.93)**	(−22.23)**	(−25.83)**	(−34.98)**	(−35.28)**	(−44.42)**	(−43.22)**	(−53.46)**	(−58.21)**	(−39.96)**
ΔQuoted depth ($)	−0.0278	−0.1563	−0.2010	−0.2183	−0.3145	−0.3663	−0.3977	−0.4732	−0.4864	−0.4976
	(−1.21)	(−8.20)**	(−11.47)**	(−5.53)**	(−20.05)**	(−18.63)**	(−25.92)**	(−41.31)**	(−25.34)**	(−24.69)**
ΔQuoted depth (#)	−0.0727	−0.1907	−0.2298	−0.2631	−0.3492	−0.3982	−0.4269	−0.4948	−0.5159	−0.5214
	(−3.25)**	(−10.20)**	(−13.68)**	(−7.68)**	(−23.42)**	(−23.54)**	(−29.70)**	(−43.75)**	(−28.37)**	(−27.06)**

** and * Statistically significant at the 1% and 5% levels, respectively.

Table 5
Determinants of the changes in the spread and depth

To examine how the observed changes in spreads and depths can be explained by the binding constraint together with these other factors, we estimate the following regression models:

$$\Delta SPREAD_i = \alpha_0 + \sum_{k=1}^{3} \alpha_k D_k + \sum_{k=4}^{8} \alpha_k \left\{ Log\left(A_{k,i}^{\text{Post}}\right) - Log\left(A_{k,i}^{\text{Pre}}\right) \right\} + \alpha_9 PQMIN_i + \alpha_{10} SPREAD_i + \alpha_{11} PODD_i + \varepsilon_{1i}$$

$$\Delta DEPTH_i = \beta_0 + \sum_{k=1}^{3} \beta_k D_k + \sum_{k=4}^{8} \beta_k \left\{ Log\left(A_{k,i}^{\text{Post}}\right) - Log\left(A_{k,i}^{\text{Pre}}\right) \right\} + \beta_9 PQMIN_i + \beta_{10} DEPTH_i + \beta_{11} PODD_i + \varepsilon_{2i}$$

where $\Delta SPREAD_i$ and $\Delta DEPTH_i$ denote the percentage change in the spread and depth, respectively, between the pre- and post-decimalization periods, (post value − pre value)/pre value; D_k (k = 1 to 3) is the dummy variable for each decimalization pilot; $A_{k,i}$ (k = 4 to 8) represents one of the five stock attributes–share price, the number of trades, trade size, the standard deviation of daily stock returns, and the market value of equity; $PQMIN_i$, $SPREAD_i$, $DEPTH_i$, and $PODD_i$ are the pre-decimalization values of the proportion of spreads that are equal to the minimum price variation, the spread, the depth, and the proportion of odd sixteenth quotes, respectively; αs and βs are the regression coefficients; and ε_{1i} and ε_{2i} are the error terms. We calculate $\Delta SPREAD_i$ and $\Delta DEPTH_i$ using the proportional spread and dollar depth. Likewise, $SPREAD_i$ and $DEPTH_i$ are the pre-decimal proportional spread and dollar depth, respectively. We include $SPREAD_i$ and $DEPTH_i$ in the model to determine whether stocks with larger spreads or depths before decimalization experienced greater reduction in these variables. We include the dummy variables D_k (k = 1 to 3) in the model to determine whether decimal pricing exerted different impacts between the first three pilots and the full implementation group. Numbers in parenthesis are t-statistics.

Independent variable	Change in quoted spread			Change in effective spread			Change in depth		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Intercept	−0.2080	−0.0914	−0.0224	−0.3137	−0.0979	−0.0262	−0.2616	−0.0067	0.0406
	(−47.29)**	(−16.72)**	(−1.42)	(−63.96)**	(−12.33)**	(−1.57)	(−27.88)**	(−0.58)	(1.28)
Pilot 1 dummy	−0.0635	−0.0918	−0.0858	−0.0450	−0.0832	−0.0707	0.1693	0.1073	0.1147
	(−1.04)	(−1.74)	(−1.64)	(−0.66)	(−1.44)	(−1.24)	(1.30)	(0.96)	(1.03)
Pilot 2 dummy	0.0477	0.0670	0.0630	0.0698	0.0797	0.0770	−0.0558	−0.0137	−0.0123
	(2.00)*	(3.25)**	(3.07)**	(2.63)**	(3.54)**	(3.45)**	(−1.10)	(−0.31)	(−0.28)
Pilot 3 dummy	0.0165	0.0325	0.0272	0.0320	0.0460	0.0341	−0.0454	-0.0105	−0.0139
	(0.89)	(2.02)	(1.69)	(1.54)	(2.61)**	(1.95)	(−1.14)	(−0.31)	(−0.41)
ΔLog(share price)	−0.3737	−0.2980	−0.3049	−0.2725	−0.1816	−0.2120	0.1202	0.2855	0.2722
	(−13.64)**	(−12.51)**	(−12.57)**	(−8.92)**	(−6.97)**	(−8.04)**	(2.06)*	(5.67)**	(5.37)**
ΔLog(number of trades)	−0.1939	−0.1740	−0.1680	−0.2188	−0.1837	−0.1679	0.0056	0.0492	0.0538
	(−17.77)**	(−18.40)**	(−17.12)**	(−17.98)**	(−17.71)**	(−15.71)**	(0.24)	(2.46)*	(2.67)**
ΔLog(trade size)	0.0227	−0.0368	-0.0398	0.0575	−0.0151	−0.0183	0.4476	0.3176	0.3158
	(2.26)*	(−4.14)**	(-4.49)**	(5.15)**	(−1.55)	(−1.90)	(20.95)**	(16.90)**	(16.78)**
ΔLog(return volatility)	0.1391	0.1207	0.1183	0.1379	0.1142	0.1089	-0.0038	−0.0440	−0.0497
	(19.08)**	(19.07)**	(18.61)**	(16.97)**	(16.49)**	(15.76)**	(-0.25)	(−3.29)**	(−3.65)**
ΔLog(market value of equity)	−0.0419	−0.0310	−0.0313	−0.0758	−0.0644	−0.0650	−0.0763	−0.0525	−0.0527
	(−3.38)**	(−2.89)**	(−2.94)**	(−5.49)**	(−5.50)**	(−5.61)**	(−2.89)**	(−2.32)*	(−2.33)*
Proportion of one-tick spreads (PQMIN)	–	−0.4277	−0.3690	–	−0.5379	−0.4329	–	−0.9351	−0.8736
		(−29.67)**	(−19.91)**		(−31.90)**	(−17.85)**		(−30.67)**	(−21.08)**
SPREAD or DEPTH	–	–	0.0278	–	–	1.0104	–	–	−1.87x10⁻⁵
			(0.16)			(3.52)**			(−1.80)
Proportion of odd sixteenths (PODD)	–	–	−0.2120	–	–	−0.3045	–	–	−0.1529
			(−4.93)**			(−5.80)**			(−1.69)
F-statistic	116.03**	235.89**	193.69**	92.78**	227.87**	195.26**	63.77**	181.72**	149.39**
Adjusted R²	0.2613	0.4483	0.4489	0.2201	0.4397	0.4509	0.1618	0.3846	0.3855

** and * Statistically significant at the 1% and 5% levels, respectively.

Table 6
Components of spread and depth reductions
This table shows how much of the observed changes in the spread and depth can be attributed to the proportion of one-tick spreads, the proportion of odd-sixteenth quotes, and the changes in stock attributes. Changes in the quoted spread, effective spread, and depth are the relative % changes with respect to the pre-decimalization level.

Decomposition of the observed changes	Change in quoted spread		Change in effective spread		Change in depth	
	Absolute	Proportion	Absolute	Proportion	Absolute	Proportion
(i) Total reduction (the full implementation mean)	-0.2781	100.00%	-0.3846	100.00%	-0.3138	100.00%
(ii) Model (1) intercept	-0.2080		-0.3137		-0.2616	
(iii) Reduction due to stock attributes, (i) – (ii)	-0.0701	25.21%	-0.0709	18.43%	-0.0522	16.63%
(iv) Model (2) intercept	-0.0914		-0.0979		0.0000	
(v) Reduction due to the binding constraint, (ii) – (iv)	-0.1166	41.93%	-0.2158	56.11%	-0.2616	83.37%
(vi) Model (3) intercept	0.0000		0.0000		0.0000	
(vii) Reduction due to front running and the pre-decimal spread, (i) - (iii) – (v)	-0.0914	32.87%	-0.0979	24.46%	0.0000	0.00%

Table 7
Regression results with alternative measures of front running and price competition

To examine how the observed changes in spreads and depths can be explained by the binding constraint together with these other factors, we estimate the following regression models:

$$\Delta SPREAD_i = \alpha_0 + \sum_{k=1}^{3} \alpha_k D_k + \sum_{k=4}^{8} \alpha_k \left\{ Log\left(A_{k,i}^{\text{Post}}\right) - Log\left(A_{k,i}^{\text{Pre}}\right) \right\} + \alpha_9 PQMIN_i + \alpha_{10} SPREAD_i + \alpha_{11} PRICE_i + \alpha_{12} NT_i + \alpha_{13} PODD_i + \varepsilon_{1i}$$

$$\Delta DEPTH_i = \beta_0 + \sum_{k=1}^{3} \beta_k D_k + \sum_{k=4}^{8} \beta_k \left\{ Log\left(A_{k,i}^{\text{Post}}\right) - Log\left(A_{k,i}^{\text{Pre}}\right) \right\} + \beta_9 PQMIN_i + \beta_{10} DEPTH_i + \beta_{11} PRICE_i + \beta_{12} NT_i + \beta_{13} PODD_i + \varepsilon_{2i}$$

where $\Delta SPREAD_i$ and $\Delta DEPTH_i$ denote the percentage change in the spread and depth, respectively, between the pre- and post-decimalization periods, (post value − pre value)/pre value; D_k (k = 1 to 3) is the dummy variable for each decimalization pilot; $A_{k,i}$ (k = 4 to 8) represents one of the five stock attributes–share price, the number of trades, trade size, the standard deviation of daily stock returns, and the market value of equity; $PQMIN_i$, $SPREAD_i$, $DEPTH_i$, PRICE, NT, and $PODD_i$ are the pre-decimalization values of the proportion of spreads that are equal to the minimum price variation, the spread, the depth, share price, the number of trades, and the proportion of odd sixteenth quotes, respectively; αs and βs are the regression coefficients; and ε_{1i} and ε_{2i} are the error terms. We calculate $\Delta SPREAD_i$ and $\Delta DEPTH_i$ using the proportional spread and dollar depth. Numbers in parenthesis are t-statistics.

Independent variable	Change in quoted spread			Change in effective spread			Change in depth		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Intercept	-0.0708	-0.0758	-0.0145	-0.0702	-0.0811	-0.0218	0.0220	0.0142	0.0400
	(-8.97)**	(-9.67)**	(-0.89)	(-6.93)**	(-8.14)**	(-1.27)	(1.53)	(0.98)	(1.24)
Pilot 1 dummy	-0.0885	-0.0881	-0.0836	-0.0758	-0.0755	-0.0688	0.1149	0.1152	0.1175
	(-1.69)	(-1.70)	(-1.62)	(-1.33)	(-1.35)	(-1.24)	(1.03)	(1.04)	(1.06)
Pilot 2 dummy	0.0762	0.0676	0.0639	0.0938	0.0830	0.0797	0.0035	-0.0071	-0.0086
	(3.70)**	(3.31)**	(3.13)**	(4.20)**	(3.79)**	(3.65)**	(0.08)	(-0.16)	(-0.20)
Pilot 3 dummy	0.0271	0.0253	0.0221	0.0329	0.0311	0.0277	-0.0204	-0.0234	-0.0250
	(1.68)	(1.58)	(1.39)	(1.88)	(1.82)	(1.62)	(-0.60)	(-0.69)	(-0.73)
ΔLog(share price)	-0.3256	-0.3423	-0.3423	-0.2404	-0.2637	-0.2649	0.2318	0.2113	0.2103
	(-13.18)**	(-13.94)**	(-13.99)**	(-8.98)**	(-10.03)**	(-10.11)**	(4.46)**	(4.06)**	(4.04)**
ΔLog(number of trades)	-0.1700	-0.1694	-0.1667	-0.1676	-0.1676	-0.1662	0.0586	0.0611	0.0630
	(-17.36)**	(-17.47)**	(-17.21)**	(-15.72)**	(-16.06)**	(-15.97)**	(2.92)**	(3.05)**	(3.13)**
ΔLog(trade size)	-0.0358	-0.0339	-0.0364	-0.0148	-0.0132	-0.0147	0.3190	0.3209	0.3197
	(-4.04)**	(-3.86)**	(-4.15)**	(-1.54)	(-1.40)	(-1.56)	(17.02)**	(17.17)**	(17.06)**
ΔLog(return volatility)	0.1208	0.1215	0.1200	0.1114	0.1122	0.1110	-0.0466	-0.0457	-0.0468
	(19.02)**	(19.32)**	(19.12)**	(16.17)**	(16.62)**	(16.49)**	(-3.45)**	(-3.39)*	(-3.45)**
ΔLog(market value of equity)	-0.0290	-0.0287	-0.0290	-0.0618	-0.0609	-0.0614	-0.0493	-0.0491	-0.0493
	(-2.72)**	(-2.72)**	(-2.76)**	(-5.34)**	(-5.38)**	(-5.44)**	(-2.18)*	(-2.18)*	(-2.19)*
Proportion of one-tick spreads (PQMIN)	-0.4404	-0.4019	-0.3532	-0.5577	-0.5082	-0.4350	-0.9441	-0.9028	-0.8794
	(-29.92)**	(-26.00)**	(-18.48)**	(-32.84)**	(-29.42)**	(-17.93)**	(-28.61)**	(-26.16)**	(-20.33)**
SPREAD or DEPTH	-0.1156	-0.2327	-0.3461	0.6036	0.2862	0.1212	0.0000	0.0000	0.0000
	(-0.63)	(-1.27)	(-1.88)	(2.02)*	(0.97)	(0.41)	(-0.89)	(-0.53)	(-0.64)
Share price (PRICE)	-0.0006	-0.0002	-0.0002	-0.0009	-0.0004	-0.0004	-0.0009	-0.0005	-0.0005
	(-4.70)**	(-1.78)	(-1.71)	(-6.98)**	(-3.12)**	(-2.91)**	(-3.69)**	(-1.91)	(-1.83)
Number of trades (NT)	–	-0.0001	-0.0001	–	-0.0001	-0.0001	–	-0.0001	-0.0001
		(-7.44)**	(-7.16)**		(-10.60)**	(-10.15)**		(-3.99)**	(-3.89)**
Proportion of odd sixteenths (PODD)	–	–	-0.1833	–	–	-0.2207	–	–	-0.0816
			(-4.30)**			(-4.28)**			(-0.90)
F-statistic	196.83**	188.83**	176.91**	197.20**	197.92**	185.32**	150.98**	140.52**	126.76**
Adjusted R²	0.4529	0.4642	0.4678	0.4534	0.4759	0.4794	0.3880	0.3915	0.3915

** and * Statistically significant at the 1% and 5% levels, respectively.

Table 8
Intraday changes in the spread and depth
We partition each trading day into thirteen 30-minute intervals and calculate the proportion of one-tick spreads for each stock based on both the quoted and effective spreads during each time interval. Similarly, we also calculate the percentage changes in the spread and depth during each time interval. We then calculate the mean values of these variables across stocks during each 30-minute interval. This table shows the mean values of the proportion of one-tick spreads and the changes in the spread and depth for each time interval. All changes are relative to the pre-decimalization levels. Paired *t*-tests of the mean differences are reported in parentheses. N denotes the sample size.

Intraday interval	Quoted spread and depth				Effective spread		
	PQMIN_QS	Change in spread	Change in depth	N	PQMIN_ES	Change in spread	N
1 (9:30AM–10:00AM)	0.2193	−0.2047 (−51.67)**	−0.1946 (−19.80)**	2,603	0.3595	−0.3013 (−53.74)**	2,595
2 (10:00AM–10:30AM)	0.2848	−0.2502 (−55.09)**	−0.2656 (−29.23)**	2,602	0.4105	−0.3381 (−52.37)**	2,594
3 (10:30AM–11:00AM)	0.3109	−0.2678 (−63.43)**	−0.2857 (−27.84)**	2,601	0.4388	−0.3445 (−49.60)**	2,592
4 (11:00AM–11:30AM)	0.3293	−0.2700 (−62.23)**	−0.3082 (−35.84)**	2,594	0.4532	−0.3572 (−50.18)**	2,586
5 (11:30AM–12:00PM)	0.3342	−0.2706 (−62.28)**	−0.3029 (−31.88)**	2,598	0.4595	−0.3559 (−53.08)**	2,583
6 (12:00PM–12:30PM)	0.3345	−0.2708 (−53.96)**	−0.3049 (−31.16)**	2,597	0.4554	−0.3636 (−51.53)**	2,581
7 (12:30PM–1:00PM)	0.3413	−0.2832 (−67.25)**	−0.3167 (−35.27)**	2,595	0.4653	−0.3694 (−48.41)**	2,582
8 (1:00PM–1:30PM)	0.3397	−0.2914 (−66.21)**	−0.3140 (−31.96)**	2,595	0.4626	−0.3784 (−46.33)**	2,572
9 (1:30PM–2:00PM)	0.3397	−0.2913 (−66.73)**	−0.3046 (−30.55)**	2,594	0.4615	−0.3657 (−21.59)**	2,580
10 (2:00PM–2:30PM)	0.3408	−0.2817 (−59.63)**	−0.2994 (−29.65)**	2,595	0.4628	−0.3742 (−52.64)**	2,587
11 (2:30PM–3:00PM)	0.3456	−0.2905 (−65.37)**	−0.3087 (−31.95)**	2,595	0.4690	−0.3622 (−15.81)**	2,590
12 (3:00PM–3:30PM)	0.3549	−0.2932 (−63.58)**	−0.3161 (−37.68)**	2,596	0.4752	−0.3381 (−7.25)**	2,590
13 (3:30PM–4:00PM)	0.3632	−0.2989 (−69.16)**	−0.2790 (−28.68)**	2,601	0.4850	−0.4111 (−56.76)**	2,590

** and * Statistically significant at the 1% and 5% levels, respectively.

Table 9
Determinants of the proportion of one-penny spreads after decimalization

We measure the probability that the minimum price variation is a binding constraint on spread widths by the proportion of quoted spreads that are equal to one cent (PQMIN_QS) during the post-decimalization study period. To assess the sensitivity of our results to different measurement methods, we also calculate the proportion of trading time during which the quoted spread is equal to one cent (PTMIN_QS). In addition, we calculate the proportion of effective spreads that are equal to one tick (PQMIN_ES). Panel A reports the descriptive statistics of the three measures of the binding constraints. Panel B presents the regression results showing how these variables are related to stock attributes (share price, number of trades, trade size, return volatility, and market value of equity). To determine whether the relation between the proportion of one-tick spreads and stock attributes differs across decimalization implementation groups, we include three pilot dummy variables in the regressions. Numbers in parenthesis are t-statistics.

Panel A: Descriptive statistics				Panel B: Regression results			
	PQMIN_QS	PTMIN_QS	PQMIN_ES	Variable	PQMIN_QS	PTMIN_QS	PQMIN_ES
				Intercept	−0.1225	−0.1251	−0.1326
Mean	0.0698	0.0673	0.1379		(−20.25)**	(−19.63)**	(−17.93)**
Standard deviation	0.0639	0.0649	0.0898	Pilot 1 dummy	0.0080	0.0012	−0.0016
					(0.49)	(0.07)	(−0.08)
Minimum	0.0000	0.0000	0.0000	Pilot 2 dummy	0.0244	0.0221	0.0165
1st percentile	0.0000	0.0000	0.0000		(3.86)**	(3.32)**	(2.13)*
5th percentile	0.0000	0.0000	0.0120	Pilot 3 dummy	0.0076	0.0064	0.0017
10th percentile	0.0052	0.0023	0.0262		(1.55)	(1.23)	(0.28)
25th percentile	0.0209	0.0169	0.0662	Log(share price)	−0.0400	−0.0342	−0.0540
50th percentile	0.0588	0.0556	0.1350		(−25.00)**	(−20.27)**	(−27.54)**
75th percentile	0.1021	0.1031	0.1979	Log(number of trades)	0.0341	0.0349	0.0573
90th percentile	0.1472	0.1452	0.2471		(25.80)**	(25.06)**	(35.40)**
95th percentile	0.1729	0.1707	0.2800	Log(trade size)	0.0083	0.0053	−0.0006
99th percentile	0.2553	0.2564	0.3796		(4.51)**	(2.73)**	(−0.27)
Maximum	0.7283	0.7589	0.7961	Log(return volatility)	−0.0335	−0.0325	−0.0467
					(−22.82)**	(−20.99)**	(−26.00)**
N	2603	2603	2603	Log(market value of equity)	0.0013	0.0002	0.0009
					(1.08)	(0.18)	(0.67)
				F–statistic	382.22**	332.05**	608.16**
				Adjusted R^2	0.5396	0.5044	0.6512

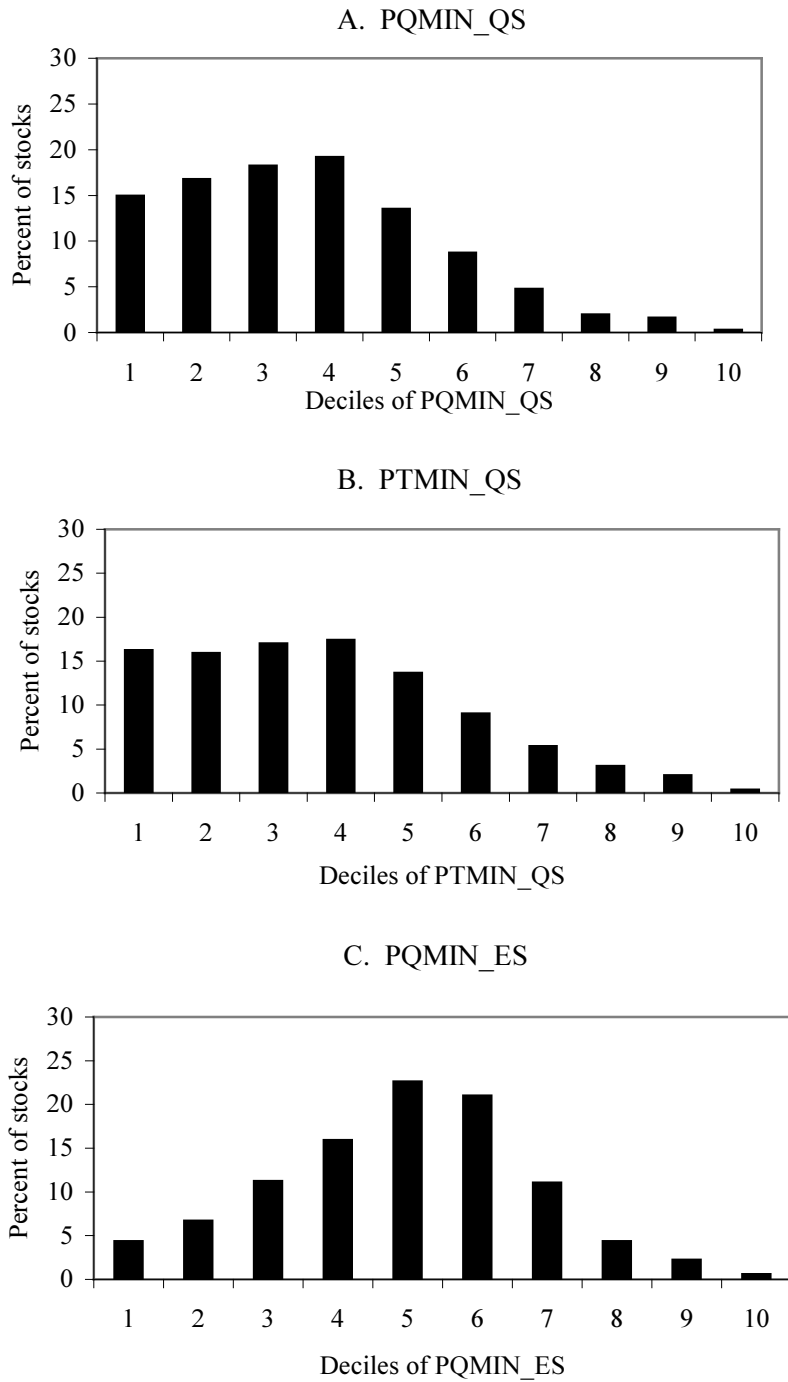** and * Statistically significant at the 1% and 5% levels, respectively.

Figure 1. Distribution of stocks by PQMIN_QS, PTMIN_QS, and PQMIN_ES deciles. PQMIN_QS is the proportion of one-tick quoted spreads, PTMIN_QS is the proportion of trading time during which the quoted spread is one tick, and PQMIN_ES is the proportion of effective spreads that are equal to one tick.
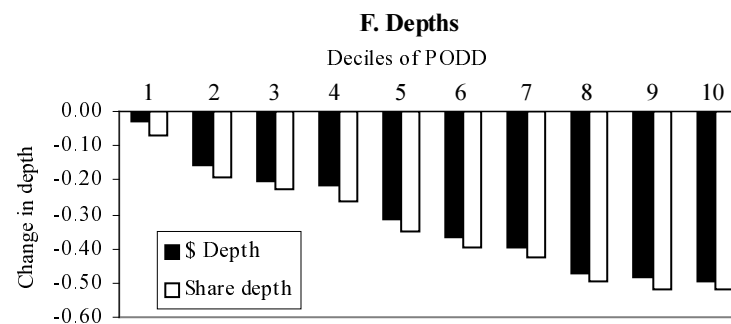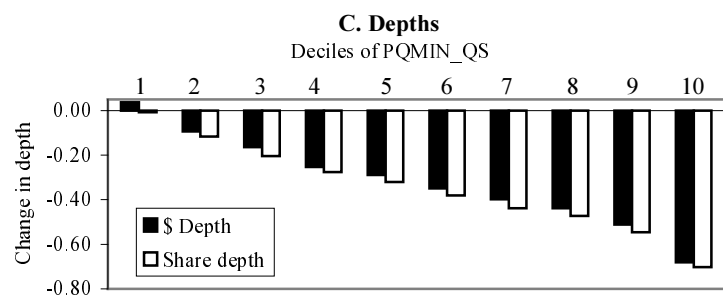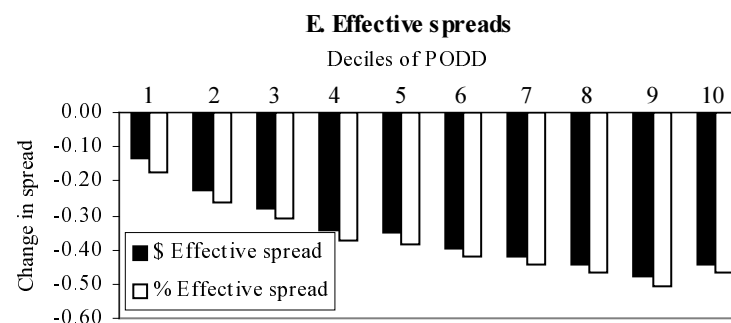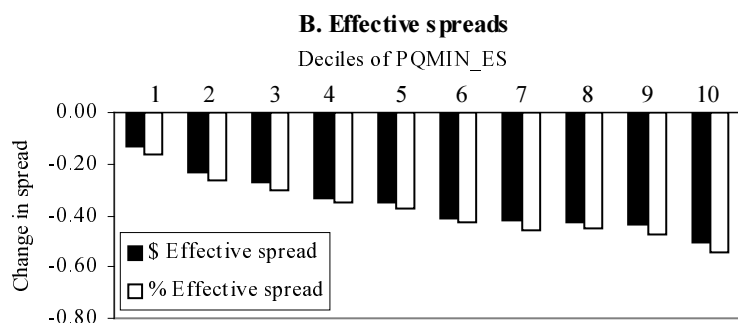
A. Quoted spreads

Deciles of PQMIN_QS

B. Effective spreads

Deciles of PQMIN_ES

C. Depths

Deciles of PQMIN_QS

D. Quoted spreads

Deciles of PODD

E. Effective spreads

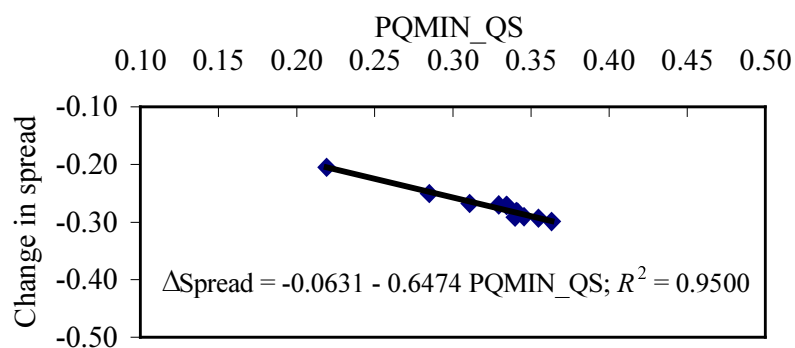Deciles of PODD
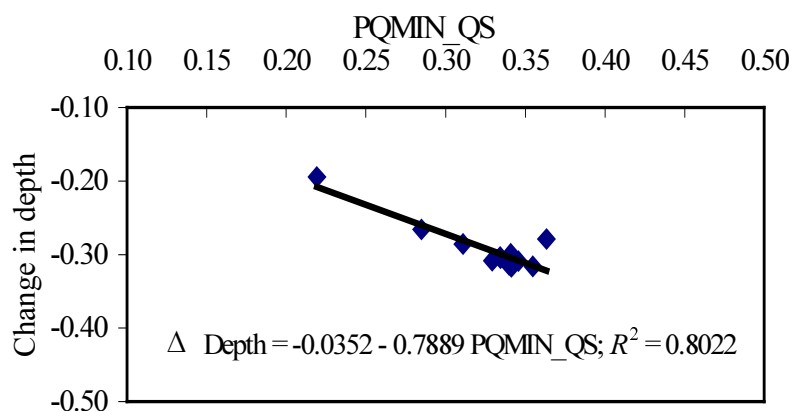
F. Depths

Deciles of PODD
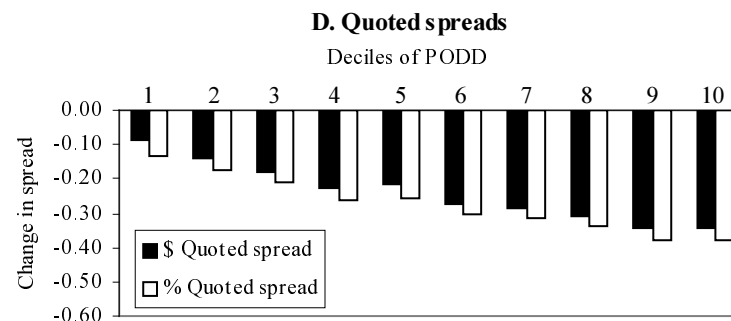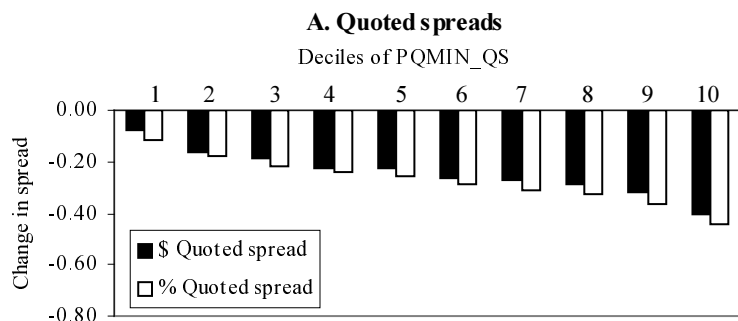
Figure 2. Proportion of one-tick spreads, proportion of odd-sixteenth quotes, and the changes in the spread and depth. The changes in the spread and depth are measured relative to their pre-decimalization values. PQMIN_QS is the proportion of one-tick quoted spreads and PQMIN_ES is the proportion of effective spreads that are equal to one tick. PODD is the proportion of odd-sixteenth quotes.

A. Quoted spread

PQMIN_QS

ΔSpread = -0.0631 - 0.6474 PQMIN_QS; $R^2 = 0.9500$

B. Quoted depth

PQMIN_QS

Δ Depth = -0.0352 - 0.7889 PQMIN_QS; $R^2 = 0.8022$

C. Effective spread

PQMIN_ES

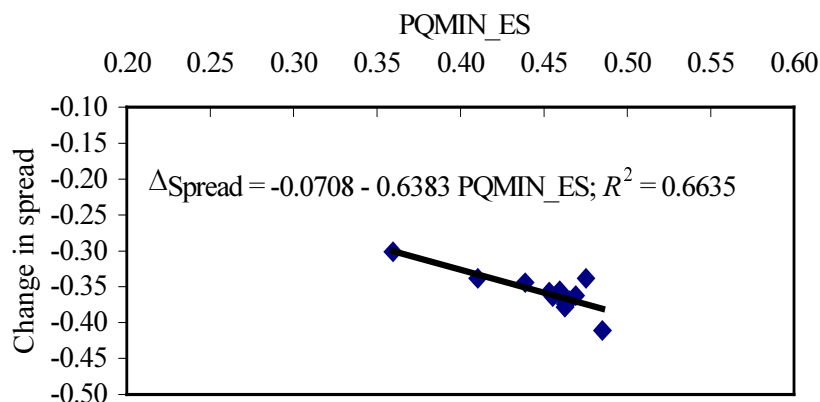ΔSpread = -0.0708 - 0.6383 PQMIN_ES; $R^2 = 0.6635$

Figure 3. Intraday relation between the proportion of one-tick spreads and the changes in the spread and depth. Each point on the diagrams denotes the mean value of PQMIN_QS or PQMIN_ES corresponding to the mean value of the change in the spread or depth during each 30-minute time interval. The changes in the spread and depth are measured relative to their pre-decimalization values. PQMIN_QS is the proportion of one-tick quoted spreads and PQMIN_ES is the proportion of effective spreads that are equal to one tick.