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Order submission strategies, liquidity supply, and trading in pennies on the New York Stock Exchange ☆

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Abstract

We use NYSE system order data to conduct a controlled experiment examining changes in trader behavior, displayed liquidity supply, and execution quality around the reduction in the minimum price variation to $0.01. Although traders do not substantially reduce their use of traditional limit orders in favor of market orders or non-displayed orders, they do decrease limit order size and cancel limit orders more frequently after decimals than before. These changes in order submission strategy appear to result in less displayed liquidity throughout the limit order book more than 15 cents from the quote midpoint. This reduction in displayed liquidity, however, does not manifest itself in poor execution quality. Even for large system orders, traditional execution quality is not worse with decimals than with fractions.

JEL: G10; G14; G18

Keywords: Decimalization; Trading strategies; Liquidity; Trading costs

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0. Introduction

Decimalization's proponents argue that reducing the minimum price variation (tick size) lowers the cost of liquidity by increasing price competition.[1] With decimals, liquidity providers previously forced to queue when the bid-ask spread was \$1/16 (\$0.0625) can set the spread as tight as \$0.01. This argument presumes that decimal pricing does not materially affect market participants' behavior. The opponents of decimalization are concerned that the reduced tick size benefits market professionals at the expense of non-professional liquidity providers. If the opponents are correct, then traders might display less of their trading interests after the tick size is reduced, resulting in a higher cost of liquidity. Whether investors alter their order submission strategies in reaction to decimalization sufficiently to affect displayed liquidity and, ultimately, the cost of liquidity is an empirical question we address using system order data from the New York Stock Exchange (NYSE) around its move to decimal prices.[2]

Harris (1996, 1997) posits that tick size changes alter traders' behavior. A narrower quoted bid-ask spread resulting from price competition initiated by the smaller tick size might increase market orders' popularity by lowering their *ex ante* cost relative to the cost of submitting limit orders. When the quoted spread is \$1/16, traders buying with market orders filling at the offer price pay \$0.0625 more than traders successfully using limit orders to supply liquidity at the bid price. As the spread tightens, this advantage of using a limit order decreases. If the limit order's execution risk is not materially changed by decimal pricing, then some traders might switch from limit to market orders.

More significantly, a smaller price increment allows traders with informational, geographical, and/or technological advantages (i.e., professional traders) to more easily impose adverse selection costs on others. Professional traders are posited to better the existing quoted price in order to obtain the priority to interact with incoming market orders when they believe it is in their best interest to do so and to allow the existing limit order to interact with market orders if market conditions do not favor providing liquidity at better prices.[3] Ready (1999), Edwards and Harris (2000) and Ronen and Weaver (2001) find that exchange specialists and other market professionals use price improvement to selectively interact with order flow. Results in Harris and Panchapagesan (1999) suggest that professionals are more likely to

[1] We use the term decimalization as if it was synonymous with a minimum tick size of \$0.01.

[2] System orders are orders that brokers/traders enter using the NYSE's SuperDOT electronic order entry system. These orders require timely submission or are deemed small/simple enough to not warrant the intervention of floor brokers. SEC (2001) finds that they represent 90% of the orders and 50% of the shares sent to the NYSE.

[3] Suppose the highest limit buy price is \$20.00 when a market order to sell arrives. The professional trader on the floor of the Exchange can choose to pay \$20.01 and buy the shares from the market-order seller. If the price rises, then the professional trader profits to the extent of the price rise. The professional's loss is limited to \$0.01 per share by the fact that he can sell into the existing limit order to buy at \$20.00. Alternatively, the professional trader wishing to step in front might submit a bid of \$20.01 upon seeing the original \$20.00 bid.

improve quotes established by large limit orders. Edwards and Harris (2000) and Battalio and Jennings (2001) find that the frequency of observing trades and quotes one tick better than prevailing quotes rises after the tick size falls to a penny. If nonprofessional traders are disadvantaged frequently enough, then they might reduce their use of limit orders. This can increase the cost of trading by reducing the supply of liquidity. Alternatively, traders might not be as sensitive to tick size as theory suggests or might respond in ways leaving the cost of liquidity unchanged. For example, traders might replace traditional limit orders, which must be displayed, with orders sent to NYSE floor brokers, who can selectively display trading interests. (See Sofianos and Werner (2000) for a discussion of the activities of floor brokers.)

Prior research generally finds that spreads fall and quoted sizes decline after previous decreases in North American security markets' tick size (see, e.g., Crack, 1995; Ahn et al., 1996; Bacidore, 1997; Porter and Weaver, 1997; Bollen and Whaley, 1998; Goldstein and Kavajecz, 2000; Ronen and Weaver, 2001).[4] These changes appear to produce lower trading costs for small market orders. Chakravarty et al. (2000) show that these trends continue with the move to decimal pricing on the NYSE. Goldstein and Kavajecz (2000), hereafter G–K, find that public limit orders are for fewer shares, have limit prices further from prevailing quoted prices, are more likely to be good-til-cancelled orders, and are more likely to be cancelled after the NYSE reduces the tick size from \$1/8 to \$1/16. They show that the changes in limit order characteristics translate to less quoted size throughout the limit order book and increased trading costs for large orders (see also Jones and Lipson, 2001).

We investigate whether the imposition of decimal pricing on the NYSE is associated with changes in the demand for or supply of liquidity and measure the resulting change in trade execution quality. The NYSE lowered the tick size to a penny for seven securities on August 28, 2000 for 57 more securities on September 25, 2000 and an additional 94 securities on December 5, 2000. All remaining securities began trading in decimals on January 29, 2001. Because the NYSE converted to decimal prices via a pilot program, we can select a non-decimal control security for each decimal security. We use the control securities to eliminate market effects that might have occurred coincidentally with the decimalization of the pilot securities' prices, something earlier studies of tick size changes could not do.

Despite an 84% tick-size reduction and an increase in the frequency with which professional traders step in front of traditional limit orders documented by Edwards and Harris (2001) and Battalio and Jennings (2001), we detect only minor changes in the order submission strategies of NYSE retail traders. There does not appear to be a dramatic shift away from system orders toward orders facilitated by floor brokers. We also do not find a substantive change in the mix of system market and limit orders. Consistent with G–K, we find that system limit orders are for fewer shares and are more likely to be cancelled after the tick size reduction. The limit order submission strategy changes result in less liquidity displayed in the limit order book more than a few cents from the inside quote. These changes appear to be less severe

[4] Ronen and Weaver (2001) find that quoted depth on the American Stock Exchange does not fall when the tick size is reduced to \$1/16.

than those found by G–K for the decrease in tick size to $1/16. However, despite reductions in displayed liquidity, execution quality does not deteriorate after decimals, even for large system orders. This suggests that the NYSE's floor provides non-displayed liquidity dynamically so that execution costs are less than the costs implied by the displayed liquidity. Overall, we find the NYSE trading environment is robust, at least in the short run, to the seemingly dramatic change in tick size, suggesting it can be dangerous to allow partial equilibrium analyses to guide policy decisions.

The remainder of the paper is contained in five sections. Section 1 describes our data and methodology. In Section 2, we illustrate how the submission of orders to the NYSE differs in the pre- and post-decimal periods. We provide descriptive statistics regarding the relative frequency of different order types, order sizes, sources of submitted orders, and cancellation frequencies. Section 3 examines changes in the supply of displayed liquidity. We document changes in the quoted size and, using a methodology similar to G–K, re-create the limit order book to examine liquidity supply at prices away from the inside quote. In Section 4, we estimate changes in the cost of trading around the reduction in the tick size to $0.01. We conclude in Section 5.

1. Methodology and data

We use standard event study methodology to examine the effect of decimalization on the 158 NYSE decimal-pilot securities (the "pilot stocks"). We study characteristics of the 158 pilot securities' trading activity one month (twenty trading days) prior to and one month subsequent to each security's conversion to decimal pricing. For the first seven pilot stocks, this suggests a pre-decimal period of July 31, 2000 through August 25, 2000. The post-decimal period for this group begins on August 28, 2000 and extends through September 25, 2000. Monday, September 25, replaces Labor Day (September 4), which is an Exchange holiday, for these seven stocks. For the second group of pilot stocks, the control period is August 28 through September 22, 2000 plus August 21, 2000 (again, to replace Labor Day) and the event period is September 25 through October 20, 2000. The control period for the third group of pilot securities begins on November 3, 2000 and ends on December 1, 2000. December 4, 2000 through January 3, 2001 is the event period for these 94 securities. We collect order, quote, and trade data for the pilot stocks on these dates. We align the time-series of these data in event time defining the weekend over which the security changes from fractional to decimal pricing as relative "time zero".

Although the pilot stocks' control and event periods are adjacent, market-wide effects unrelated to the tick-size change might exist. If so, then these systematic effects can make it difficult to isolate decimals' impact. To control for market effects, we gather the same data for a matched sample of securities, where we match each pilot stock to a non-pilot NYSE security on industry, security type (e.g., common stock, preferred stock, closed-end mutual fund), stock price, equity capitalization, and trading volume. A match is selected for each pilot stock from all NYSE stocks with the same NYSE industry code and security type as the pilot stock. The 158 pilot stocks are comprised of 119 common stocks, 17 preferred stocks, and 22 closed-end funds. Each matched stock is chosen to minimize the expression,

$$\sum_{k=1}^{3} (c_j^k - c_i^k)^2/[(c_j^k + c_i^k)/2], \tag{1}$$

where c_i^k (c_j^k) is the pilot (matched) stock measurement of characteristic k. We match on stock price, equity market capitalization, and trading volume. In addition to minimizing the sum, no single element of the summation is allowed to exceed unity. We collect order, quote, and trade data on these securities (the "matched stocks") from the relevant control and event periods and align these data in event time.

The 158 matched stocks begin trading in pennies on January 29, 2001. To study these stocks, we reverse the "sample" and "control" roles. That is, we use the 158 matched stocks acting as controls for the pilot stocks as the sample securities and use the 158 pilot stocks as the control securities. For this examination, the control period includes December 11–12 (to replace New Year's day and the January 15, 2001 Martin Luther King Day holiday) and December 29, 2000 though January 26, 2001 and the event period covers January 29, 2001 through February 26, 2001 (Monday, February 26, 2001 replaces Monday, February 19, President's Day).

We use proprietary NYSE data. To select the matched stocks, we use the NYSE's Master file. The data items we employ are industry code, security type, closing stock price on the final day of the control period, shares outstanding on the control period's final day (which, combined with share price, allows us to compute equity capitalization), and trading volume in the control period. The System Order Data (SOD) file contains order data for both pilot and matched stocks. This file provides the security's symbol, an order-side indicator (buy or sell), order type (market or limit), time-in-force (day or good-'til-canceled), number of shares in the order, the date and time of order arrival, limit price (if applicable), account type (e.g., individual investor, program trade, index arbitrage, agency, principal, NYSE member), execution date and time, the execution price and number of shares, cancellation data, and counter-party identity. We supplement these data with quote data from the companion SOD-Quote file, which provides the order-arrival-time and the execution-time quotes. Finally, to reconstruct the limit order book, we use the NYSE's open limit order file (LOFOPEN). This file contains the portion of all good-'til-cancelled limit orders that are neither completely executed nor cancelled by the end of a trading day (day orders expire automatically at the close of trading).

We report changes in the mean of the variables of interest for the sample stocks in the pre-decimal period and in the post-decimal period. We also examine the change in the pilot stocks' mean relative to the change in the control stocks' mean. The second calculation attempts to hold constant non-decimalization events that might occur in the market around the time one or more of the groups of securities converts from fractional to decimal pricing. We use a traditional t-test to compare the differences in means. In addition, we use a chi-squared test to determine whether the proportion of the stocks experiencing an increase/decrease in the mean of the variable of interest differs from one-half.

2. Order submission strategies

Edward and Harris (2001) and Battalio and Jennings (2001) find that the frequency of trading and quoting one tick better than prevailing quotes increases as the tick size is reduced to a penny. These findings suggest that traders might face additional adverse selection costs post-decimals. Taking this as given, we investigate whether traders appear to respond to this change in the trading environment. We analyze the apparent changes in both market- and limit-order submission strategies surrounding the reduction in tick size to \$0.01 in this section. We study the distributions of order types, order sizes, and the types of traders (within the SOD-file framework) submitting orders. In addition, we document changes in the limit-order cancellation rate and the relation between system and total trading volume. The latter statistic proxies for the mix between system orders, which must be displayed, and floor-broker orders, which need not be displayed.

The 158 pilot stocks have (across all three decimal pilot dates) 2,052,075 orders arriving in their pre-decimal control periods and 2,469,666 orders arriving in their post-decimal event periods. During the twenty trading days prior to when the matched stocks convert to decimal pricing, they have 2,726,128 orders. The matched stocks receive 2,769,778 orders in their post-decimal event period.

Table 1 reports statistics about the mix of order types, focusing on the choice between market and limit orders.[5] Limit orders are further divided into marketable and non-marketable orders. A buy (sell) marketable limit order has a limit price that is greater (less) than the National Best Offer (Bid) price.[6] Because marketable limit orders are immediately executable, they are similar to market orders.[7] We combine the results from the three pilot decimalization dates because the results are qualitatively similar across the three events. Arguments in Harris (1997) suggest that

[5] Market and limit orders are the dominant order types. The other order types SOD recognizes are: stop, stop limit, market on close, market or better, market if touched, cabinet, market with or without round-lot sale, limit or better, limit with or without round-lot sale, limit basis price, limit on close, and crossing session orders. Orders other than market and limit are less than 3.5% of all orders submitted on the NYSE before and after decimals.

[6] The National Best Bid (Offer) price is the highest bid (lowest offer) price across market centers (i.e., the NYSE, the regional stock exchanges, and Nasdaq market makers) providing quotes for the security at the time the order arrives at the NYSE. See Peterson and Sirri (2002) for a more complete discussion of marketable limit orders.

[7] Note that marketable limit orders can fail to execute if the quote moves between the time of order entry and the time the order is due an execution. Suppose, for example, that the current bid price is \$20.00 and two marketable limit sell orders with a limit price of \$20.00 arrive in rapid succession. The first order is filled at \$20.00 and the bid price decreases to \$19.75. The second marketable limit order is no longer executable.

Table 1
Order-type descriptive statistics for the securities in the NYSE's decimal pilot study and their matched securities[a]

	Three pilot decimal introduction dates				Final conversion to decimals			
	Before	After	%Post > Pre[b]	t-stat[c]	Before	After	%Post > Pre	t-stat
Panel A. Percent market orders (mean)								
Pilot stocks	23.26%	24.53%	59.62%**	0.9869	23.05%	21.92%		
Matched stocks	23.69%	23.90%			22.82%	21.47%	37.91%***	−1.1092
t-statistic[d]	−0.3540	0.4904			0.1919	0.3538		
Panel B. Percent marketable limit orders (mean)								
Pilot stocks	9.76%	10.62%	55.77%	1.4754	10.59%	10.87%		
Matched stocks	10.21%	10.83%			11.52%	10.83%	40.52%**	−1.6271
t-statistic	−1.0140	−0.3529			−1.5943	0.0726		
Panel C. Percent non-marketable limit orders (mean)								
Pilot stocks	64.55%	62.51%	37.82%***	−1.5724	63.09%	63.96%		
Matched stocks	63.63%	62.52%			62.01%	64.02%	67.69%***	1.5736
t-statistic	0.7734	−0.0077			0.7909	−0.1640		

[a] The Pilot Stocks are the 158 securities included in the New York Stock Exchange's phased decimal implementation pilot. The Matched Stocks are the 158 securities matched to the Pilot Stocks based on industry, security type, price, equity market capitalization, and trading volume.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed t-test.

[d] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed t-test.

*Significant at the 0.10 significance level.

**Significant at the 0.05 significance level.

***Significant at the 0.01 significance level.

the smaller tick size makes traders less likely to submit limit orders. Thus, for the pilot dates, we expect an increase in the use of market orders relative to limit orders for the pilot stocks. For the final conversion date, we anticipate finding a similar shift in the matched stocks' order mix.

On an absolute basis, the fraction of market and marketable limit orders increases and the proportion of non-marketable limit orders decreases around the three pilot dates for the pilot stocks. About 60% of the pilot stocks show an increase in the use of market orders and over 62% of the pilot stocks register a decrease in the use of non-marketable limit orders. Both of these fractions significantly exceed 0.50 at traditional significance levels and are consistent with Harris' predictions. Conversely, we note that the changes in matched stocks' order mix surrounding their conversion to decimal pricing is counter to theory. We find decreases in the fraction of market and marketable limit orders and increases in non-marketable limit order usage.[8] Thus, although the pilot stocks exhibit behavior that is weakly consistent with the

[8] Using order volume instead of the number of orders produces qualitatively similar results.

Table 2
Order-size descriptive statistics for the securities in the NYSE's decimal pilot study and their matched securities[a]

	Three pilot decimal introduction dates				Final conversion to decimals			
	Before	After	%Post > Pre[b]	t-stat[c]	Before	After	%Post > Pre	t-stat
Panel A. Mean market order size (shares)								
Pilot stocks	822	976	58.33%***	2.250**	1,041	1,013		
Matched stocks	1,270	1,152			1,084	1,005	41.06%**	−0.417
t-statistic[d]	−1.169	−1.323			−0.342	0.039		
Panel B. Mean marketable limit order size (shares)								
Pilot stocks	2,723	2,821	53.25%	0.4931	2,881	2,604		
Matched stocks	3,131	3,584			3,232	3,016	34.21%***	−0.5823
t-statistic	−1.0821	−1.6765			−1.2675	−1.2472		
Panel C. Mean non-marketable limit order size (shares)								
Pilot stocks	2,095	1,976	34.62%***	−0.4769	1,744	1,707		
Matched stocks	2,138	2,329			2,371	1,892	21.71%***	−1.8367*
t-statistic	−0.1776	−1.2884			2.5954***	0.8998		

[a] The Pilot Stocks are the 158 securities included in the New York Stock Exchange's phased decimal implementation pilot. The Matched Stocks are the 158 securities matched to the Pilot Stocks based on industry, security type, price, equity market capitalization, and trading volume.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed t-test.

[d] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed t-test.

*Significant at the 0.10 significance level.

**Significant at the 0.05 significance level.

***Significant at the 0.01 significance level.

predicted shift in order mix, we conclude that decimals appear to have no substantive effect on traders' choice between market and limit orders overall.[9]

In Table 2, we present an analysis of the size of submitted orders. Although the shift in order type documented above is inconsequential, it is possible that traders increase the size of their marketable orders and reduce the size of their non-marketable limit orders.

[9] We repeat the analysis reported in Table 1 (and the other tables) for changes in the differences between the sample firms' statistic and the control firms' statistic, i.e., the net statistic. The net statistic for each sample-control pair of stocks is computed by subtracting the control stock's statistic from the sample stock's statistic. We then compute a t-statistic and a chi-squared statistic using the 158 differences as the variable of interest. Consistent with the analysis in Table 1, we find no changes in the order flow mix that are significant at traditional significance levels. Throughout the paper, we find only minimal differences in conclusions using net change statistics. In addition, our conclusions do not change if we eliminate the least actively-traded sample securities.

When we focus on the pilot events, we find evidence consistent with the claim that market order size rises and non-marketable limit order size falls around decimalization. Mean market order size for the pilot stocks increases after they convert to decimals while the matched stocks' mean market order size decreases. About 58% of the pilot stocks experience an increase in market order size between the pre- and post-decimal periods. Consistent with G–K, the average size of the pilot stocks' non-marketable limit orders falls slightly. The matched stocks' mean order size increases. Over 65% of the pilot stocks experience a decrease in their mean non-marketable limit order size around their switch to decimals.

Around their decimalization, the change in the matched stocks' mean market order size is counter to the results for the pilot dates. The matched stocks' mean non-marketable limit order size falls substantially at their conversion to decimal pricing. This mean change is statistically significant at the 0.10 significance level and the matched stocks' mean non-marketable limit order size changes from being significantly greater than the pilot stocks' mean market order size to being insignificantly different from the pilot stocks upon conversion to decimals. Further, 78% of the matched stocks experience a decrease in the size of submitted non-marketable limit order between the pre- and post-decimal periods. Thus, as in G–K, we find evidence of a decline in non-marketable limit order size at the reduction in tick size. The size of marketable orders, however, does not change.

Limit order traders also can cancel limit orders. To determine whether the cancellation frequency changes around the pricing change, we compute cancellation rates on both an order and a share basis. The order cancellation rate is the number of non-marketable limit orders with at least one share cancelled divided by the total number of submitted non-marketable limit orders. The share cancellation rate is the number of cancelled non-marketable limit order shares divided by the total number of shares in submitted non-marketable limit orders. We display these cancellation rates in Table 3.

The cancellation rate for the pilot stocks exhibits a statistically significant increase (at the 0.01 level for orders and the 0.10 significance level for shares) around decimalization. In addition, 127 (106) of the 158 decimal stocks experience an increase in the order (share) cancellation rate. These fractions are statistically different from 0.50 at the 0.01 significance level. For both orders and shares, the pilot stocks' mean cancellation rate is statistically indistinguishable from the matched stocks' mean rate in the pre-decimal period and statistically greater (again, at the 0.01 significance level for orders and 0.10 significance level for shares) in the post-decimal period. We reach similar conclusions for the matched stocks upon their conversion to decimal prices. Thus, we conclude that traders tend to cancel non-marketable limit orders more frequently post-decimals. This result is similar to G–K, who find that the cancellation rate rises from 35% to 37% around the reduction in tick size to \$1/16.

The final examination we undertake in our investigation of order submission strategy is to determine the party submitting the order. NYSE-collected account types include indications of whether the order is part of an index arbitrage or other program trade, whether the order comes from an individual investor, a non-member

Table 3
Non-marketable limit order cancellation rates descriptive statistics for the securities in the NYSE's decimal pilot study and their matched securities[a]

	Three pilot decimal introduction dates				Final conversion to decimals			
	Before	After	%Post > Pre[b]	*t*-stat[c]	Before	After	%Post > Pre	*t*-stat
Panel A. Order cancellation rate								
Pilot stocks	40.05%	46.62%	80.38%***	3.218***	48.04%	48.47%		
Matched stocks	41.33%	41.88%			42.22%	48.44%	77.85%***	2.928***
t-statistic[d]	0.6184	2.365**			2.893***	0.0146		
Panel B. Share cancellation rate								
Pilot stocks	35.08%	38.50%	67.08%***	1.8463*	38.93%	38.96%		
Matched stocks	34.55%	35.22%			35.56%	39.28%	70.89%***	2.1152**
t-statistic	0.3058	1.8490*			1.9366*	0.1765		

[a] The Pilot Stocks are the 158 securities included in the New York Stock Exchange's phased decimal implementation pilot. The Matched Stocks are the 158 securities matched to the Pilot Stocks based on industry, security type, price, equity market capitalization, and trading volume.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed *t*-test.

[d] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed *t*-test.

*Significant at the 0.10 significance level.

**Significant at the 0.05 significance level.

***Significant at the 0.01 significance level.

broker-dealer, or a member firm, and whether the order is floor entered.[10] We focus on six categories. Any order specified as a program trade is placed in our program trading category. Member orders are non-program orders for a member's proprietary account or a non-program agency trade for another member. CAP (also called participating or percentage) orders are orders floor brokers leave with the specialist that are to be one-half of subsequent volume. Individual investor orders are non-program orders submitted on behalf of an individual (not a member firm or a non-member broker-dealer) investor. Agency orders are non-program orders handled on an agency basis that are not marked as being for individual investors. Table 4 summarizes these statistics.

On an absolute basis, there is a significant increase in the average fraction of member-firm orders between the pre- and post-decimal time periods using either the *t*-test or the chi-square test. The rise in member orders is mostly at the expense of individual orders, although the decrease in the mean percent of individual investor

[10] Recall that we are examining system orders only. Thus, the only floor-entered orders we capture are those classified as system orders. These are orders that the floor broker decides to enter into the system, after receiving the order and observing market conditions. In other words, these are orders that the floor broker believes can receive a favorable execution without the floor broker's intervention (or the floor broker has other, more pressing, orders that require attention).

Table 4
Descriptive statistics regarding the account type of the party submitting orders before and after stocks switched to decimal pricing on the New York Stock Exchange[a]

	Three pilot decimal introduction dates				Final conversion to decimals			
	Before	After	%Post > Pre[b]	*t*-stat[c]	Before	After	%Post > Pre	*t*-stat
Panel A. Mean percent agency orders (SOD account types A and B)								
Pilot stocks	1.48%	1.51%	47.13%	0.1007	1.66%	1.13%		
Matched stocks	1.61%	1.98%			1.34%	0.97%	13.79%***	−1.8289*
t-statistic[d]	−0.4249	−0.6822			1.1855	0.7807		
Panel B. Mean percent individual investor orders (SOD account types I and H)								
Pilot stocks	35.99%	30.17%	32.29%***	−1.6639*	31.83%	28.05%		
Matched stocks	30.00%	27.06%			28.30%	23.47%	28.10%***	−1.4566
t-statistic	1.6845*	0.9390			0.9860	1.3763		
Panel C. Mean percent floor orders (SOD branch code YYY, ZZZ, or QQQ)								
Pilot stocks	3.27%	2.58%	31.91%***	−1.2577	3.05%	2.52%		
Matched stocks	3.81%	3.16%			3.53%	2.56%	11.01%***	−1.7238*
t-statistic	−0.7574	−1.1407			−0.7854	−0.0824		
Panel D. Mean percent convert and parity (CAP) orders (SOD order qualification 24–27)								
Pilot stocks	1.54%	1.25%	42.75%*	−1.1039	1.64%	1.41%		
Matched stocks	1.98%	1.89%			2.16%	1.68%	37.60**	−1.3513
t-statistic	−1.1039	−2.048**			−1.3513	−0.8869		
Panel E. Percent member orders (SOD account types D, P, R, S, W, E, F, L, X, and Z)								
Pilot stocks	35.97%	41.29%	82.05%***	2.968***	36.89%	44.66%		
Matched stocks	37.39%	41.89%			38.10%	47.56%	90.20%***	5.018***
t-statistic	−0.7663	−0.3344			−0.6588	−1.5026		
Panel F. Mean percent program trading orders (SOD account type C, D, J, K, M, N, U, and Y)								
Pilot stocks	21.75%	23.20%	59.62%**	0.7310	24.94%	22.24%		
Matched stocks	25.22%	24.13%			26.57%	23.76%	22.63%***	−1.5033
t-statistic	−1.6499	−0.4979			−0.8035	−0.8526		

[a] The Pilot Stocks are the 158 securities included in the New York Stock Exchange's phased decimal implementation pilot. The Matched Stocks are the 158 securities matched to the Pilot Stocks based on industry, price, security type, equity market capitalization, and trading volume.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed *t*-test.

[d] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed *t*-test.

*Significant at the 0.10 significance level.

**Significant at the 0.05 significance level.

***Significant at the 0.01 significance level.

orders is not statistically significant at traditional levels. However, the increase in the fraction of member orders for the stocks affected by decimalized prices is offset by an increase in the control stocks' member orders, suggesting that the change is unrelated to the tick size reduction. The mix of member and individual investor account types for order volume (results not shown) is virtually undisturbed by the introduction of decimals. Thus, we conclude that there appears to be no substantive decimal-induced change in the type of trader submitting orders.

To determine whether traders bypass the NYSE's SuperDOT system entirely in favor of floor brokers, we compare NYSE system trading volume to NYSE total volume. Assuming that there are not major changes in the relation between submitted and executed orders on the floor and through the system, trading volume proxies for order volume. Prior to decimalization, the mean ratio of system-to-total NYSE volume for the pilot stocks is 56.5%. The pilot stocks' average ratio *increases* to just over sixty percent in the month after they begin decimal trading. Furthermore, system-to-total volume ratio increases for 98 of the 158 pilot stocks. Finally, if we aggregate the total system volume and total volume across all 158 stocks before taking the ratio, we find that system volume is 54.9% of total volume before decimals and 57.7% afterwards. This suggests that traders did not reroute orders from the system to the floor.[11]

Contrary to theory, we find little evidence that traders respond to a smaller tick size by decreasing their use of limit orders or by moving from system orders to floor orders. We find that non-marketable limit orders are somewhat smaller and are more frequently cancelled in decimal trading than in fractional trading, continuing the trends noted in G–K for the earlier reduction in tick size. Both of these results suggest that there might be less displayed liquidity after decimals than before.

3. Supply of liquidity

After decimalization, we find that the frequency of limit orders relative to market orders is constant, that limit order size decreases, and that limit orders are more likely to be cancelled. These facts suggest that the supply of displayed liquidity falls relative to the demand for liquidity as tick size is reduced. Assuming that traders compete across more price points, however, suggests that liquidity is available on a finer price grid with decimals than with fractions. With the finer price grid, traders can supply liquidity closer to the quoted spread's midpoint and at more price points. The net effect on displayed liquidity is an empirical question.

We investigate the amount of displayed liquidity at prices equal to and away from the quote. To do so, we note the quoted prices and sizes and re-create the limit order book for each pilot and matched stock hourly (on the hour, from 10:00 a.m. to 4:00 p.m.) each day in the control and sample periods. For each hourly snapshot, we record the existing NYSE bid and offer quoted prices and sizes. In order to aggregate over stocks, we restate prices as distances from the midpoint of the quoted bid-ask spread at the snapshot time. Computing the simple mean of the quoted sizes across snapshots, days, and stocks provides the average quoted size of the inside bid and

[11] On a relative basis, we find that the pilot stocks' mean system-to-total volume ratio increases somewhat less than the matched stocks' ratio. However, the pilot stocks' mean ratio does not differ significantly from the matched stocks' mean ratio either before or after the pilot stocks are decimalized.

offer prices. To determine the displayed liquidity at prices other than the inside quotes, we use the NYSE's open limit order file (LOFOPEN) and the SOD file. The LOFOPEN file provides the limit orders remaining on the book at the end of the previous trading day after day limit orders expire. As in Kavajecz (1999), we then use the SOD file to add orders with a given limit price arriving prior to the time of the snapshot being taken and subtract shares in existing limit orders that fill or cancel prior to the time of the snapshot being taken. Again, to facilitate the averaging across stocks, we restate limit prices as distances from the snapshot's quoted spread midpoint.[12]

In Table 5, we report the average NYSE quoted spread and size by equally weighting the spread and size observed at each hourly snapshot for each sample stock. The quoted spread is computed by subtracting the contemporaneous National Best Bid price from the contemporaneous National Best Offer price. The mean size is computed by equally weighting each stock's hourly bid and offer sizes.

Liquidity suppliers appear to compete on the finer price grid offered by decimal pricing. As in studies examining previous reductions in tick size and Chakravarty et al. (2000) examining decimalization, quoted spreads fall. The average quoted spread falls by almost four cents per share after stocks begin trading in decimals. The mean decrease in the sample-stocks' quoted spreads is significant using a t-test and 81% of the sample stocks experience a decrease in their quoted spread.

At their conversion dates, the pilot stocks' average quoted size falls by 3,136 shares (or 52% of its prior size). Furthermore, mean quoted size falls for 79% of the pilot stocks, which significantly differs from 50% at the 0.01 level. Finally, the difference in the mean quoted size between the matched and pilot stocks is significant after the pilot stocks convert to decimals, but not before. When the matched stocks begin decimal trading, their mean quoted size falls by 2,656 shares (by about 50%). Although the matched stocks' mean quoted size significantly exceeds the pilot stocks' mean quoted size before decimals, the matched stocks' mean quoted size is nearly identical to the pilot stocks' mean quoted size after the matched stocks begin decimal trading. Of the 158 matched stocks, 114 have less quoted depth after moving to decimal pricing. Again, these results are consistent with the findings of Chakravarty et al. (2000) and work examining the reduction in tick size to \$1/16.

The Table 5 results show that the supply of liquidity at the quoted prices declines precipitously when stock prices are decimalized. We cannot determine whether the fall in quoted size is due to traders spreading their trading interests across more available price points or represents a decrease in displayed liquidity without

[12] For example, assume that the LOFOPEN file from day t-1 indicates that 500 shares of sell limit orders with a limit price of \$25.00 remain open. Suppose that a 100-share sell order with a limit price of \$25.00 arrives at 9:40, 200 shares from the day t-1 order fill at 10:10, and another 100-share sell order with a limit price arrives at 10:55 on day t. The day t 10:00 snapshot indicates that there are 600 shares (500 + 100) offered at \$25.00. The 11:00 snapshot indicates that there are 500 shares (600 − 200 + 100) offered at \$25.00. If the quoted bid (offer) price is \$24.75 (\$24.85), then the \$25.00 offer price is \$0.20 from the quoted spread midpoint. The existence of the LOFOPEN file implies that we do not need to create the beginning book as did Kavajecz (1999). Furthermore, we re-create the limit order book only on an intra-day basis because we have access to the "official" book at the end of each trading day.

Table 5
Descriptive statistics regarding the quoted bid-ask spread and the associated quoted sizes for the pilot and the matched stocks around the change to decimal pricing[a]

	Three pilot phases				Final decimal conversion			
	Before	After	%Post > pre[b]	*t*-stat[c]	Before	After	%Post > pre	*t*-stat.
Panel A. Quoted spreads								
Pilot stocks	\$0.1157	\$0.0760	18.99%***	16.99***	\$0.0652	\$0.0677		
Matched stocks	\$0.1135	\$0.1052			\$0.1119	\$0.0746	9.49%***	11.55***
t-stat	−1.3673	13.00***			16.25***	2.6015***		
Panel B. Quoted depths								
Pilot stocks	6,012	2,876	20.25%***	−3.3249***	2,627	2,656		
Matched stocks	6,128	5,326			5,322	2,666	27.85%***	−2.8527***
t-test	−0.0895	−2.7107***			−2.9241***	−0.0374		

[a] The Pilot Stocks are the 158 securities included in the New York Stock Exchange's phased decimal implementation pilot. The Matched Stocks are the 158 securities matched to the Pilot Stocks based on industry, price, security type, equity market capitalization, and trading volume.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed *t*-test.

[d] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed *t*-test.

* Significant at the 0.10 significance level.

** Significant at the 0.05 significance level.

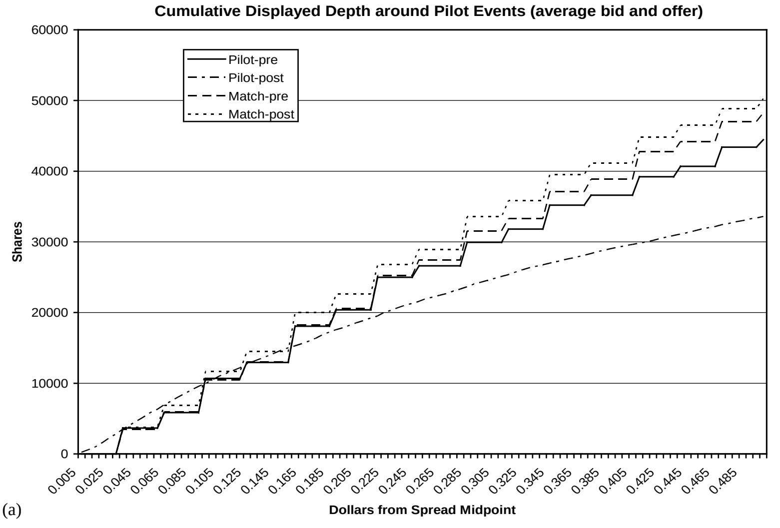
*** Significant at the 0.01 significance level.

examining the liquidity available at prices away from the quoted prices. Figs. 1a and b provide visual images of changes in the limit order book around the switch to penny trading for the pilot stocks and the matched stocks, respectively. To produce Figs. 1a and b, the hourly snapshots of the limit order book are averaged (equally weighing each stock, hour, and day) and accumulated at successive price points. That is, as we move further away from the spread midpoint, we add the shares with the new limit price to the cumulative shares with limit prices closer to the spread midpoint. To conserve space, we average the bid and the offer sides of the book by taking the bid size a given distance below the spread midpoint and the offer size the same distance above the quote midpoint. (Examining the two sides of the book separately does not lead to substantively different conclusions.)

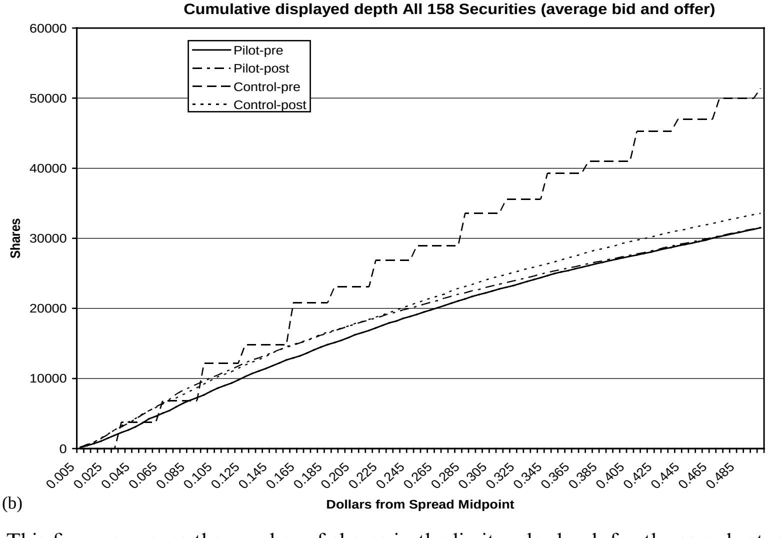
Fig. 1a illustrates the change in the cumulative limit order book at prices within \$0.50 of the spread midpoint at the time, the book is re-created for the pilot stocks and their matched stocks around the times of the decimal pilots. In Fig. 1b, we plot the limit order books for the pilot and matched stocks around the matched stocks' switch to decimals on January 29, 2001.

In Fig. 1a, the pre-decimal graph for the pilot stocks and both the pre- and post-decimal graphs for the control stocks are the expected step functions. Furthermore, the amounts of cumulative displayed liquidity for the pilot and matched stocks are similar before the pilot stocks convert to decimals. Because the tick size falls between the pre- and post-decimal periods for the pilot stocks, investors can provide liquidity for the pilot stocks closer to the spread midpoint (as close as \$0.005 if the spread is \$0.01) with decimals than with fractions (no closer than \$0.03125). This is illustrated by the fact that the post-decimal pilot-stock graph begins closer to the origin (i.e., the spread midpoint) than the pre-decimal pilot-stock graph and the matched-stock graphs. Generally speaking, the advantage of offering liquidity at prices closer to the spread midpoint is erased quickly. The displayed depth available at the first four price points available in the fractional world (\$0.03125, \$0.0625, \$0.09375, and \$0.125 from the spread midpoint) is nearly identical to the cumulative displayed depth available after the tick size is reduced. By the time the fifth fractional increment is reached (\$0.15625 or about 15,000 shares), displayed depth with decimal pricing is less than that available pre-decimals. An arbitrary \$0.25 into the book, post-decimal cumulative depth is 81% of pre-decimal cumulative depth. Although the matched stocks display some variation in depth between the control and sample periods, the two cumulative curves are nearly identical deep into the book. Furthermore, the control stocks' sample-period cumulative depth curve lies slightly above their control-period curve suggesting that the decreased depth observed for the pilot stocks is not due to a market-wide decrease in displayed liquidity.

Fig. 1b shows the effect of the 158 matched stocks' move to decimals. In this case, the graph of the control-stock book is a step-function in the pre-decimal period and becomes smoother post-decimals. The post-decimal depth is greater than or equal to the pre-decimal depth through the first two old half-ticks into the book (\$0.03125 and \$0.0625) and is less than or equal to pre-decimal depth after the third old price point (\$0.09375). In terms of shares, the post-decimal matched stocks' cumulative depth curve crosses the pre-decimal cumulative depth curve at about 8,500 shares. At



(a)



(b)

Fig. 1. (a) This figure averages the number of shares in the limit order book for the sample stocks in the control period, before decimal pricing (-pre), and event period, after decimal pricing (-post), across all seven daily re-creations of the limit order book. The bid side of the limit order book is averaged with the offer side. After normalizing price by the midpoint of the quoted bid-ask spread, we cumulate the shares a stated distance away from the spread midpoint. For example, if there are 500 shares available on the limit order book at the first price point and an additional 250 shares available at the second price point, then the second price point is associated with a total of 750 shares. (b) This figure averages the number of shares in the limit order book for the 158 sample stocks in the control period, before decimal pricing (-pre), and event period, after decimal pricing (-post), across all seven daily re-creations of the limit order book. The bid side of the limit order book is averaged with the offer side. After normalizing price by the midpoint of the quoted bid-ask spread, we cumulate the shares a stated distance away from the spread midpoint. For example, if there are 500 shares available on the limit order book at the first price point and an additional 250 shares available at the second price point, then the second price point is associated with a total of 750 shares.

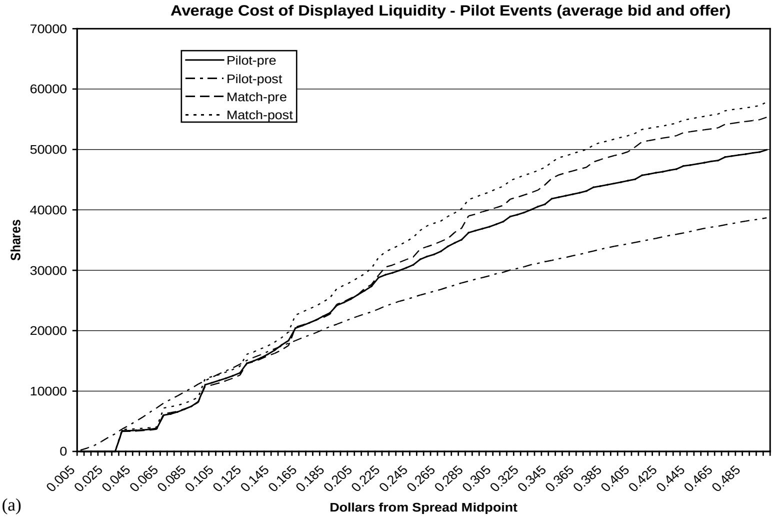
a distance of \$0.25 into the book, the post-decimal depth is 76% of the pre-decimal level for the control stocks.

In summary, the switch to decimal prices provides an advantage to demanders of liquidity in that liquidity suppliers can and do offer liquidity on a finer price grid in the decimal world than in the fractional environment. This advantage is offset by the apparent increased reluctance of liquidity suppliers to commit to trade, leaving larger orders less displayed liquidity with which to interact. Generally speaking, within \$0.10–\$0.15 of the spread midpoint, the post-decimal cumulative depth is greater than the pre-decimal cumulative depth. Further into the book, the decimal environment offers less displayed liquidity than the fractional world. This result differs somewhat from that in G–K. They find that the cumulative depth \$1/8 into the limit order book (i.e., the first price point available prior to the tick size reduction they study) is about 23% less after the decrease in tick size than before. We must go more than \$0.25 into the book to find a reduction in cumulative displayed liquidity of this magnitude.

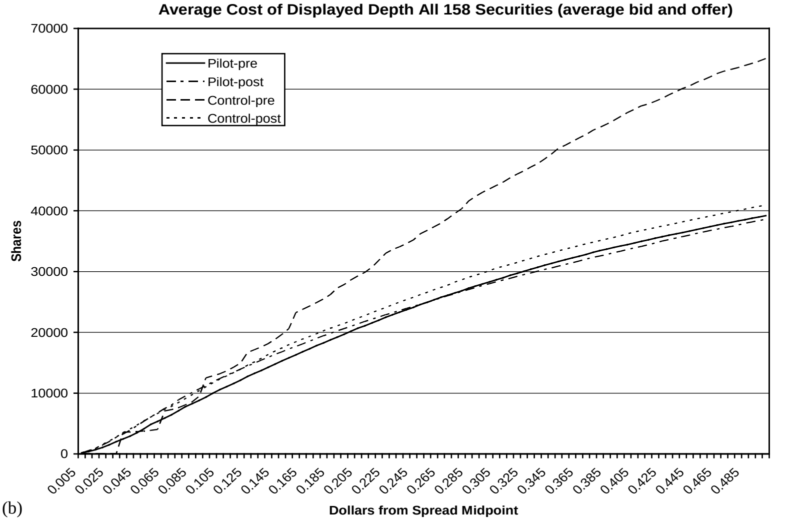
Thus far, we have examined the cumulative depth at a price point and how far up or down the displayed supply curve we must move to complete a trade of a particular size (i.e., the cost of the last share traded). Another approach to addressing changes in liquidity cost is to determine the *average* price one would expect to pay (receive) relative to the spread midpoint for a trade of a given size using the cumulative limit order books in Figs. 1a and b. (Again, we separately consider the depth on the bid and offer sides of the market and then average the two.) For example, suppose that 500 shares are offered \$0.01 from the spread midpoint and 250 shares are offered \$0.015 from the midpoint, on average. In Fig. 1a, we show 500 shares at \$0.01 and 750 shares at \$0.015. From this, we determine that the marginal cost of a share in a trade for 501–750 shares is \$0.015. In the proposed analysis, we find that the average cost of a 750 share trade is \$0.01167 (500 shares at \$0.01 and 250 shares at \$0.015). This is the average cost (relative to the spread mid-point) that a trader bears to buy or sell a given number of shares without any non-displayed liquidity arising on the Exchange floor. We summarize this calculation for all price points up to average costs \$0.50 away from the spread midpoint in Figs. 2a and b. Again, we separately consider the decimal pilot phases and the switch to decimals for the matched stocks.

The average-cost curves of Figs. 2a and b are probably most easily read by selecting a given trade size from the vertical axis and then reading the resulting expected cost from the horizontal axis. Consider a 10,000 share trade for the pilot stocks illustrated in Fig. 2a. Prior to decimalization, a trader would expect to pay an average cost of between \$0.09 and \$0.095 relative to the spread midpoint (compared to a marginal cost from Fig. 1a of \$0.095). In the decimal environment, the expected cost decreases to \$0.085 (with a marginal cost of \$0.10).

The smaller tick size is reflected in the fact that a positive number of shares can be obtained at prices less than \$0.03125 away from the spread in the event periods, but no shares can be obtained at those prices in the control periods. Relative to the fractions, traders find themselves better off in the decimal world for price points close to the spread midpoint, nearly indifferent at the first available price point in the fractional world, again better off to about \$0.15 into the book, and then worse off



(a)



(b)

Fig. 2. (a) The figures plot the average cost of buying (selling) the stated number of shares of a sample stock in terms of a price above (below) the midpoint of the quoted bid-ask spread. We use the cumulative limit order books created in Fig. 1 by averaging across hourly re-creations of the limit order book for the control period, before decimal pricing (-pre), and the event period, after decimal pricing (-post). The cost calculation assumes that all liquidity is displayed and takes a share-weighted average of each price point in the cumulative limit order book. For example, if there are 500 shares available in the limit order book at the first price point away from the spread's midpoint and 250 available at the second price point, then the average cost is 1.33 price points. (b) The figures plot the average cost of buying (selling) the stated number of shares of a sample stock and a control stock in terms of a price above (below) the midpoint of the quoted bid-ask spread. We use the cumulative limit order books created in Fig. 1 by averaging across hourly re-creations of the limit order book for the control period, before decimal pricing (-pre), and the event period, after decimal pricing (-post). The cost calculation assumes that all liquidity is displayed and takes a share-weighted average of each price point in the cumulative limit order book. For example, if there are 500 shares available in the limit order book at the first price point away from the spread's midpoint and 250 available at the second price point, then the average cost is 1.33 price points.

for the remainder of the book. The difference in projected expected costs for a particular order size (read as the horizontal difference between the two curves) illustrate the apparent tradeoffs associated with reducing the minimum tick size discussed earlier. For a small order, the investor expects to save about \$0.025 in the decimal environment (with a \$0.01 spread, one can buy shares \$0.005 above the spread midpoint while one cannot buy shares in the fractional world for less than \$0.03125). This advantage is available only to orders for few shares. Consider a 20,000 share order. For the pilot stocks (Fig. 2a), the trader expects to be \$0.02 worse off with decimals than with fractions. If displayed liquidity is the only available liquidity, a 20,000 share order in the matched stocks (Fig. 2b) receives an average price \$0.025 worse per share in decimals than in fractions. At an order size of 30,000 shares the trader can be much worse off with decimals if displayed liquidity is the only liquidity available. Expected costs are \$0.06 to \$0.08 per share higher after decimalization than before. Both Fig. 2a and b indicate that the break-even trade size for expected cost of trading with only displayed liquidity exceeds 10,000 shares. This is considerably greater than the similar comparison in G–K (their Figs. 1 and 2).

The expected costs computed above assume that the only liquidity available on the Exchange is displayed either by the floor community (specialists and floor brokers) or in the limit order book. Clearly, the NYSE provides substantial amounts of non-displayed liquidity (see Bacidore et al., 2002), which reduces the cost of trading relative to that displayed in Figs. 2a and b. Thus, the effect of decimalization on actual execution costs is an empirical issue.

4. Execution quality

4.1. Market orders

In the previous section, we find that there is less displayed liquidity with decimal trading than with fractions. Earlier, we showed that market orders comprise about the same proportion of system orders pre- and post-decimals and that system market orders are relatively larger after decimals. Given these results, we might expect market orders to receive poorer execution quality after decimals than before. Without additional, non-displayed liquidity, large market orders execute against less supplied liquidity, which suggests that these orders might use limit orders far from the current price to fill. Alternatively, the ability of liquidity suppliers to provide liquidity at additional price points (some quite close to the spread midpoint) and the existence of non-displayed liquidity might imply better post-decimal execution quality.

The effective spread is our execution quality metric. The effective spread is twice the signed difference between the trade price and the midpoint of the quoted NBBO spread at the time the order arrives at the NYSE. For buy orders, the effective spread is two times the trade price less the spread midpoint. For sell orders, the effective spread is the spread midpoint less the trade price times two. That is, the effective spread is the imputed cost of a round-trip trade relative to the spread midpoint. If a trader buys (sells) at a price above (below) the midpoint, then that trader incurs a cost to purchase (sell) the stock relative to the spread midpoint. If the midpoint represents the security's value, then the effective spread is how much more than value buyers pay (less than value sellers receive) when trading.[13]

Table 6 reports mean effective spreads. To calculate the reported means, we compute the effective spread for each trade (orders can result in several trades at different prices) using the order-receipt-time quote as the benchmark for all trades resulting from the order. Individual order averages are found by volume-weighting the effective spread from each trade resulting from a filled order. The figures reported in Table 6 are the volume-weighted averages across all orders. We report the overall means and the means for five *order*-size categories; 100–499 shares, 500–1,999 shares, 2,000–4,999 shares, 5,000–9,999 shares, and greater than or equal to 10,000 shares.

Overall, average effective spreads fall by about three cents around a security's conversion to decimal pricing. For the four smallest order size categories, the decrease in the average effective spread for the stocks affected by decimal pricing is statistically significant using either a binomial test (at the 0.01 significance level) or a *t*-test (at the 0.05 level). Mean effective spreads fall for the largest order-size category after decimal pricing begins. However, the control stocks also experience a decrease in quoted spread making it difficult to conclude that the sample stocks' mean quoted spread decreases relative to their control. Generally, the results suggest that execution quality improves after decimalization for the smaller order sizes and does not deteriorate for the largest orders.

Using the point estimates of effective spreads in Table 6 allows us to assess the price impact of large trades before and after the switch to decimal pricing. Consider the estimates in Panel E. For the three decimal pilot events, a 10,000 (or larger) system order executes seven cents (\$0.2315 – \$0.1597) closer to the order-receipt-time quoted bid-ask spread's midpoint after decimals than before. This suggests that large system orders had substantially less price impact in the decimal environment than in the fractional world. A seven cents per share savings on a 10,000 share order is meaningful statistically and economically. The conversion of the matched stocks to decimals is associated with a less impressive decrease in the large system orders' price impact. Estimated effective spreads fall by only \$0.0147, suggesting a modestly lessened price impact with decimals (but still \$147 on a 10,000 share order). This is consistent with Chakravarty et al. (2002), who find that institutional traders' execution costs decrease with decimals.[14]

[13] Because we use order data, we can have negative effective spreads if a buy (sell) order executes below (above) the spread midpoint.

[14] We reach similar conclusions using percentage effective spreads (i.e., the dollar effective spread divided by the spread midpoint). Our conclusions are similar to Goldstein and Kavajecz (2000) who use order data for the change to a \$1/16 tick size and Chakravarty et al. (2001) who use trade data for decimalization.

Table 6
Dollar effective bid-ask spreads around the conversion to decimal pricing of the pilot decimal stocks and a sample of control stocks[a]

Statistic	Three pilot phases: Before	After	%Post > pre[b]	t-stat[c]	Final decimal conversion: Before	After	%Post > pre	t-stat
Panel A. Order size between 100 *and* 499 *shares*								
Orders[d]	180,468	250,152			268,769	261,109		
Pilot	\$0.0710	\$0.0436	15.82%***	12.42***	\$0.0388	\$0.0404		
Match	\$0.0682	\$0.0725			\$0.0690	\$0.0458	9.49%***	6.606***
t-stat[e]	−0.6580	4.8370***			12.13***	1.5264		
Panel B. Order size between 500 *and* 1,999 *shares*								
Orders	109,585	172,210			181,778	192,753		
Pilot	\$0.1009	\$0.0651	23.42%***	9.643***	\$0.0603	\$0.0589		
Match	\$0.0700	\$0.0746			\$0.0950	\$0.0689	15.82%***	6.266***
t-stat	−16.14***	1.3591			13.34***	2.2373**		
Panel C. Order size between 2,000 *and* 4,999 *shares*								
Orders	34,462	55,071			65,282	50,636		
Pilot	\$0.1219	\$0.0954	30.38%***	7.567***	\$0.0778	\$0.0750		
Match	\$0.1174	\$0.1130			\$0.1112	\$0.0903	20.89%***	5.300***
t-stat	−2.0577**	4.0345***			10.70***	2.7947***		
Panel D. Order Size between 5,000 *and* 9,999 *shares*								
Orders	12,838	20,991			19,872	17,055		
Pilot	\$0.1451	\$0.1221	27.85%***	3.743***	\$0.1035	\$0.1006		
Match	\$0.1422	\$0.1353			\$0.1298	\$0.1120	27.85%***	2.671***
t-stat	−0.4270	2.2109**			5.196***	1.3449		
Panel E. Order size greater than or equal to 10,000 *shares*								
Orders	11,834	20,754			15,399	17,051		
Pilot	\$0.2315	\$0.1597	24.68%***	2.4935**	\$0.1358	\$0.1438		
Match	\$0.1646	\$0.1193			\$0.1718	\$0.1571	22.78%***	0.5301
t-stat	−2.3118**	−1.8950*			1.4581	0.6391		
Panel F. All order sizes								
Pilot	\$0.1448	\$0.1023	27.10%***	4.246***	\$0.0861	\$0.0896		
Match	\$0.1185	\$0.0995			\$0.1237	\$0.1031	24.68%***	2.229**
t-stat	−3.228***	−0.2835			4.445***	1.7969*		

[a] The Pilot Stocks are the 158 securities included in the New York Stock Exchange's phased decimal implementation pilot. The Matched Stocks are the 158 securities matched to the Pilot Stocks based on industry, price, security type, equity market capitalization, and trading volume.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed *t*-test.

[d] In the left side of the table (Three Pilot Phases), the number of orders is the number of orders in the pilot stocks in their pre-decimal and post-decimal sample periods. In the right side of the table (Final Decimal Conversion), the number of orders is the number of orders in the control stocks in their pre-decimal and post-decimal sample periods.

[e] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed *t*-test.

*Significant at the 0.10 significance level.

**Significant at the 0.05 significance level.

***Significant at the 0.01 significance level.

4.2. Limit orders

In the previous section, we examine the execution quality associated with market orders. As Table 1 indicates, marketable orders are about one-third of NYSE system orders. Non-marketable limit orders are the remainder of system orders. Although Figs. 1a and b provide an overview of how limit order traders respond to decimals, the change in the minimum price variation makes it difficult to conduct an exhaustive controlled evaluation of limit order strategies.[15] For example, a stock trading at a $1/16 spread before decimals cannot have limit orders bettering the quoted prices. The same stock trading at a $0.06 spread after decimals has five price points for a limit order to narrow the spread. Likewise, limit order traders selecting prices worse than the current quoted prices have many more price points to select from after decimals, making it difficult to compare worse-than-the-quote limit orders. Therefore, we focus on a limit order strategy available to traders both before and after decimalization. Specifically, we examine the relative execution quality of day, on-the-quote limit orders before and after decimals. A day limit order is one that expires (if not executed) at the end of the trading day it is submitted. An on-the-quote limit order is a buy (sell) order with a limit price equal to the current quoted bid (offer) price.

Similar to Harris and Hasbrouck (1996), we compare the on-the-quote limit order strategy to a market order strategy. In making this comparison, we presume that traders are committed. That is, we assume that traders convert unfilled (cancelled and expired) on-the-quote limit orders to market orders that promptly fill at the quoted price (offer price for buy orders and bid for sell orders). Using on-the-quote limit orders instead of market orders trades-off the advantage of buying (selling) at the bid (offer) when filled against chasing the price when not filled. We estimate the net advantage of the on-the-quote limit order strategy relative to the market order strategy before and after decimals. For each cancelled order, we assume that a market order of the same size executes at the quoted price when the limit order is cancelled. For orders expiring at day's end, we presume that the order fills at the closing quoted price that day. We assume that the trade price equals the limit price for filled limit orders. Consider the following example. If the quote is $20 bid and $20.10 offered, then a filled buy limit order for $20 saves the trader $0.10 per share. Should the quotes move to $20.10 bid and $20.20 offered and the trader cancel the limit order (or the limit order expires), we assume that the order fills at $20.20. This is $0.10 worse than the trader could have done with an immediate market order when the offer was $20.10. In this example, if one-half of the limit order's shares fill and one-half are cancelled, then the net advantage to the limit order is zero. Conversely, if more (less) than one-half of the limit order's shares fill, then the advantage of the limit order strategy relative to the market order strategy is positive (negative).

Table 7 summarizes our calculations. To compute the average net advantage to on-the-quote limit orders, we share-weight each order for a given stock and then equally-weight the stocks.

[15] We thank the referee for suggesting this analysis.

Table 7
The average net advantage to an on-the-quote limit order strategy relative to a market order strategy for the decimal pilot stocks and a matched sample of non-pilot stocks[a]

	Three pilot decimal introduction dates				Final conversion to decimals			
	Before	After	%Post > Pre[b]	t-stat[c]	Before	After	%Post > Pre	t-stat
Pilot stocks	−\$0.0159	\$0.0177	50.00%	1.0887	−\$0.0750	−0.0146		
Matched stocks	\$0.0278	−\$0.0714			−\$0.0427	−\$0.1154	53.85%	−0.4920
t-statistic[d]	−1.4252	1.1330			−0.2894	0.6508		

[a] To implement this comparison, we examine all buy (sell) limit orders with limit prices equal to the order-receipt-time quoted bid (offer) price. The execution prices of these limit orders are compared to a buy (sell) market order that is assumed to execute at the quoted offer (bid) price. Buy (sell) Limit orders that do not fill are assumed to be converted to buy (sell) market orders that execute at the offer (bid) price when the limit order is cancelled or expires. A positive number indicates that the limit order strategy provides better prices than the market order strategy. The average is computed by share-weighting orders for an individual stock and equally-weighting stocks.

[b] The reported fraction is compared to 50% using a chi-square test with one degree of freedom.

[c] The change in the reported mean (post-decimal mean minus pre-decimal mean) is compared to zero using a two-tailed t-test.

[d] The difference in the reported means (pilot stock mean minus matched stock mean) is compared to zero using a two-tailed t-test.

* Significant at the 0.10 significance level.

** Significant at the 0.05 significance level.

*** Significant at the 0.01 significance level.

Before the pilot stocks' conversion to penny increments, the on-the-quote limit order strategy provides prices \$0.0159 worse than a market order strategy. After decimals, the average advantage to the limit order strategy increases to a positive \$0.0177. This change (from −\$0.0159 to \$0.0177) is not statistically significant, however, using either a t-test or a chi-squared test that the proportion of positive changes differs from one-half. In addition, the pilot stocks' average advantage does not statistically differ from the matched stocks' average advantage before or after the pilot stocks' change to decimal pricing. Upon the matched stocks' conversion to decimal prices, the limit order strategy advantage falls from −\$0.0427 to −\$0.1154. Although this is a substantial change, it does not differ from zero at traditional significance levels using either parametric or non-parametric tests. Thus, we conclude that the change to decimal increments did not significantly affect the relative advantage to our on-the-quote limit order strategy.[16]

5. Conclusion

We examine changes in order submission strategies, in displayed liquidity, and in execution quality around the switch to decimal pricing for the NYSE pilot stocks

[16] Focusing only on decimal-matched pairs with at least 5,000 shares does not change our conclusions.

and a sample of matched stocks. We find no evidence that traders switch from traditional limit orders toward floor orders or toward market orders. As in Goldstein and Kavajecz (2000), the average size of non-marketable limit orders falls in the post-decimal periods, suggesting that traders reduce the size of the trading option they provide to other traders. We find that the limit order cancellation rate increases significantly in the post-decimal sample period, which also is consistent with G–K. Not surprisingly given the previous work on tick size reductions, quoted depth falls dramatically. Because of the finer price grid, displayed liquidity is available at prices closer to the quoted bid-ask spread's midpoint in the decimal environment than with fractions. This advantage is erased within a few cents of the quoted spread midpoint, however. Examining cumulative displayed liquidity, we find less limit order book depth beginning about ten cents into the limit order book. The decrease in cumulative displayed liquidity for our sample securities does not appear to be as dramatic as that found by G–K when studying the decrease in tick size to \$1/16. The reduction in displayed depth does not adversely affect traditionally measures of market orders' execution quality. As in G–K, small market orders enjoy better executions with decimals. Even for large market orders, however, execution quality is not worse after decimalization. Relative to market orders, limit order execution quality appears to be unaffected by decimals. Thus, the NYSE floor appears to provide dynamic, non-displayed liquidity in sufficient quantities to permit traders to execute market orders as well in the decimal environment as with fractions. This suggests that, from a trading cost perspective, the NYSE and institutional investors might be more positive about the decimal trading environment than they have to date.

The failure to find substantive changes in traders' order submission strategies and the resulting execution costs does not imply that the switch to decimal pricing was costless to traders. It is clear that less displayed depth makes it more difficult for off-floor traders to determine the price at which a block of stock should trade. This might force upstairs traders to use floor brokers for price discovery or to more frequently bring both sides of the trade to cross on the Exchange floor. Floor traders also might find decimals more challenging than fractions. With more price points available, specialists can struggle to find the "right" price for large trades. For example, with fractions everyone might agree that \$19.9375 is too low and \$20.0625 is too high, allowing a block to trade at \$20. With decimals, however, there can be disagreement about whether \$19.99 is too low and/or \$20.01 is too high. This suggests that it can take more effort to get a trade on the tape at a particular price.

The fact that large orders' execution quality does not deteriorate even though displayed liquidity decreases suggests that at least one aspect of floor traders' behavior changes in the post-decimal environment. Maintaining execution quality in the face of less displayed liquidity implies that floor traders (specialists and floor brokers) supplement the liquidity in the limit order book more frequently, at better prices, and/or for more shares after decimalization than before. That is, large orders do not "walk" the limit order book any farther after decimals than they did before, on average. Our comparison of system trading volume to total trading volume, however, indicates that floor traders (non-system volume) do not play a greater role in trading after decimal pricing begins. If the floor community is not supplementing displayed liquidity more frequently, then we conclude that they are trading at better prices and/or for more shares when they do supplement displayed liquidity. The smaller tick size gives floor traders the ability to trade more aggressively (in terms of prices and/or shares) and they use this new power when filling large orders to offset the reduction in displayed liquidity.

References

Ahn, H., Cao, C., Choe, H., 1996. Tick size, spread, and volume. Journal of Financial Intermediation 5, 2–22.

Bacidore, J., 1997. The impact of decimalization on market quality: an empirical investigation of the Toronto Stock Exchange. Journal of Financial Intermediation 6, 92–120.

Bacidore, J., Battalio, R., Jennings, R., 2002. Depth improvement and adjusted price improvement on the NYSE. Journal of Financial Markets 5, 169–195.

Battalio, R., Jennings, R., 2001. Getting 'Pennied': the effect of decimalization on traders' willingness to lean on the limit order book at the New York Stock Exchange. New York Stock Exchange Working paper 01-01.

Bollen, N., Whaley, R., 1998. Are 'Teenies' Better? The Journal of Portfolio Management, 10–24.

Chakravarty, S., Harris, R., Wood, R., 2000. The effect of decimal trading on market liquidity. Unpublished paper, Purdue University.

Chakravarty, S., Panchapagesan, V., Wood, R., 2002. Has decimalization hurt institutional investors? An investigation into trading costs and order routing practices of buy-side institutions. Unpublished paper, Purdue University.

Crack, T., 1995. Tinkering with ticks: choosing minimum price variation for the U.S. equity markets. Unpublished paper, Indiana University.

Edwards, A., Harris, J., 2000. Stepping ahead of the book. Unpublished paper, Securities and Exchange Commission.

Goldstein, M., Kavajecz, K., 2000. Eighth, sixteenths, and market depth: changes in tick size and liquidity provision on the NYSE. Journal of Financial Economics 56, 125–149.

Harris, L., 1996. Does a large minimum price variation encourage order display? Unpublished paper, University of Southern California.

Harris, L., 1997. Decimalization: a review of the arguments and evidence. Unpublished paper, University of Southern California.

Harris, L., Hasbrouck, J., 1996. Market versus limit orders: the superDOT evidence on order submission strategy. Journal of Financial and Quantitative Analysis 31, 213–231.

Harris, L., Panchapagesan, V., 1999. The information-content of the limit order book: evidence from NYSE specialists actions. Unpublished paper, University of Southern California.

Jones, C., Lipson, M., 2001. Sixteenths: direct evidence on institutional trading costs. Journal of Financial Economics 59, 253–278.

Kavajecz, K., 1999. A specialist's quoted depth and the limit order book. Journal of Finance 54, 747–771.

Peterson, M., Sirri, E., 2002. Order submission strategy and the curious case of marketable limit orders. Journal of Financial and Quantitative Analysis, forthcoming.

Porter, D., Weaver, D., 1997. Tick size and market quality. Financial Management 26, 5–26.

Ready, M., 1999. The specialist's discretion: stopped orders and price improvement. Review of Financial Studies 12, 1075–1112.

Ronen, T., Weaver, D., 2001. Teenies' anyone? Journal of Financial Markets 4, 231–260.

Securities and Exchange Commission, 2001. Order directing the exchanges and NASD to submit a decimalization implementation plan. Release No. 34-42360, January 28.

Sofianos, G., Werner, I., 2000. The trades of NYSE floor brokers. Journal of Financial Markets 3, 139–176.