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'Teenies' anyone?[☆]

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Abstract

We use the American Stock Exchange's May 1997 market-wide adoption of $1/16 ticks to examine several hypotheses relating to tick size reduction. Specifically, we consider volatility, other aspects of market quality, trader behavior, and specialist profits. The hypothesis that volatility is directly related to tick size is supported by significant decreases in both daily and transitory volatility. We also find that while spreads decline, depths do not. Finally, while we find no significant changes in overall specialist profits, we develop a direct test of changes in professional traders' activity in 'stepping ahead of the book', and find an increase in this behavior.

JEL classificaion: G14; G15; G18

Keywords: Market microstructure; Tick size; Volatility; Trader behavior

1. Introduction

A recent policy issue for security exchanges has been the adoption of decreased tick size for traded equity issues. The Toronto Stock Exchange

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(TSE), American Stock Exchange (AMEX), New York Stock Exchange (NYSE), and Nasdaq have all undergone market-wide tick size reductions in the past few years.

On May 7, 1997 the AMEX became the first U.S. exchange to adopt \$1/16 ticks for all stocks priced over \$1.[1] We use this event to examine several previously untested hypotheses regarding tick size reduction. For example, we test the hypotheses that observed volatility and trader behavior are related to tick size. Additionally, our dataset offers the unique opportunity to examine the impact of a tick size reduction in a price–time priority system, which is the structure generally assumed in the theoretical literature. For example, Harris (1994) states that a reduction in tick size will cause spreads to narrow and depths to decline when price–time priority rules prevail. Since the AMEX is the only US exchange that has price/time priority for all stocks, this paper affords the opportunity to provide evidence that can be directly linked to this extant literature.[2] Finally, this paper provides the first empirical analysis of tick size impacts on professional trader behavior (such as the practice of 'stepping ahead of the book'), as well as estimates of specialists' profits.

The tests we conduct provide evidence in support of the hypothesis that market quality is not hampered by the tick reduction: while dollar spreads decline, depths do not decrease. Further, significant volatility decreases are observed, and are attributed to the tick size reduction. This paper can thus be seen as having important policy implications for exchanges that use trading rules such as tick size, to attract order flow and is of interest to both academics and regulators (who must measure the social cost of different trading rules).

The growing literature on tick size and its impact on market quality and trading behavior is extensive, both on the theoretical and the empirical spectrums. For example, Harris (1996) examines the impact of tick size on order exposure; Cordella and Foucault (1996), Angel and Weaver (1998), and Panchapagesan (1997) examine the impact of tick size and priority rules on order submission strategies. Anshuman and Kalay (1994), Bernhardt and Hughson (1996), Chordia and Subrahmanyam (1995) and Kandel and Marx

[1] The Amex has been gradually decreasing its tick size since 1992. In August 1992, the tick size was reduced from \$1/8 to \$1/16 for all stocks priced below \$5, and subsequently for all stocks below \$10 in February 1995.

[2] The NYSE maintains price/parity priority (the first order at a price has priority, otherwise larger orders generally have priority over smaller orders with various tie-breakers being used), Nasdaq has no priority rules, and the TSE currently uses price/sharing priority rules (the secondary priority rule allocates incoming orders among members with orders on the book first equally for a minimum amount and then pro-rata) for all of its stocks. One trading system of the TSE used price/time priority rules (incoming orders are filled against orders on the book using a time ordered queue) for its stocks at the time of a tick reduction. However, the stocks in that system were generally less liquid than stocks in the other TSE system. Therefore, results for the TSE cannot be generalized across all stocks.

(1997) show that non-trivial ticks can lead to the existence of uncompetitive spreads, while Chordia and Subrahmanyam (1995) further show that they can lead to uncompetitive practices such as preferencing of order flow. Finally, Angel (1997) points out that firms can keep their relative tick constant by splitting their shares as tick sizes are reduced. Thus, firms, rather than exchanges, will determine the lower bound on relative ticks. Theoretical predictions regarding the expected changes in depths following tick reductions include those in Harris (1994), who predicts that depths for stocks with binding spread widths (bound by the tick size) will decline since liquidity providers face an increased risk of price improvement. In contrast, Chordia and Subrahmanyam (1995) suggest that depths will not decline since liquidity providers are competing to capture excess rents.

Empirical evidence on the impact of tick reductions upon trading costs includes Jones and Lipson (1999), who use institutional data from trades on the NYSE and Nasdaq to show that the benefits of tick reduction are largely confined to small orders, and Goldstein and Kavajecz (2000) who document depth reductions throughout the NYSE's limit order book following the July 1997 NYSE tick size reduction. Both Ahn et al. (1996) and Crack (1995) examine the 1992 tick reduction on the AMEX for stocks trading under \$5 and find reduced spreads of about 10%.[3] Several other studies examine recent decreases in tick changes on the Toronto Stock Exchange. They include Ahn et al. (1998), Bacidore (1997), Huson et al. (1997), and Porter and Weaver (1997). While these studies differ in sample and methods, they generally conclude that market quality improved following the TSE's tick size reduction.

We develop a model that illustrates how the probability that the bid–ask spread narrows as a result of a tick size reduction is directly related to the amount of tick-induced rounding prior to the reduction. We also show that narrowing can occur even for stocks with spreads greater than one tick. Consistent with the predictions of our model and results of previous studies, our tests indicate that bid–ask spreads generally decrease after the AMEX tick size reduction. However, in contrast with prior findings, we document no significant depth changes overall. We also examine the impact of a tick size reduction on trader behavior. In particular we find that incidences of "stepping ahead of the book" increase following the tick size reduction. Further, our specialist participation data indicates that no changes in market maker profits occur as a direct result of the AMEX tick size reduction. Finally, we document a significant reduction in volatility following the tick size reduction. This last result can be seen as further support of the notion that tick size reductions can

[3] Ahn et al. (1996) examine the impact of the September 3, 1992 Amex switch to 'teenies' for low price stocks only (stocks with prices under \$5). The authors find reductions in spreads, accompanied by no significant changes in depths or volume.

improve market quality. Interestingly, this study is the first to provide direct evidence on the impact of tick reductions on volatility.

The paper is organized as follows. Section 2 provides a data description. Section 3 discusses the issues, states our hypotheses, and discusses our results. Section 4 provides concluding remarks.

2. Data

Our data set consists of all American Stock Exchange stocks that underwent a regime change in tick size on Wednesday, May 7, 1997. The data span the period April 1, 1997 through June 30, 1997. We omit from the sample one full trading week of data both before and after the change in order to prevent potential biases. We thereby define the pre-change period as the four-week period from Wednesday, April 2 through Tuesday, April 29, and the post-change period as the four-week period from Thursday, May 15 through Thursday June 12. Each sample consists of 20 trading days.

Certain inclusion constraints are enforced. We consider all common stocks that traded above \$10 during the pre-period, provided that they did not split or undergo a price change of more than 50% over the entire period, and for which there are at least 50 quote revisions in each period (pre and post). These constraints result in a sample size of 324 firms.

Our data include all trade and quote records for the period surrounding our study. Each quote record details the time-stamped bid and ask quote as well as respective size and exchange origin. Each transaction record is time-stamped, includes price and quantity, and separates each AMEX-originated trade into its components. Thus, we are able to determine the exact nature of each side of the trade. For example, large orders are often filled by multiple contra-orders. If a market order to buy 10,000 shares is filled by several limit orders at the inside (with the remainder filled from the specialist's inventory), our data set separately identifies the large buy order, the individual sell orders filling it, and the specialist participation (buy or sell) in each trade.

For tests involving volume and volatility measures, we control for factors other than tick size by constructing a matched sample of NYSE or Nasdaq stocks. For each AMEX stock, a match is identified on either the NYSE or Nasdaq as the stock closest in price and nearest in pre-change period number of trades to the AMEX stock.[4]

[4] We included the number of trades as a matching criterion. This was critical in the comparison of volatility measures across samples, where non-synchronous trading patterns can render statistical inferences difficult.

3. The issues

In this section, we develop the arguments regarding the potential impacts of a tick size reduction on market quality. Specifically, we consider execution costs, other forms of liquidity, and volatility. We then consider the effects on trader behavior. Finally, we discuss potential market maker profits that may change as a result of the switch to 'teenies'. Our results are consistent with the hypothesis that market quality is not hampered by the tick reduction: While spreads decline, we observe no significant changes in quoted depth along with significant decreases in volatility.

3.1. Spreads

In this section, we investigate the impact of the AMEX tick reduction on execution costs, which are typically measured as the bid–ask spread. We consider several different spread measures. The most common measure is quoted dollar spread (defined as $A_{i,t} - B_{i,t}$), where $A_{i,t}$ and $B_{i,t}$ are the inside ask and bid quotes for firm i at time t. Alternatively, the quoted percentage spread (defined as $[2(A_{i,t} - B_{i,t})/(A_{i,t} + B_{i,t})]100$) expresses the quoted spread as a percentage of price. Effective dollar spreads (defined as $2\,|P_{i,t} - M_{i,t}|$ where $P_{i,t}$ is the price of stock i at time t, and $M_{i,t}$ is the midpoint of the spread for firm i at time t), take into account the transaction price. Finally, effective percentage spreads (defined as $([2\,|P_{i,t} - M_{i,t}|]/M_{i,t})100$) express the effective spread as a percentage of price.

We test whether any observed spread reductions are consistent across the various measures used, and for variation across trade sizes and stock price levels. For example, we expect higher priced stocks to exhibit the greatest reductions in dollar quoted spreads following the tick reduction. This is especially true if the level of competition among traders is inversely related to the tick size.

The theoretical predictions of spread reductions can be attributed to either the price competition argument (the propensity of traders to improve on existing limit orders increases with tick size reductions), or to the price discreteness argument (discrete prices cause traders to round desired spreads to the next highest tick, which will be nearer in the face of smaller tick sizes). It has been argued that another impact of discreteness is that ticks can create lower bound constraints on relative spreads for low-priced stocks.[5] This would imply that tick-induced discreteness prevents spreads from narrowing below \$1/8. Indeed, Chung et al. (1997) find that on the Toronto Stock Exchange, stocks that have binding ticks prior to the tick reduction experience the largest spread reductions following the change. While this "discreteness effect"

[5] See, for example, Harris (1990).

prevents spreads from narrowing below \$1/8 it can also prevent spreads greater than \$1/8 from reaching their equilibrium level. Therefore, the "discreteness effect" potentially exists for both dollar and percentage spreads for *all* stocks, as shown by the following model.[6]

Let the "true" spread, S^*, be defined as the minimum spread necessary for market makers to earn an economic profit in a competitive market.[7,8] Further, let S be the quoted spread and τ be the exchange-imposed non-zero tick size.[9] It can then be shown that

$$S = Int\left(\frac{S^*}{\tau}\right)\tau + \gamma\tau, \tag{1}$$

where $Int(\bullet)$ yields the integer portion of a function and γ is an indictor variable equal to 1 if $Int(S^*/\tau) \neq (S^*/\tau)$, otherwise 0. It can then be seen that $S = S^*$ only if S^* is a multiple of τ, otherwise $S > S^*$.[10] That is, the quoted spread equals the true spread only when the tick size approaches zero, or when the true spread is a multiple of the tick size. Otherwise, the quoted spread will be rounded up to the next largest tick (if the quoted spread were less than "true" spread, market makers would not earn an economic profit and would exit the market). Therefore, discreteness may cause quoted spreads to be wider than "true" spreads.

Further examination of the model allows us to determine the conditions under which quoted spreads will narrow following a reduction in tick size. Let τ' be the new tick such that $\tau' < \tau$ and let S' be the observed quote following the reduction in tick. It can be shown that $S' < S$ only if $S - S^* > \tau'$, otherwise $S' = S$. In the case of the AMEX, this is consistent with spreads narrowing (after the switch to 1/16th's) only if the difference between the old quoted spread and the old 'true spread' is greater than 1/16th. Thus, we show that the

[6] The model we present is rather simplistic, and cannot be easily used to model price changes. An ordered probit model as used by Hausman et al. (1992) may be more appropriate to that end. However, our simple model is used for illustrative purposes only, to show that a binding spread condition is not a necessary condition to observe a narrowing of spread following a reduction in tick size.

[7] Those market makers with larger required profits will not make a market in the stock.

[8] An alternative interpretation of S^* is the equilibrium spread, defined as the upper bound on spread in an informationally efficient market with a single market maker and a central limit order book with public precedence.

[9] A similar model can be developed for relative spreads by dividing S and τ by price.

[10] Our model is similar in spirit to Harris (1994), Kandel and Marx (1997) and Rhodes-Kropf (1998). Kandel and Marx examine competing market makers under a random priority rule. The lack of time priority allows for multiple Nash equilibria, with market makers preferring a spread one tick wider than the smaller equilibrium spread. Cordella and Foucault (1996) show that time priority (which is descriptive of the Amex) will lead to a smaller spread than under random priority. Rhodes-Kropf (1998) develops a model of competing market makers in a single auction setting.

Table 1
Descriptive statistics of portfolios for AMEX stocks that experienced a reduction in tick size

This table shows average price, average percentage of \$1/8 spreads, average daily share volume (000s), and the number of stocks in our sample. Groups were formed by ranking stocks by average price and separately by binding percentage for the period April 2–29, 1997. Binding is the percentage of \$1/8 spreads experienced for the stock prior to the tick reduction. Stocks were ranked and placed into price and binding quartiles. All numbers reported below are for the ranking period April 2–29, 1997. Overall averages are also provided.

A. Price quartiles					
	All firms	1 (Lowest)	2	3	4 (Highest)
Average price	\$21.28	\$11.74	\$14.29	\$18.79	\$40.31
Average % \$1/8 quotes	28.9%	37.9%	31.2%	27.5%	18.9%
Average volume	22.204	8.54	10.66	23.90	45.70
N	324	81	81	81	81
B. Binding quartiles					
		1 (Most)	2	3	4 (Least)
Average price		\$16.51	\$16.31	\$21.05	\$31.27
Average % \$1/8 quotes		58.3%	33.6%	18.4%	5.2%
Average volume		65.49	15.47	5.09	2.76
N		81	81	81	81

spread reduction can occur due to discreteness even if equilibrium spreads are greater than \$1/8. In other words, reductions are expected to occur even in stocks without binding spread conditions. However, a binding spread condition may indeed increase the probability of a spread narrowing (following the tick size reduction).

Since the hypotheses predict that the spread impacts depend upon whether the tick was binding, and upon the price levels, we form both price and 'binding' quartiles (where 'binding' refers to the percentage of \$1/8 spreads observed per stock prior to the tick reduction). Table 1 contains descriptive statistics for our sample.

The first execution cost examined is quoted spread. Table 2 contains the results for dollar quoted spreads (Panel A) and for percentage quoted spreads (Panel B). In both cases the spreads are time-weighted. Overall dollar spreads decline by about \$.02 and percentage spreads decline by 0.2 percentage points. The highest price quartile indicates the smallest reductions and the second-lowest price quartile exhibits the largest reduction for percentage quoted spreads. However, examining the results grouped by binding quartile reveals that even those stocks with least binding spreads experience spread reductions. This is consistent with the prediction of our model.

Table 2
Change in time-weighted quoted spreads following the reduction in tick size

This table shows the average time-weighted quoted spreads for AMEX stocks during the periods April 2–29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick size reduction, which occurred on May 7, 1997. Also reported is the average change between the two periods. Panel A lists the results for quoted spreads expressed in dollar terms and defined as $A_{i,t} - B_{i,t}$, where $A_{i,t}$ and $B_{i,t}$ are the inside ask and bid quotes for firm i at time t. Panel B lists the results for quoted spreads expressed as a percentage of the spread midpoint at time t. Stocks are grouped by price (A.1 and B.1) and binding (A.2 and B.2) quartile. Binding is defined as the percentage of $1/8 spreads in the pre-period. In Panels A and B, tests of significance are paired t-tests. Panel C reports the results of the regression

$$\overline{S_{i,t}} = \beta_0 + \beta_1 \overline{Price_{i,t}} + \beta_2 \overline{Volume_{i,t}} + \beta_3 \sigma_{i,t} + \beta_4 \, TickDummy_{i,t} + \beta_5 \, BindDummy_{i,t},$$

where $\overline{S_{i,t}}$ is the average quoted (dollar or percentage) spread for firm i in period t (pre- or post-reduction); $\overline{Price_{i,t}}$ is the average closing price for firm i during period t; $\overline{Volume_{i,t}}$ is the average daily share volume for firm i during period t; $\sigma_{i,t}$ is the standard deviation of daily return for firm i during period t; *TickDummy* is a dummy variable assigned the value of 1 if the period is post, otherwise zero, and *BindDummy* is a dummy variable assigned the value of 1 if the proportion of quoted spreads equaling $.125 in the pre-period is greater than 50%, and otherwise zero. Parameter t statistics based on Hansen-White heteroskedastic consistent standard errors are in italics.

A: Quoted spread (in dollars)

A.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
Before	0.296	0.219	0.255	0.266	0.445
After	0.277	0.205	0.230	0.251	0.423
Mean change	−0.019[a]	−0.015[a]	−0.024[a]	−0.015	−0.022
Median change	−0.018	−0.015	−0.019	−0.026	−0.012

A.2: Binding quartiles

	1 (Most)	2	3	4 (Least)
Before	0.177	0.225	0.278	0.050
After	0.159	0.207	0.263	0.480
Mean change	−0.018[a]	−0.019[a]	−0.015[a]	−0.024
Median change	−0.019	−0.016	−0.019	−0.019

B: Quoted spread (as percentage of spread midpoint)

B.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
Before	1.569%	1.878%	1.786%	1.424%	1.187%
After	1.392	1.674	1.550	1.277	1.067
Mean change	−0.177[a]	−0.204[a]	−0.236[a]	−0.147[b]	−0.119[a]
Median change	−0.158	−0.202	−0.212	−0.200	−0.088

Table 2 (*continued*)

B.2: Binding quartiles	1 (Most)	2	3	4 (Least)
Before	1.204	1.507	1.581	1.983
After	1.038	1.327	1.384	1.819
Mean change	−0.166[a]	−0.181[a]	−0.196[a]	−0.164[b]
Median change	−0.144	−0.163	−0.190	−0.148

C. Regression results

Measure	Intercept	Price	Volume	σ	Tick dummy	Bind dummy	*F*-Stat R^2
Quoted	0.130	0.007	−0.0004	2.755	−0.024	−0.082	144.2
dollar spread	*8.684*[a]	*16.557*[a]	*−2.917*[a]	*3.294*[a]	*−2.015*[b]	*−9.226*[a]	0.525
Quoted	0.016	−0.00008	−0.00002	0.163	−0.001	−0.003	30.7
percentage spread	*19.979*[a]	*−3.279*[a]	*−3.071*[a]	*4.039*[a]	*−2.822*[a]	*−7.911*[a]	0.187

[a] Denotes significant at the 0.01 level.
[b] Denotes significant at the 0.05 level.

A relevant concern in our analysis is that the observed reduction in quoted spreads may not be directly attributable to the tick reduction. That is, confounding effects may be driving the level changes.[11] Accordingly, we perform a regression analysis to determine the cause of the observed reduction in quoted spreads. For each firm *i*, *we regress* the average spread (dollar or percentage), $\bar{S}_{i,t}$, against: average closing price, $Price_{i,t}$; average daily share volume, $Volume_{i,t}$; and average standard deviation of daily return, $\sigma_{i,t}$. The subscript *t* indicates whether the observation is pre- or post-tick reduction. Two dummy variables are included: $TickDummy_{i,t}$ is assigned the value 1 if the spread measure is for the pre-tick reduction period, and 0 otherwise. To capture the impact of a binding condition on the stock's spread, we also include a dummy variable, $BindDummy_{i,t}$, that takes on the value of 1 if the proportion of quoted \$1/8 quoted spreads in the pre-period was greater than 50%, and is otherwise zero.

The regression equations can be generally written as[12]

$$\overline{S_{i,t}} = \beta_0 + \beta_1\,\overline{Price_{i,t}} + \beta_2\,\overline{Volume_{i,t}} + \beta_3\sigma_{i,t} + \beta_4\,TickDummy_{i,t} + \beta_5\,BindDummy_{i,t}. \tag{2}$$

[11] Stoll (1985) shows that relative spread is inversely related to price and trading activity, and directly related to vzolatility.

[12] It could be argued that the relationship between spread and the independent variables changes between the pre- and post-period, and that interactive variables should therefore be used. For example, Harris (1994) argues that tick size reduction will increase volume, while Angel (1997)

We expect the parameter estimate for *TickDummy* to be significantly different from zero if the tick size reduction affects the spread. Tests of significance are based on Hansen-White heteroskedastic consistent standard errors. Panel C of Table 2 indicates that the results for quoted spreads are robust to these specifications, and are therefore probably not merely artifacts of confounding factors. In particular, we find that a binding condition contributed to the observed decline in quoted spreads, as evidenced by the statistically significant negative parameter estimate for *BindDummy*. The parameter estimate for *TickDummy* is negative and statistically significant for both spread measures. Thus, the tick reduction still contributes to the observed decline in spreads even after controlling for a binding condition. This further confirms the predictions of our model for quoted spreads.

Effective spreads (which take into account the relationship between execution price and quoted spread) are often considered a more appropriate measure of trading costs than are quoted spreads for large traders. See, for example, Hasbrouck (1991), who argues that large-order traders must often make price concessions to execute. In addition, Lee and Ready (1991) find that about 30% of the trades in their sample of NYSE stocks execute inside the quoted spread. The findings of Benston et al. (1997) as well as Jones and Lipson (1999) suggest that trade size is an additional important factor for effective spreads. Specifically, both studies show that tick size reductions have a differential effect on trades of different sizes.[13] Accordingly, we also test whether the spread reductions observed may be a function of trade size. As in Jones and Lipson (1999), we examine effective spreads for portfolios formed of all trades; trades of less than 1,000 shares; trades between 1,000 and 9,999 shares; trades between 10,000 and 99,999 shares, and trades of 100,000 shares or

footnote (*continued*)
argues that actual ticks are related to price levels, since firms use stock splits to establish an optimal relative tick. Therefore, it may be impossible to disentangle tick size induced changes from structurally induced changes in the relationships between independent and dependent variables. Thus, we do not report results of regressions including interaction variables. However, we find that when we include interaction variables, *TickDummy* is still of the correct sign but is statistically significant only for percentage quoted and percentage effective spreads.

[13] Benston et al. (1997) develop a measure of effective spread that is independent of a transaction occurring and incorporates a notion of price impact. They assume that incoming orders will execute exclusively against the book at subsequent price levels. They argue that changes in depth away from the inside market will impact order execution quality. They employ order data to reconstruct a dynamic limit order book. We do not have order data, and are therefore unable to construct their measure. Jones and Lipson (1999) use the Plexus database, and as such are able to calculate transaction cost measures based on the standing quotes *at the time the order was placed*. Standard effective spread measures assume the order was placed at the time of execution, and therefore may impart a bias for large orders that may take a while to be "worked".

Table 3
Change in volume-weighted effective spread following the reduction in tick size

This table shows the average volume-weighted effective spread for AMEX stocks during the periods April 2–April 29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick reduction, which occurred on May 7, 1997. Also reported is the average change between the two periods. Panel A lists the results for effective spread in dollar terms, defined as 2 $|P_{i,t}-M_{i,t}|$, where $P_{i,t}$ is the price of stock i at time t, and $M_{i,t}$ is the midpoint of the spread for firm i at time t. Panel B lists the results as a percentage of the spread midpoint at time t. Effective spreads are weighted by the number of shares for each transaction. Stocks are grouped by price (A.1 and B.1) and binding (A.2 and B.2) quartile as well as by trade size (A.3 and B.3). Binding is defined as the percentage of $1/8 spreads in the pre-period. In Panels A and B, tests of significance are paired t-tests. Panel C reports the results of the regression

$$\overline{M_{i,t}} = \beta_0 + \beta_1\,\overline{Price_{i,t}} + \beta_2\,\overline{Volume_{i,t}} + \beta_3\sigma_{i,t} + \beta_4\,TickDummy_{i,t} + \beta_5\,BindDummy_{i,t},$$

where $\overline{M_{i,t}}$ is the average quoted or dollar spread for firm i in period t (pre- or post-reduction); $\overline{Price_{i,t}}$ is the average closing price for firm i during period t; $\overline{Volume_{i,t}}$ is the average daily share volume for firm i during period t; $\sigma_{i,t}$ is the standard deviation of daily return for firm i during period t; *TickDummy* is a dummy variable assigned the value of 1 if the period is post, otherwise zero, and *BindDummy* is a dummy variable assigned the value of 1 if the proportion of quoted spreads equaled $.125 in the pre-period, otherwise zero. Parameter t statistics based on Hansen-White heteroskedastic consistent standard errors are in italics.

A: Effective spread (in dollars)

A.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
Before	0.229	0.165	0.203	0.198	0.354
After	0.214	0.154	0.183	0.189	0.328
Mean change	−0.016[b]	−0.010	−0.019	−0.008	−0.026
Median change	−0.011	−0.016	−0.008	−0.007	−0.015

A.2: Binding quartiles

	1 (Most)	2	3	4 (Least)
Before	0.147	0.158	0.213	0.399
After	0.129	0.155	0.200	0.370
Mean change	−0.018	−0.003	−0.013	−0.029
Median Change	−0.013	−0.001	−0.016	−0.014

A.3: By trade size

	< 1,000	1,000–9,999	10,000–99,999	> 99,999
Number of firms with trade size	324	302	113	10
Before	0.208	0.223	0.146	0.279
After	0.197	0.202	0.137	0.121
Mean change	−0.011[a]	−0.021[a]	−0.009	−0.157
Median change	−0.016	−0.015	−0.004	−0.036

Table 3 (*continued*)

B: Effective spread (as percentage of spread midpoint)

B.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
Before	1.211%	1.403%	1.423%	1.061%	0.946%
After	1.072	1.259	1.228	0.965	0.833
Mean change	−0.139[a]	−0.144[a]	−0.205[a]	−0.095	−0.113[b]
Median change	−0.113	−0.168	−0.102	−0.104	−0.065

B.2: Binding quartiles

	1 (Most)	2	3	4 (Least)
Before	1.005	1.064	1.219	1.555
After	0.835	0.988	1.047	1.416
Mean change	−0.169[a]	−0.076	−0.172[a]	−0.139
Median change	−0.124	−0.057	−0.140	−0.11

B.3: By trade size

	< 1,000	1,000–9,999	10,000–99,999	> 99,999
Number of firms with trade size	324	302	113	10
Before	1.104	1.214	0.857	1.684
After	0.984	1.045	0.749	0.572
Mean change	−0.120[a]	−0.169[a]	−0.108	−1.112
Median change	−0.116	−0.137	−0.088	−0.208

C. Regression results

Measure	Intercept	Price	Volume	σ	Tick dummy	Bind dummy	F-Stat R^2
Effective dollar spread	0.104	0.005	−0.0003	2.312	−0.019	−0.046	76.09
	6.122[a]	*9.599*[a]	*−2.903*[a]	*2.957*[a]	*−1.653*	*−4.016*[a]	0.367
Effective percentage spread	0.012	−0.00006	−0.00002	0.137	−0.001	−0.002	17.09
	17.381[a]	*−3.358*[a]	*−3.092*[a]	*3.821*[a]	*−2.324*[b]	*−2.210*[a]	0.111

[a] Denotes significant at the 0.01 level.
[b] Denotes significant at the 0.05 level.

more. Table 3 indicates that effective spreads decline overall. We find no clear pattern of significant changes in effective spreads for either price or binding quartiles. However, we do find a statistically significant reduction in effective spreads for trades of less than 10,000 shares. This finding may indicate that small traders benefit most as a result of the tick size reduction.[14]

Finally, we conduct regressions (Eq. (2)) controlling for potentially confounding effects. Overall, the results suggest that the observed reductions documented in panels A and B of Table 3 are not mere artifacts of potentially confounding factors. Table 3, Panel C indicates that the majority of the reduction in effective spreads is confined to stocks for which the tick was binding prior to the tick reduction.

In summary, the reduction in tick size is accompanied by a reduction in both quoted and effective spreads. The fact that spread reductions are observed for all binding quartiles supports the predictions of our model. This suggests that a binding tick condition is not a necessary condition for spread narrowing. Finally, the evidence regarding effective spread changes suggests that small traders benefit most from the tick reduction. In the next two sections, we examine the impact of tick size reduction on other measures of liquidity.

3.2. Depths and volumes

Recent studies indicate that spreads should not be examined in isolation when considering liquidity provision.[15] Extant theoretical predictions support a decline in depths following tick reductions. See, for example, Harris (1994), who argues that large minimum ticks (and time precedence) may protect traders from 'quote matchers' who improve on price following the exposure of a large (informed) trade. Thus, a smaller tick should reduce the cost of stepping in front of exposed orders, rendering traders reluctant to expose orders in the advent of tick size declines. This in turn should lead to lower quoted depths. Indeed, recent empirical evidence documents depth reductions following tick reductions on different exchanges. Bacidore (1997) and Porter and Weaver (1997) both report significant reductions in depths for their sample of Toronto Stock Exchange stocks subsequent to tick

[14] Ahn et al. (1998), Porter and Weaver (1997), and Goldstein and Kavajecz (2000) suggest that trading activity is an important predictor of tick size effects. In a previous version of this paper we ranked stocks according to high/low price and volume and formed two-dimensional quadrants. The results from partitioning by price and volume are consistent with the findings reported here for both quoted and effective spreads.

[15] See, for example, Lee et al. (1993) who find that volume shocks impact liquidity by simultaneously widening spreads and reducing depths, and Rhodes-Kropf (1998) who provides theoretical justification for spread narrowing to be accompanied by depth reductions following tick reductions under the assumption of competitive market makers in an auction setting.

Table 4
Change in time-weighted NBBO quoted depth following the reduction in tick size

This table shows the average time-weighted NBBO quoted depth for AMEX stocks during the periods April 2–29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick size reduction, which occurred on May 7, 1997. Also reported is the mean and median logarithmic difference between the two periods (post/pre). We define quoted depth as the sum of the inside ask and bid depths for firm i at time t. Stocks are grouped by price (Panel A) and binding (Panel B) quartile. Binding is defined as the percentage of \$1/8 spreads in the pre-period. Mean logarithmic differences more than two standard deviations from the mean for each price quartile are considered outliers and excluded from the sample. Tests of significance are a t-test.

A: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
N	305	76	77	76	76
Before	74.643	89.285	89.739	62.378	53.687
After	66.805	80.887	87.345	59.531	47.204
Mean logarithmic difference (%)	−3.12	0.75	−1.02	4.04	−16.28[a]
Median logarithmic difference (%)	−2.78	−3.84	0.68	2.19	−12.96
Percentage with depth reduction	54.09%	55.26%	49.35%	47.37%	64.57%

B: Binding quartiles

	1 (Most)	2	3	4 (Least)
N	79	76	78	72
Before	142.033	68.175	54.229	27.212
After	119.523	73.941	51.681	29.962
Mean logarithmic difference (%)	−8.79	7.69	−1.85	−2.39
Median logarithmic difference (%)	−16.39	−0.67	−1.19	1.87
Percentage with depth reduction	65.82%	51.32%	52.56%	45.83%

[a] Denotes significant at the 0.01 level.

price changes. Goldstein and Kavajecz (2000) examine the impact of the NYSE tick reduction and find that quoted depths decline throughout the limit order book.

We test the hypothesis that depth, measured as the sum of the NBBO ask and bid depths, is equal before and after the tick reduction. Since we find that the distribution of depths for each quartile is skewed, we calculate the log of the ratio of post- to pre-period depth for each firm. Table 4 reports the mean and median of the logarithmic difference for each quartile as well as the number of firms that exhibited a reduction in depth following the tick change.[16]

[16] See Ahn et al. (1996) who implement a similar procedure. We also eliminate outliers by excluding observations more than two standard deviations from the mean.

With the exception of price quartile 4, no significant changes in depth are exhibited following the tick reduction.[17,18]

Another important aspect determining liquidity is volume. Harris (1994) predicts an increase in volume following a tick reduction as a result of increased propensity to trade when execution costs decline. However, recent evidence from other exchanges documents insignificant changes in trading volume after tick reductions. See, for example, Ahn et al. (1998), Bacidore (1997), Bessembinder (2000), Huson et al. (1997), and Porter and Weaver (1997).

Since the volume distributions are also found to be skewed, we again report the logarithmic difference measures. In order to control for exogenous volume changes, we construct a control sample of similar stocks not trading on AMEX, and therefore unaffected by the switch to 'teenies'. For each AMEX stock, a match is found as the Nasdaq or NYSE stock closest in price to our AMEX stock, with a similar level of trading activity in the pre-change period. Table 5 indicates that while mean logarithmic AMEX share volume increases significantly after the tick reduction, the increase is not as large as that of the matched sample. This implies that the volume increases are not directly attributable to the switch to 'teenies'. The volume results found in this paper, and mirrored in other studies may be viewed as puzzling if volume increases are expected as a result of smaller tick sizes.[19] Since we are concerned that our results may be an artifact of the partitioning method employed in this paper, we also condition

[17] Although we find that depths decline for some stocks, the fact that the majority of the stocks in our sample do not experience depth changes is surprising, especially in light of recent evidence from other exchanges, reporting significant depth declines. We test whether a specialist convention of quoting minimum depths (500–1,000 shares) may explain the fact that we find no statistically significant overall change in depth. Frequency distributions of quoted bid and (separately) ask depths indicate that the most commonly found NBBO bid or ask depths observed in both the pre- and post-periods are 500 and 1,000 (occurring about 12% of the time each for the pre-period, and 13% of the time each in the post-period). Indeed, the minimum quoted size convention may be masking a reduction in public liquidity on the Amex and regional exchanges. Finally, the minimum quoted depth convention, which we observe on Amex, suggests that small firms may benefit from being listed on a specialist-based system.

[18] A second possible explanation for this discrepancy is that our definition of depth is capturing other effects not associated with tick size reduction. Recall that we use the NBBO depth, which is the aggregate sum of inside quote depths across exchanges. If one or more of the exchanges had an increase in depth unrelated to the tick reduction, this may mask any decrease in the depth quoted by the remaining exchanges. Prior to the beginning of our study period, the Chicago Stock Exchange undertook a program to increase trades in Amex-listed stocks, which may account for our results.

[19] See, for example, Harris (1994), who predicts increases in volume due to a smaller tick size. Since traders face lower trading costs, they are more willing to trade (increasing volume).

Table 5
Change in share volume following the reduction in tick size

This table shows the average share volume for the AMEX, as well as a matched sample, per stock during the periods April 2–29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick size reduction, which occurred on May 7, 1997. Also reported are the mean and median logarithmic differences (post/pre) in percentage terms. For each AMEX stock a match was found on either the NYSE or Nasdaq. Matches were determined by finding the stock closest in price and number of trades, to the AMEX stock. Panel A (Panel B) contains the results for stocks grouped by price (binding) quartile. Binding is defined as the percentage of \$1/8 spreads in the pre-period. Panel C contains results for stocks grouped by ranking by average price and separately by average daily volume for the period April 2–29, 1997. Stocks were then placed in one of four quadrants according to their joint price and volume ranking (high or low). Mean logarithmic differences more than two standard deviations from the mean for each group's price quartile are considered outliers and excluded from the sample. Its pair (AMEX or Match) is then also excluded. Tests of significance are a *t*-test.

A: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
N	292	74	74	73	71
AMEX before	443,293	162,959	210,609	469,453	944,219
AMEX after	379,820	186,589	219,749	435,891	685,746
Mean logarithmic difference (%)	10.45[a]	20.86[a]	6.56	16.60[b]	−2.95
Median logarithmic difference (%)	7.52	13.30	−1.81	10.99	−10.02
Match before	361,687	196,877	279,419	413,668	560,074
Match after	513,819	262,803	305,542	714,995	780,271
Mean logarithmic difference (%)	24.23[a]	32.63	19.80[b]	26.17[a]	18.49[b]
Median logarithmic difference (%)	18.87	18.19	20.11	28.08	1.54
Test of the null hypothesis for equality of logarithmic differences (AMEX−Match)	−2.482[b]	−1.155	−1.187	−0.836	−1.856

B: Binding quartiles

	7	1 (Most)	2	3	4 (Least)
N		76	76	78	62
AMEX before		1,330,132	314,130	97,209	55,890
AMEX after		1,043,501	341,567	105,274	47,885
Mean logarithmic difference (%)		12.15	8.12	11.91	9.71
Median logarithmic difference (%)		6.05	2.95	7.23	17.52

Table 5 (*continued*)

7	1 (Most)	2	3	4 (Least)
Match before	895,930	338,828	140,214	56,143
Match after	1,293,046	431,295	237,011	83,073
Mean logarithmic difference (%)	30.69[a]	19.09[b]	24.60[a]	20.86[b]
Median logarithmic difference (%)	35.39	14.86	18.21	17.13
Test of the null hypothesis for equality of logarithmic differences (AMEX−Match)	−1.761	−0.959	−1.187	−0.826

C. Price/Volume Quadrants

Price level		Volume Level: Low	Volume Level: High
	N	68	80
	AMEX before	37,926	318,216
	AMEX after	51,922	339,114
	Mean logarithmic difference (%)	26.34[a]	3.69
	Median logarithmic difference (%)	27.39	−2.95
Low	Match before	67,661	394,315
	Match after	104,526	450,913
	Mean logarithmic difference (%)	43.28[a]	12.03
	Median logarithmic difference (%)	38.58	3.06
	Test of the null hypothesis for equality of logarithmic differences (AMEX−Match)	−1.484	−0.823
	N	73	71
	AMEX before	29,641	1,490,300
	AMEX after	45,378	1,161,593
	Mean logarithmic difference (%)	21.13[a]	−7.85
	Median logarithmic difference (%)	22.78	−6.52
High	Match before	76,930	936,578
	Match after	142,731	1,423,762
	Mean logarithmic difference (%)	21.70[b]	21.21[a]
	Median logarithmic difference (%)	19.32	14.69
	Test of the null hypothesis for equality of logarithmic differences (AMEX−Match)	−0.045	−2.672[a]

[a] Denotes significant at the 0.01 level.
[b] Denotes significant at the 0.05 level.

on volume levels.[20] We form two-dimensional (price and volume) quadrants and test if pre-tick-reduction volume is a determinant of volume changes. Table 5, Panel C indicates significant increases in volume both for the low price/low volume quadrant and for the high price/low volume quadrant. However, since these increases are not significantly different from those observed for the matched sample, we again conclude they are not induced by the tick reduction. Therefore, in the short run, a reduction in tick size does not appear to be associated with an increase in volume. It is possible that over a much longer period volumes do indeed increase.

3.3. Volatility

A major issue addressed in this paper is the effect of a tick size reduction on volatility magnitudes and patterns throughout the day.[21] The theoretical predictions regarding the effect of the tick reduction upon volatility are mixed and attributable to different factors. The first argument predicts an increase in observed volatility: If quoted depths decrease as a result of the tick reduction, available liquidity (i.e., quoted plus floor depth) may be exhausted, resulting in greater transaction price variations. Conversely, Harris shows that the variance of price changes can in part be attributed to (tick size induced) rounding errors. Discreteness may cause observed prices to be 'sticky': trades will not occur at new prices unless reservation prices change by at least a tick, which in turn causes observed deviations to be at least a tick. Thus, a reduction in tick size should reduce this (discreteness-induced) volatility, indicating an improvement in market quality.

In general, these two predictions regarding the effect of tick reductions on volatility may co-exist and have potentially confounding effects, rendering their empirical observability difficult. This is especially true in light of recent evidence from other exchanges, documenting depth reductions following tick reductions (see, for example, Bacidore, 1997; Porter and Weaver, 1997). In this paper, however, we are able to empirically distinguish between the two hypotheses. Since quoted depths do not decrease, any observed decreases in volatility would be most consistent with the discreteness-induced volatility hypothesis.

Panel A of Table 6 indicates that volatility, measured as the variance of the midpoint of quote revisions, generally decreases after the tick reduction. Variance ratios are constructed as the ratio of pre-reduction variance to post-reduction variance, and pooled F-statistics are calculated to test for

[20] See, for example, Ahn et al. (1998), Porter and Weaver (1997), and Goldstein and Kavajecz (2000) who suggest that pre-change trading activity can be an important predictor of tick size effects.

[21] See, for example, Forster and George (1995), Cao and Choe (1994), and George and Hwang (1995).

significance.[22] An issue of concern is whether the documented reductions in volatility are associated with the tick reduction, as opposed to exogenous volatility changes. Thus, we construct a control sample of similar stocks not subject to the switch to teenies.[23] Table 6, Panel A shows that while the control sample also exhibits volatility declines after the AMEX tick reduction, these reductions are significantly smaller than those shown for the AMEX group. Overall, the pre-post-reduction variance ratio for AMEX stocks is 1.37 versus 1.04 for the matched group. Variance ratio tests indicate that the null, that the variance ratios of the AMEX and matched samples are equal, is rejected at the 1% significance level. We conclude that the observed variance reductions on AMEX are not merely artifacts of market wide changes. These results comprise the first documented evidence of significant decreases in volatility following a reduction in tick size, and are consistent with the reduced incidence of rounding induced by discreteness.[24,25]

Table 6, Panel B indicates that daily return (defined as the return of closing quote midpoints) volatility is also reduced after the tick reduction, providing further evidence of market quality improvements. These results are even more compelling than those found for the intraday variance changes. While the AMEX sample exhibits significant daily variance reductions (the variance ratio for the overall sample is 1.21), the control sample exhibits overall increases in variance after the switch to teenies (with an average variance ratio of 0.81). Variance ratio tests indicate that the null, that these ratios are equal, is rejected at any reasonable significance level. This pattern is largely consistent across both the different price quartiles and the binding quartiles.

To control for other potentially confounding variables, we regress daily return volatility against the number of trades and a pre- or post-period indicator variable. See, for example, Jones et al. (1994), who find that the number of transactions is directly related to daily return volatility. Since we find that almost two-thirds of the stocks in the stocks in binding quartile 1 (most binding) had a reduction in quoted depth, we include a binding tick dummy variable and fit the following regression:

$$\sigma^2_{i,t} = \beta_0 + \beta_1\, N\_Trades_{i,t} + \beta_2\, TickDummy_{i,t} + \beta_3\, BindDummy_{i,t}, \qquad (3)$$

[22] We apply an outlier filter (observations outside two standard deviations from the mean are excluded).

[23] We thank the editor and reviewer for this suggestion.

[24] Indeed, all of the quartiles exhibit statistically significant reduction in variance of quote revisions, while only the high price quartile exhibits a significant reduction in depth.

[25] The reductions documented in Table 6 are much larger in magnitude than those expected to arise purely from rounding. We thank the reviewer for pointing out that for a typical $20 stock, the addition to the variance imposed by discreteness would be much smaller than what we find. The magnitudes we observe could be due in part to potentially cascading effects, such as indirect effects of investor behavior, which are in turn affected by the tick reduction.

Table 6
Change in volatility following the reduction in tick size

This table shows average volatility measures for AMEX stocks, as well as a matched sample, during the periods April 2–29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick size reduction, which occurred on May 7, 1997. For each AMEX stock a match was found on either the NYSE or Nasdaq. Matches are determined by finding the stock closest in price and number of trades, to the AMEX stock. In Panel A, volatility is defined as the variance of returns based on the midpoint of BBO quote revisions. In Panel A, each observation with a variance ratio more than two standard deviations from the mean for each group's price quartile are considered outliers and excluded from the sample. The corresponding pair (AMEX and Match) is then also excluded. In Panel B, volatility is defined as the variance of return based on closing BBO spread midpoints. Stocks are grouped by price (A.1 and B.1) and binding (A.2 and B.2) quartile. Binding is defined as the percentage of \$1/8 spreads in the pre-period. In Panels A and B, tests of significance are based on pooled *F*-tests (i.e., pre-period variance over post period variance). Panel C reports the results of the regression

$$\sigma^2_{i,t} = \beta_0 + \beta_1\, N\_Trades_{i,t} + \beta_2\, TickDummy_{i,t} + \beta_3\, BindDummy_{i,t},$$

where $\sigma^2_{i,t}$ is the variance of return (in $\%^2$ terms) based on closing spread midpoints for firm i in period t (pre or post,) $N_Trades_{i,t}$ is the number of transactions for firm i in period t (pre or post), $TickDummy_{i,t}$ is a dummy variable assigned the value of 1 if the period is post, otherwise zero, and $BindDummy_{i,t}$ is a dummy variable assigned the value of 1 if the percentage of quoted spreads equal \$1/8 in the pre-period is greater than 50%, otherwise zero.. Parameter t statistics based on Hansen-White heteroskedastic consistent standard errors are in italics. Panel D presents results for the variance of return measured at different times of day for the 25 highest volume firms in our sample. Open is the first price of the day. Close is the last price observed for the day. The remainder are the last prices observe in the interval. 10 AM is the interval 9:30–9:59; 11 AM is the period 10:00–10:59, etc. If an interval had no trade the previous day's interval price was used. Tests of significance are based on pooled *F*-tests. All variance numbers are reported in squared percentage terms

A. Change in variance of quote revision midpoints

A.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
N	211	53	54	51	53
AMEX before ($\%^2$)	0.117	0.148	0.142	0.085	0.092
AMEX after ($\%^2$)	0.091	0.116	0.109	0.059	0.076
Pooled F-test	1.368[a]	1.320[a]	1.421[a]	1.394[a]	1.220[a]
Match before ($\%^2$)	0.246	0.431	0.249	0.184	0.184
Match after ($\%^2$)	0.230	0.409	0.202	0.175	0.175
Pooled F-test	1.041[a]	0.866[a]	1.394[a]	1.234[a]	1.026[a]
$\frac{\text{AMEX variance ratio}}{\text{Match variance ratio}}$	1.314[a]	1.524[a]	1.019	1.129[a]	1.189[a]

Table 6 (*continued*)

A.2. Binding quartiles

	1 (Most)	2	3	4 (Least)
N	55	57	51	48
AMEX before (%^{2})	0.068	0.109	0.117	0.186
MEX after (%^{2})	0.050	0.083	0.084	0.153
Pooled F-test	1.503[a]	1.368[a]	1.401[a]	1.138[a]
Match before (%^{2})	0.249	0.294	0.254	0.176
Match after (%^{2})	0.242	0.275	0.198	0.196
Pooled F-test	1.032[a]	1.069[a]	1.102[a]	0.973
$\frac{\text{AMEX variance ratio}}{\text{Match variance ratio}}$	1.456[a]	1.279[a]	1.271[a]	1.169[a]

B. Change in variance of daily returns

B.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
AMEX before (%^{2})	2.567	2.407	2.473	3.054	2.332
AMEX after (%^{2})	2.007	2.354	2.325	1.811	1.535
Pooled F-test	1.207[a]	1.021	1.048	1.504[a]	1.383[a]
Match before (%^{2})	2.992	2.502	3.843	3.175	2.449
Match after (%^{2})	3.620	4.299	2.747	2.638	4.797
Pooled F-test	0.812[a]	0.566[a]	1.406[a]	1.174[a]	0.498[a]
$\frac{\text{AMEX variance ratio}}{\text{Match variance ratio}}$	1.486[a]	1.804[a]	0.745[a]	1.281[a]	2.777[a]

B.2: Binding quartiles

	1 (Most)	2	3	4 (Least)
AMEX before (%^{2})	2.433	3.303	2.216[a]	2.314
AMEX after (%^{2})	1.483	2.755	1.840	1.958
Pooled F-test	1.633[a]	1.094[b]	1.172a	1.084
Match before (%^{2})	5.796	3.187	1.919	1.067
Match after (%^{2})	6.167	4.599	2.430	1.286
Pooled F-test	0.956	0.677[a]	0.728[a]	0.956
$\frac{\text{AMEX variance ratio}}{\text{Match variance ratio}}$	1.551[a]	1.640[a]	1.609[a]	1.134[a]

C. Regression results

Intercept	*N_Trades*	Tick dummy	Bind dummy	*F*–Stat R^2
2.377	0.002	−0.588	−1.574	25.7
13.123[a]	*4.232*[a]	*−2.483*[b]	*−7.143*[a]	0.103

Table 6 (*continued*)

D. Change in patterns of transitory volatility

Time period	AMEX before (%^{2}) AMEX after (%^{2}) *Pooled F*-test	Match before (%^{2}) Match after (%^{2}) *Pooled F*-test	AMEX variance ratio / Match variance ratio
Open	5.687	10.038	
	2.358	22.172	5.357[a]
	2.416[a]	0.451[a]	
10 AM	6.452	10.765	
	2.386	20.398	5.151[a]
	2.699[a]	0.524[a]	
11 AM	6.858	9.692	
	2.308	20.698	6.511[a]
	3.034[a]	0.466[a]	
12 PM	6.883	10.082	
	2.320	19.210	5.654[a]
	2.9403[b]	0.520[a]	
1 PM	7.189	9.938	
	2.491	18.751	5.482[a]
	2.867[a]	0.523[a]	
2 PM	6.743	9.945	
	2.500	18.855	5.154[a]
	2.680[a]	0.520[a]	
3 PM	6.789	9.818	
	2.335	19.241	5.743[a]
	2.883[a]	0.502[a]	
Close	5.329	9.852	
	2.205	20.038	4.981[a]
	2.416[a]	0.485[a]	

[a] Denotes significant at the 0.01 level.
[b] Denotes significant at the 0.05 level.

where $\sigma^2_{i,t}$ is the variance of return based on closing spread midpoints for firm i in period t (pre or post), $N\_Trades_{i,t}$ is the number of transactions for firm i in period t (pre or post), $TickDummy_{i,t}$ is a dummy variable assigned the value of 1 if the period is post, otherwise zero, and $BindDummy_{i,t}$ is a dummy variable assigned the value of 1 if the percentage of quoted spreads equal to \$1/8 in the pre-period is greater than 50%, otherwise zero. Table 6, Panel C documents the results from these tests. Although the coefficient on the variable for number of trades is statistically significant and positive, consistent with Jones et al. (1994), the parameter estimates for Tick Dummy and Binding Dummy are also significant and negative. We conclude that the observed volatility reduction is not merely an artifact of confounding factors.

Of particular interest are the patterns of transitory volatility observed throughout the trading day, both before and after the tick reduction. Several studies document transitory volatility patterns on different exchanges (see, for example, Cao et al., 2000); Forster and George, 1995; Smith, 1994; Madhavan and Panchapagesan, 2000. Accordingly, we calculate daily return volatilities based upon prices observed at different times of the day. Open, close, and variances based on other 24 hour returns calculated at each hour (10, 11, 12,1, 2, and 3) of the trading day are reported for both the pre- and post-tick reduction periods. The results complement those in Panel B, and illustrate that the daily variance of the AMEX sample returns decreases, regardless of the time of day used as a base price for the 24-hour return series. Table 6, Panel C indicates that each of the post-period AMEX 24-hour variances is significantly lower than those of the pre-period. However, each of the matched sample 24-hour variances exhibit significant increases. Variance ratio tests indicate the null, that the AMEX changes are equal to the matched sample changes, is rejected at any reasonable level of significance.[26]

Finally, Smith (1994) documents a U-shaped pattern in 24-hour volatility throughout the day. Fig. 1 graphs the pattern of daily volatility both before and after the tick reduction. Interestingly, while this U-shaped pattern is observed in the pre-period, the post-period pattern is clearly flatter.

In summary, we find that market quality is not diminished following the adoption of the smaller tick size. While spreads decline, depths generally do not. Volume remains largely unchanged, while volatility is reduced. In the next two sections we examine two issues related to market quality – trader behavior and specialist profits.

3.4. Trader behavior

Recent studies on price competition suggest that smaller tick sizes may increase price competition. This can result either from traders submitting better-priced limit orders, or from specialists and/or floor brokers bidding or offering better prices to incoming market orders than exist on the limit order book. This last practice ('stepping ahead of the book') may result in both an

[26] Ronen (1997) shows the importance of conducting multivariate tests on the differences of such variances to incorporate the contemporaneous and overlapping correlations in these variances. However, our sample length does not allow for tests of such rigor, as they typically require longer samples for adequate statistical power. Thus, our significance levels are subject to certain interpretive difficulties.

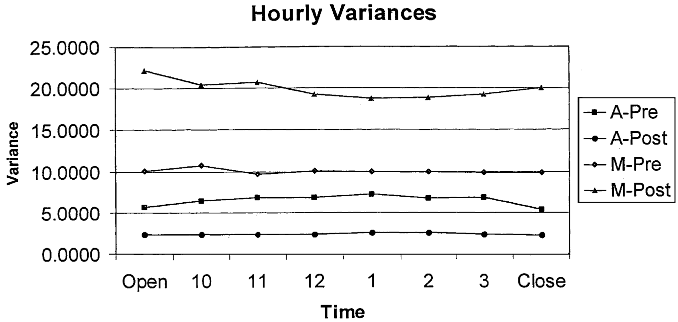

Fig. 1. Patterns of transitory volatility. This figure graphs the results for the variance of return measured at different times of day for the 25 highest volume firms in our sample as well as a matched sample. For each AMEX stock a match was found on either the NYSE or Nasdaq. Matches were determined by finding the stock closest in price and number of trades, to the AMEX stock. Open is the first price of the day. Close is the last price observed for the day. The remainder are the last prices observed in the interval. 10 AM is the interval 9:30–9:59; 11 AM is the period 10:00–10:59, etc.

increased time to execution for limit orders on the book, and price improvement for market orders.[27] This paper tests directly for the incidence of 'stepping ahead of the book' behavior, both before and after the switch to 'teenies'. Our results may be seen as consistent with smaller tick sizes causing an increased probability that a professional trader will improve on quoted prices. Specifically, we test the null that the number of trades occurring inside the spread remains constant in the pre- and post-periods.

Table 7 documents increases in the number of trades occurring inside the spread (accompanied by a decrease in the number of trades occurring at the spread) in all cases except for the least binding quartile. The results for the price quartiles do not appear to have a pattern. Nonetheless, the increases in stepping ahead of the book appear to be directly related to how binding the tick was prior to the reduction. Recall that depths are found to decline (albeit by a statistically insignificant amount) for those stocks in the most binding quartile. These combined results may be indicative of traders' fears of exposing their orders to potential price-improvers.

We now repeat the analysis for only those transactions in which the specialist is involved. Panel B indicates that the observed patterns persist when only specialist transactions are considered. This further supports the notion that the frequency of 'stepping ahead of the book' behavior increases after the reduction. The investor welfare effects of this increased

[27] See, for example Harris (1996,1997).

Table 7
Change in transaction price location following the reduction in tick size

This table shows the equally-weighted proportion of trades occurring at, inside, or outside the NBBO quote for AMEX listed stocks for the periods April 2–29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick size reduction, which occurred on May 7, 1997. Panel A reports the results for all trades, while Panel B reports the results for trades involving the specialist. Stocks are grouped by price (A.1 and B.1) and binding (A.2 and B.2) quartile. Binding is defined as the percentage of $1/8 spreads in the pre-period.

A. All trades

A.1: Price quartiles

	All firms		1 (Lowest)		2		3		4 (Highest)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
At quote	76.1%	73.3%	76.2	74.0	77.1	72.4	78.2	74.7	74.3	72.4
Inside	22.6	25.2	22.6	24.8	21.7	26.0	20.5	23.5	24.5	26.5
Outside	1.2	1.5	1.2	1.2	1.2	1.7	1.3	1.8	1.2	1.2

A.2: Binding quartiles

	1 (Most)		2		3		4 (Least)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
At quote	80.2	76.9	71.8	69.4	69.6	69.3	64.5	66.5
Inside	18.9	21.9	26.9	29.0	28.7	28.9	32.5	31.3
Outside	1.0	1.2	1.3	1.6	1.7	1.9	3.0	2.2

B. Only trades involving the specialist

B.1: Price quartiles

	All firms		1 (Lowest)		2		3		4 (Highest)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
At quote	60.8%	56.5%	60.7	55.4	62.1	56.9	62.9	58.7	58.7	55.0
Inside	36.7	40.6	37.4	42.0	35.5	40.0	34.3	38.0	38.6	42.4
Outside	2.6	2.9	1.9	2.6	2.4	3.1	2.8	3.3	2.7	2.6

B.2: Binding quartiles

	1 (Most)		2		3		4 (Least)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
At quote	62.2	56.7	60.1	53.8	59.9	58.4	58.1	60.1
Inside	35.7	40.8	37.2	43.1	37.5	38.5	37.8	36.2
Outside	2.1	2.5	2.7	3.0	2.6	3.1	4.1	3.7

activity are mixed. Indeed, It is possible that this increased activity yields better transactions price for market orders, but not for limit orders. The professional trader who steps ahead of the book is essentially competing with the limit order book, resulting in possibly worse execution for the limit order investor.[28]

3.5. Profits

The recent changes adopted by various exchanges regarding tick sizes have raised questions regarding the resulting impact on market maker welfare. This issue is of concern, since a sufficient decrease in profits may cause market makers to exit the market. However, if volume increases (as we observe for some stocks), reductions in per share profits caused by narrower spreads may be mitigated by an increase in the number of trades.

Our approach is similar to Sofianos (1995) and Hansch et al. (1999). Let $x_{i,t}$ be the signed volume representing specialist participation in stock i for transaction t. The sign is determined by the direction of the specialist's cash flow (+ for sell, −for buy). $p_{i,t}$ is the price of transaction t, while $I_{i,t}$ is the specialist's inventory in stock i at time t. Sofianos (1995) shows that specialists trade inside the spread more than 40% of the time. To be conservative, we therefore measure inventory using the quote midpoint for stock i at time t, $m_{i,t}$. Total profits can be written as

$$TP_i = \sum_{t=1}^{n} p_{i,t}x_{i,t} + m_{i,n}I_{i,t} - m_{i,0}I_{i,0}, \tag{4}$$

where $I_{i,t} = \sum_{t=1}^{n} x_{i,t}$ and n is the number of trades the specialist was involved in.[29] We assume that $I_{i,0} = 0$ (due to data limitations).

As in Sofianos (1995), we decompose profits into spread (SR) and positioning revenue (PR). Spread revenue is based on the half spread:

$$SR_i = \sum_{t=1}^{n} (P_{i,t} - m_{i,t})x_{i,t}, \tag{5}$$

$$PR_i = TP_i - SR_i. \tag{6}$$

Table 8 indicates that overall total profit as well as spread revenue (measured per stock) decreases, albeit not by a statistically significant amount. Further this result is not consistent across all quartiles. Binding quartile 3 shows a statistically significant decrease in total profits. In contrast, price quartile 3

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[28] We also examine trades not involving the specialist and find a similar increase in 'stepping ahead of the book' for those trades as well. The pre and post "inside the spread" numbers are about 40% of those reported for specialists. However, since we lack order data, we cannot distinguish between public limit orders executed before they are included in the quote and those orders involving floor traders. Therefore, we cannot distinguish professional from public orders.

[29] A general weakness of profit models including ours is that they do not take into account market movements that are not in the specialist's control.

Table 8
Change in specialist profits following the reduction in tick size

This table shows specialist profits for AMEX listed stocks for the periods April 2–29, 1997 (pre-period) and May 15 to June 12, 1997 (post-period). These periods surround the tick size reduction, which occurred on May 7, 1997. Panel A reports total profit defined as

$$TP_i = \sum_{t=1}^{n} p_{i,t}x_{i,t} + m_{i,n}I_{i,t} - m_{i,0}I_{i,0},$$

where $x_{i,t}$ is the signed volume representing specialist participation in stock I for transaction t. The sign is determined by the direction of the specialist's cash flow (+ for sell, − for buy). p_{it} is the price of transaction t, while I_{it} is the specialist's inventory in stock i at time t. m_{it} is the quote midpoint for stock i at time t, and $I_{i,t} = \sum_{t=1}^{n} x_{i,t}$. We assume that $I_{i,0} = 0$ due to data limitations. Panel B reports spread revenue per stock, which is defined as $SR_i = \sum_{t=1}^{n} (P_{i,t} - m_{i,t})x_{i,t}$. Stocks are grouped by price (A.1 and B.1) and binding (A.2 and B.2) quartile. Binding is defined as the percentage of \$1/8 spreads in the pre-period. Tests of significance are paired t-tests.

A: Total profits (in dollars)

A.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
Before	\$20,842.87	−\$570.19	\$1,981.87	\$2,777.58	\$4,729.17
After	−1,238.54	−58.67	2,927.39	2,614.58	−18,250.19
Mean change	−22,081.41	511.52	945.52	−163.00	−22,979.36
Median change	−21.88	242.19	12.50	−50.00	−618.75

A.2: Binding quartiles

	1 (Most)	2	3	4 (Least)
Before	3,467.42	3,849.61	1,624.69	26.54
After	−11,747.30	213.39	−1,576.35	199.07
Mean change	−15,214.73	−3,636.23	−3,201.04[a]	172.53
Median change	292.19	12.50	−568.75	281.25

B: Spread revenue

B.1: Price quartiles

	All firms	1 (Lowest)	2	3	4 (Highest)
Before	\$7,499.09	2,290.78	3,362.11	4,130.63	8,615.28
After	6,217.25	2,800.98	3,600.39	4,969.52	7,088.62
Mean change	−1,281.85	510.19	238.27	838.89[a]	−1,526.66
Median change	−821.88	317.19	−18.75	162.50	50.00

B.2: Binding quartiles

	1 (Most)	2	3	4 (Least)
Before	8,738.79	4,356.67	3,066.63	2,316.32
After	7,800.39	5,499.61	3,184.07	2,037.15
Mean change	−938.39	1,142.94	117.44	−279.17
Median change	365.63	300.00	−15.63	−6.25

[a] Denotes significant at the 0.05 level.

shows a statistically significant increase in spread revenue. The remainder of the quartiles exhibits no statistically significant changes. These results may be interpreted as indicating a negligible net effect of tick size reductions on profits. While spreads decline, volume increases, thereby mitigating the loss from reduced spread revenue.[30,31]

4. Concluding remarks

Recent studies have focused on the potential effects of a reduction in tick size on various aspects of market quality. Although theoretical predictions address the effects on trader behavior and volatility, the extant empirical studies focus on the impact on spreads and depths. This paper examines the impact of the AMEX's May 1997 tick reduction on volatility, other aspects of market quality, trader behavior, and specialist profits. We view our results as carrying important policy implications, especially in light of the fact that previous research has been limited to studying tick size changes on exchanges that do not have price/time priority rules and a level of pre-trade transparency similar to those assumed by the theoretical models (which the AMEX does).

We find that while bid–ask spreads decline, depths do not. We also find that specialist profits are relatively unchanged. These results are consistent with decreased transactions costs and increased liquidity. Further confirmation of improved (not impaired) market quality lies in our evidence on volatility changes. The interday and intraday return volatility decreases observed after the tick reduction are shown not to be attributable to potentially confounding factors. Additionally, we find that transitory volatility, based on daily returns measured at different points during the day, decreases. Examining the pattern of changes throughout the day reveals a flattening of the typical U-shaped pattern following the tick reduction. Finally, our results indicate that the tick size reduction is accompanied by an increase in the occurrence of professional traders providing price improvement to arriving market orders, to the detriment of existing limit orders.

The results in this paper may be viewed as indicating improvements in some aspects of market quality after the tick reduction, and are consistent with current research examining impacts on execution costs and other forms of

[30] We demonstrate earlier that the observed volume increases are probably not due to the tick reduction. Therefore, it is possible that profits directly related to the tick reduction, may have fallen by more than Table 8 indicates.

[31] As an interesting aside, the nature of the data employed in this study allows us to compare spread revenues for AMEX specialists with those previously reported for NYSE specialists in Sofianos (1995). We find that AMEX specialist daily spread revenues ($7,499.09/20 = $375) are about 1/3 of the daily amount of NYSE revenues ($970).

liquidity for other market structures. Future investigation of these issues may determine if our results regarding volatility and trader behavior are robust over longer time horizons, across alternative market structures or particular to price/time priority rule markets. Finally, while the results in this paper indicate that AMEX market quality improved following the tick reduction from \$0.125 to \$0.0625, implications for market quality improvements resulting from further reductions are not immediate. Indeed, this paper does not aim to rebut the notion that there may exist an optimal non-zero tick size.[32]

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[32] See Harris (1997) for empirical support for the notion that an optimal non-zero tick size exists. Harris shows that while market quality on the Toronto Stock Exchange improved for stocks experiencing a tick reduction to nickels, a further reduction from nickels to pennies resulted in no market quality improvements.

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