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管理科學系 碩士班

碩士論文

美國證券市場小數化對指數期貨、現貨間套利機會的影響

Index-Futures Arbitrage Before and After the Decimalization on the NYSE

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摘要

2001 年 1 月 29 日，紐約證券交易所（NYSE）再次將最小價格變動單位從 1/16 美元降為一美分；縮小升降單位有助於減少買賣價差（bid-ask spread）；然而市場深度（market depth）也同步下降，造成在解釋市場績效時，出現左右相悖的爭論。

於是有相當多的學者針對這個議題進行研究，結果發現於小數化之後，雖然買賣價差及市場深度都有同步的減少，但對整體市場的流動性及交易成本實質上卻有正面的助益。本篇論文即針對小數化後減少交易成本的現象，考慮實際的交易成本，包括手續費用及買賣價差；利用 S&P 500 及 NASDAQ 100 Index、E-mini 和 ETF 的逐筆報價與成交價格資料代入持有成本模型進一步探討小數化對期貨、現貨間套利機會的影響；透過事後邊界違反分析，發現小數化後無套利區間縮小，邊界違反的次數增加，顯示小數化有助於套利活動的進行；另外將第一次違反訊號延伸作事前獲利分析，結果發現小數化後現貨與期貨商品價格間的的聯動性更為緊密，表示小數化後二者定價效率變好。

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ABSTRACT

Starting January 29, 2001, all stocks trading on the NYSE and the American Stock Exchange are quoted in decimals. This paper examines the impact of the decrease in arbitrage costs in the pricing of ETFs and their E-minis on S&P 500 and NASDAQ 100 indexes. Different with Henker and Martens (2004) who investigate index-futures arbitrage before and after the introduction of sixteenths on the NYSE only focus on testing "theoretical mispricing" without considering transaction costs or ex-ante trading, this study explicitly includes transaction costs and examines ex-ante arbitrage opportunities.

Results of empirical analysis generally confirm that E-minis exhibit more frequent boundary violations after the decimalization in the ex-post test, suggesting that decimalization enhance arbitrage opportunities. Through the ex-ante test, this study finds that the introduction of decimalization improves the pricing efficiency between ETFs and their E-minis.

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進入交大彷彿才像昨天的事，轉眼間又要從這裡離開。從大學的領域到今日從管理的碩士班畢業，這之間的轉變讓我這個當時初來乍到的交大管科新生有些適應不良，所幸這一路上始終不乏師長、同儕與朋友不忘給我鼓勵，才有動力堅持到最後。

論文的完成代表碩士班階段的結束，雖然它不算臻於完美，卻也花費不少心思，尤其感謝指導教授鍾惠民老師與許和鈞老師的耐心指導，適時地給予我修正的方向；還要感謝副總跟蔡大哥熱心地提供實務上的佐證；另外感謝口試委員周冠男老師、謝文良老師給我懇切的意見。

謝謝親愛的家人在這段時間對我的包容與鼓勵，還有研究所同學姿羽、映均、淑芬、柏蓁、坤岐、張簡在我情緒低落時給我打氣，尤其是同門的永慶讓我深刻的體驗到什麼叫做好人的真諦；另外，謝謝阿恩、嘉仁、弘家學長在我初入交大給我的協助，還要感激建宏、小傑、光閔、潔瑩、奕緯、嘉芳、明正、怡如，就是有他們自始至終不停歇的支持跟幫助，我才能堅強地勇敢面對一切考驗。還有那些在我生命中曾經出現的人、事、物，如果沒有這些美麗的過去，不會成就今日的我，由衷感謝。

CONTENTS

TABLES

1. INTRODUCION

Starting January 29, 2001, all stocks trading on the NYSE and the American Stock Exchange are quoted in decimals.[1] NASDAQ began converting to decimal pricing on March 12, 2001, and completed the process on April 9, 2001. A two-hundred-year tradition of trading in fractions is history. This paper examines the impact of the decrease in arbitrage costs in the pricing of these relatively new, but high volume, financial instruments on S&P 500 and NASDAQ 100 indexes.

Decimalization of stock markets is relevant for policymakers because it has the potential to affect market liquidity, and therefore the overall functioning of financial markets. Advocates of the adoption of decimalization argue that the finer gradation of stock prices will benefit investors. This is because the pricing increment dictates the smallest possible bid-ask spread for a given stock. This spread represents the difference between the lowest price an investor can pay for a stock and the highest price an investor can receive for selling the same stock. Lower transaction costs should result in decrease in the index-futures mispricing error that triggers arbitrage.

However, decimalization may affect more than a stock's bid-ask spread. As Harris (1994, 1997) and Furfine (2003) have argued, a smaller tick size can inhibit incentives to provide liquidity, potentially damaging market quality. In general, these studies found that a smaller tick size decreased quoted and effective bid-ask spread, but also decreased liquidity provision. For large traders, quoted depth at the best-quoted prices may be insufficient to fill the desired order. For such trades, the effective transaction price lies somewhere outside the posted bid and ask. These costs arise from a lack of an infinite supply of shares that can be purchased and sold at the same price.

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[1] Specifically, the NYSE lowered the minimum tick size to a penny for seven securities on August 28, 2000, 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.

To reconcile the apparently contradictory findings reported in those papers, many studies use different estimators to examine whether and/or to what extent market liquidity was affected by decimalization. Most of them eventually found that after decimalization, it did improve to decrease the overall transaction cost. (Chakravarty, Van Ness, and Van Ness, 2002; Furfine, 2003; Bessembinder, 2003; Chakravarty, Panchapagesan, and Wood, 2003).

This article examines the pricing efficiency and arbitrage opportunities between ETFs (SPDRs and QQQs) and their E-minis in the intraday level before and after decimalization. Specifically, this investigation addresses the following research question:

1. Does decimalization improve the arbitrage opportunity and pricing efficiency of the S&P 500 and NASDAQ 100 index markets at the intraday level?

This article differs from previous research in three major aspects. First, this study uses E-mini as future proxy while most related studies take regular futures contracts into the Cost-of-Carry Model (MacKinlay & Ramaswamy, 1988; Sarno & Valente, 2000; Chu & Hsieh, 2002). In practice, both E-mini futures prices and ETF prices tend to trade at or very near fair value most of the time. As a result, both instruments provide institutional traders with effective ways of trading the general levels of stock prices. Second, comparing with those only look into the performance of S&P 500 or NASDAQ 100 (Chu & Hsieh, 2002; Kurov & Lasser, 2002), this investigation considers both data sets of S&P 500 and NASDAQ 100. Besides, different with Henker and Martens (2004) who investigate index-futures arbitrage before and after the introduction of sixteenths on the NYSE only focus on testing "theoretical mispricing" without considering transaction costs or ex-ante trading, this study explicitly includes transaction costs and examines ex-ante arbitrage opportunities. The result provides evidence for the market efficiency under real-world arbitrage.

Results of empirical analysis generally confirm that E-minis exhibit more frequent boundary violations after the decimalization, suggesting that decimalization enhance arbitrage opportunities. Through the ex-ante test, this study finds that the introduction of decimalization improves the pricing efficiency between ETFs and their E-minis. Evidence of this article is consistent with previous findings by Henker and Martens (2004).

The remainder of this study is organized as follows. The next section reviews the literature related to the effects of tick size changes. Section 3 describes the methodology and the trade-by-trade data used in this study. Section 4 presents empirical results for the index ETFs and their E-minis contracts and Section 5 concludes.

2. LITERATURE REVIEW

Decimalization of the U.S. stock markets has attracted considerable contemporaneous research attention. Chakravarty, Wood, and Van Ness (2004) use high-frequency data and a carefully constructed matched sample of control (non decimal) stocks, and isolate the effects of decimalization for a sample of NYSE-listed common stocks trading in decimals. They find that both quoted and effective bid-ask spreads and depths have declined significantly following decimalization. Both trades and trading volume have declined significantly in all trade size, as well as in all stock size, categories. Stock return volatilities display an initial increase but a decline over the longer term — probably as traders become more comfortable in their new milieu. Finally, although there is some evidence of increased presence among regional stock exchanges in the wake of decimalization, the NYSE still appears to be very much in the lead in all categories.

Furfine (2003) examine the impact of decimalization on the liquidity of NYSE stocks. Analyzing transaction data for a sample of 1,339 stocks listed on the NYSE over a five-week period. He found that decimalization led to a narrowing of average bid-ask spreads. The largest declines in spreads were found for the most actively traded stocks, where the average decline in spread was over 35 percent. The decline in depth was also most pronounced for the most actively traded stocks. Because previous findings suggest that decimalization had an ambiguous impact on market liquidity using spreads and depth as proxies for liquidity, Furfine estimated the price impact of a trade for each stock in his sample and then found that actively traded socks generally experienced an increase in liquidity following decimalization.

Harris (1994), using data from a time when the minimum tick was 1/8, fits a regression model estimating the frequency at which spreads are at the minimum. Using this relationship, Harris estimates that the impact of reducing the minimum tick size to 1/16 would be accompanied by both lower bid-ask spreads and lower quoted depth. His results are therefore also consistent with the notion that optimal tick size is related to the size of a trade. He indicates that small traders would almost certainly benefit from smaller tick sizes, but that large traders might be hurt if the depth of the market were to fall sufficiently.

Unlike Harris (1994), Chakravarty, Panchapagesan and Wood (2003) examine the effect of decimalization on institutional investors using proprietary data. They find no evidence that decimalization has increased trading costs for institutions. In fact, institutional trading costs appear to have declined by about 23 basis points (or, roughly 5 cents per share) after decimalization. In economic terms, this decrease roughly translates to an average monthly saving of $133 million in institutional trading costs. Estimations involving robust multivariate techniques that condition on order, manager and market characteristics yield roughly similar reductions as well. Their result are surprising in light of an oft-repeated, and increasingly louder, complaint among professional traders that liquidity is hard and expensive to find in a post-decimal treading milieu. Though there is significant changes in order routing practices overall, they find an increase usage of alternate brokers (represented by ECNs and crossing networks such as Instinet) for easy-to-fill (i.e., smaller) orders and full service and independent research brokers for orders that are difficult to fill (i.e., larger size orders).

Chakravarty, Van Ness and Van Ness (2003) examine adverse selection costs around decimalization and relationship between adverse selection costs and trade size by using a sample of NYSE stocks around the implementation of complete decimalization and tick-by-tick trade and quote data. They find a significant reduction in adverse selection costs following complete decimalization on the NYSE. This decline in adverse selection costs is associated with all stocks in their sample except the very smallest. They further try to understand the source of this decrease in adverse selection costs. They find that both the number of trades and trading volume in medium and large size trades fell significantly following complete decimalization on the NYSE while those in small size trades increased significantly. On estimating the adverse selection components by trade size classes, they find a decline in adverse selection costs in trades of all sizes, with the strongest evidence coming from medium size trades, following by small and large size trades. One implication of their findings is that there appears to be less stealth trading following complete decimalization and less institutional trading overall.

Goldstein and Kavajecz (2000) analyze the NYSE's reduction in tick size from 1/8 to 1/16 and address the relationship between minimum tick size, bid-ask spread, and market liquidity. What is unique about this study is that these authors not only look at the depth reported at the best bid and ask prices, they also collect data on liquidity available at some distance away from the best bid and ask prices. This complete collection of prices and available depth is called the limit order book. They find that not only did depth at the best bid and ask decline, but cumulative depth similarly declined throughout the limit order book following the NYSE's previous reduction in minimum tick size. Using implied average price of a trade of a given derived from the limit order book, these authors find that large traders were not made better off by the smaller tick sizes and were made worse off for infrequently traded stock.

Bessembinder (2003) assesses trade execution costs and market quality for NYSE and NASDAQ stocks before and after the 2001 change to decimal pricing. Quoted bid-ask spreads declined substantially on each market, with the largest declines for heavily traded stocks. The percentage of shares receiving price improvement increased on the NYSE, but not on NASDASQ. However, those trades completed at prices within or outside the quotes were improved or disimproved by smaller amounts after decimalization, and trades completed outside the quotes saw the largest reductions in trade execution costs, as a class. Effective bid-ask spreads as a percentage of share price, arguably the most relevant measure of execution costs for smaller trades, averaged 0.33% on a volume-weighted basis after decimalization for both NYSE and NASDAQ stocks. There is no evidence of systematic intraday reversals of quote changes on either market, as would be expected if decimalization had damaged liquidity supply.

Bollen and Busse (2003) measure changes in equity mutual fund trading costs following two changes in tick size on NASDAQ and NYSE: the switch from eighths to sixteenths and the switch from sixteenths to decimals. They estimate trading costs by comparing a mutual fund's daily returns to the daily returns of a synthetic benchmark portfolio that matches the fund's holdings but has zero trading costs by construction. They find that index fund performance is unaffected by the switch to pennies. In contrast, actively managed funds under perform their benchmark by an additional one percent of fund assets per year after decimalization.

Henker and Martens (2004) find that market efficiency increased and the arbitrage link between index-futures and the stock market strengthened after Jane 24, 1997, by examine the impact of the New York Stock Exchange reduced the minimum change for stock prices and quotes from an eighth to sixteenth of a dollar. After the change they find a substantial increase in the number of arbitrage trades reported to the Securities and Exchange

Commission. The average number of stocks traded and the average dollar amount underlying each arbitrage trade increase and decrease respectively. The average index-futures mispricing error that triggers arbitrage is lower and reverts to zero more quickly.

3. METHODOLOGY AND DATA

3.1. Measuring the No-Arbitrage Band

The analysis follows the information share approach of Chu and Hsieh (2002). The theoretical futures price used to test for market efficiency is the Cost of Carry relationship, which is derived form an arbitrage strategy that consists of a long position in the index portfolio, with a price S_0 and a short position in an equal amount of index futures, priced at F_0. The hedged strategy will yield a flow of dividends over time, as well as a fixed capital gain of $F_0 - P_0$. Since the position is riskless, it should earn the riskless rate of interest. To prevent profitable arbitrage, the theoretical equilibrium futures price at time t is thus:

$$F(t) = S(t)e^{(r-d)(T-t)} \tag{1}$$

where F(t) stands for the theoretical futures price at time t for a contract expiring at time T; S(t) is the spot price of the underlying asset at t; r is the risk-free interest rate; and d is the dividend yield on the stock index portfolio. The rate r is often refereed to as carrying charge, since it represents the opportunity cost of carrying the spot asset to maturity of the futures contract. The buyer of stock index securities incurs the opportunity cost of his funds but receives dividends. Therefore, the futures price should equal the cost of buying the spot index securities, including the opportunity cost, adjusted for dividends paid during the remaining life of the futures contract. As the futures contract approaches maturity, the futures price converges to the value of the spot index. Equivalently, the basis, that is, the difference between the futures price and spot index value, converges to zero at expiration. The implicit assumptions underlying the cost-of-carry model include perfect markets, constant carrying charges, and constant dividend flow to the index stocks. Any price deviations form Equation 1 will be corrected as arbitrageurs sell the overpriced instrument and buy the underpriced one.

The impact of transaction costs is to permit the future price to fluctuate within a band around the formula value in Equation 1 without triggering profitable arbitrage opportunities. The width of the band derives from round-trip commissions in the stock and futures markets and from the market impact costs of putting on the trade initially. Most studies view commissions as fixed costs, although fees vary by groups of traders as well as by order size. Market-impact costs can be measured by bid-ask spreads that vary by trader. This study took an approach similar to Chu and Hsieh (2002) and measured arbitrage profit at different levels of transaction costs. The three levels of two-way transaction costs are specified as 0.20, 0.30, and 0.40% of theoretical futures price. Equation 2 describes the no-arbitrage band for the futures price

$$[S(t)e^{(r-d)(T-t)}]-C<F(t)<[S(t)e^{(r-d)(T-t)}]+C \tag{2}$$

where C stands for the total transaction costs of executing arbitrage including round-trip stock commission, round-trip futures commission, market impact in futures, and market impact in stocks[2]. If the futures price penetrates the upper bound, a long arbitrage trade will simultaneously short the futures and buy the spot. If the futures price drops below the lower bound, a short arbitrage will make the reverse transactions.

Using the cost-of-carry relationship, this article establishes ex-post and ex-ante no arbitrage conditions between the spot index and futures in Equations 3-5 (see the Appendix), as well as between ETFs and E-minis in Equations 6-11. The ex-post test

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[2] This assumes that the transaction costs are the same for long and short positions in futures and for purchases and sales in stocks. It is not crucial to the analysis.

focuses on the frequency and persistence of boundary violations. The ex-ante calculates arbitrage profit with explicit consideration of the transaction lag.

The ex-post no-arbitrage relationship between index futures and the spot index is

$$IDX(t)e^{(r-d)(T-t)} - C_{c+m} < F(t) < IDX(t)e^{(r-d)(T-t)} + C_{c+m} \tag{3}$$

where IDX(t) is the reported spot index, and C_{c+m} represents the transaction costs consisting of both commissions and market-impact costs of bid-ask spread.

Equation 3 implicitly assumes that arbitrageurs trade a basket of underlying stocks against index futures. Given the time lags in program trading, an ex-post boundary violation provides merely a mispricing signal but not realized arbitrage profit. To measure the ex-ante arbitrage profit, this study imposes a 5-min transaction lag for program trading.

The ex-ante profits for long and short arbitrage are calculated in Equations 4 and 5

$$AP_L = F(t^+) - [IDX(t^+)e^{(r-d)(T-t)} + C_{c+m} \tag{4}$$

$$AP_S = [IDX(t^+)e^{(r-d)(T-t)} - C_{c+m}] - F(t^+) \tag{5}$$

where $F(t^+)$ and $IDX(t^+)$ represent the futures price and the spot index, respectively, 5 min after an ex-post mispricing signal (Chu and Hsieh, 2002). Arbitrageurs using program trading can realize profits only if the violations lasts longer than 5 min.

Alternatively, traders can view ETFs as a cash proxy and arbitrage the mispricing between ETFs and E-minis. Suppose an arbitrage is entered at t and lifted at futures expiration date T. With the consideration of transaction costs, the no-arbitrage band between SPDRs and S&P 500 E-minis becomes Equation 6. For QQQs and NASDAQ 100 E-minis is in Equations 7.

$$10 \times SPDR(t)_{bid} e^{(r-d)(T-t)} - C_c \le F(t) \le 10 \times SPDR(t)_{ask} e^{(r-d)(T-t)} + C_c \tag{6}$$

$$40 \times QQQ(t)_{bid} e^{(r-d)(T-t)} - C_c \le F(t) \le 40 \times QQQ(t)_{ask} e^{(r-d)(T-t)} + C_c \tag{7}$$

There are a few notable differences between Equation 6 and 7 and the conventional futures pricing equation. First, prices of SPDRs are multiplied by 10 to make them comparable to futures prices; prices of QQQs are multiplied by 40 to the same reason. Second, using the ETFs quote price for a better measure of transaction costs. ETF bid and ask prices [$ETF(t)_{bid}$ and $ETF(t)_{ask}$] are used to calculate the no-arbitrage boundaries. Here assumed that arbitrageurs buy at the ask and sell at the bid price when they trade ETFs. Because the market-impact costs have been explicitly considered, the transaction costs C_c in Equation 6 and 7 consist only of trade commissions.

Equations 8 and 9 define the ex-ante profit of long and short arbitrage using SPDRs against S&P 500 E-minis, and Equations 10 and 11 for NASDAQ 100. This study assumes that arbitrageurs can trade at the next available ETF quote price and futures trade price immediately after a mispricing signal.

$$AP_L = F(t^+) - [10 \times SPDR(t^+)_{ask} e^{(r-d)(T-t)} + C_c \qquad (8)$$

$$AP_S = [10 \times SPDR(t^+)_{bid} e^{(r-d)(T-t)} - C_c] - F(t^+) \qquad (9)$$

$$AP_L = F(t^+) - [40 \times QQQ(t^+)_{ask} e^{(r-d)(T-t)} + C_c \qquad (10)$$

$$AP_S = [40 \times QQQ(t^+)_{bid} e^{(r-d)(T-t)} - C_c] - F(t^+) \qquad (11)$$

3.2. Data

The sample period considered here is October 2, 2000 through May 29, 2001. Quote data of ETFs (SPDRs and QQQs) for this study were obtained from the NYSE's Trade and Quote (TAQ) Database and trade data of Indexes (the S&P 500 Index and the NASDAQ 100 Index) and their E-minis contracts were from the Tick Data Database. In the TAQ data, only regular AMEX quotes were used. All prices were filtered.[3] The

[3] To minimize errors, we omit quotes if the TAQ database indicates that are out of time sequence or involve either an error. TAQ quotes were screened to remove zero and negative spreads, and spreads greater than

dividend data are from the CRSP daily database. As a proxy for the opportunity cost in the calculation of futures mispricing, monthly three-month Treasury Bill rates from web database of the Federal Reserved Board were used for the riskless rate of interest. In the intraday analysis, this article assumed that daily T-bill rates and dividend yields were continuous and constant intraday.

To form trading pairs, this investigation matched every reported index and ETF quote with the most recent E-mini trade prices. The number of matches is equal to the total number of index values reported or the number of ETF quoted for the corresponding period. To computing mispricing series, futures prices are synchronized with the spot values using a MINSPAN procedure suggested by Harris, McInish, Shoesmith, and Wood (1995). If there is no futures trade at the exact time of the reported spot value, the closest futures observations within the previous 7 seconds and the net 7 seconds are considered. When only one futures trade meets this criterion, a pair is form. If both a leading and lagging futures trades are obtained, the closer trade is used to form the pair and the other one is discarded.

There are 104,788 spot-index and E-minis matches in the pre-decimalization period and 107,904 in the post-decimalization period. For pairs of SPDRs and S&P 500 E-minis, there are 206,622 observations in the pre-decimalization period and 224,602 in the post-decimalization period. For NASAQ 100, there are 109,706 spot-index and E-minis matches in the pre-decimalization period and 113,592 in the post-decimalization period. For pairs of QQQs and NASDAQ 100 E-minis, there are 237,594 observations in the pre-decimalization period and 291,020 in the post-decimalization period.

4. EMPIRICAL RESULTS

Table 1 reports summary statistics for the ETF index products. The results show that

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$4. Besides, data before-the-open and after-the-close trades and quotes also are eliminated.

after decimalization, SPDR has a statistics significant reduction in bid-ask spread and quote depth, but for QQQ only bid-ask spread decreases significantly, and an increase in the average daily trading volume, especially for QQQ. This finding is consistent to the previous findings mentioned. From the last column, suggesting that the market tends to overprice SPDRs and underprice QQQs in the sample period may affect the direction of boundary violation.[4]

TABLE 1

Statistic Summary of SPDRs and QQQs

	Quote Depth	Average Daily Trading Volume	Average Percentage Bid-Ask Spread	% difference between ETF and Index
Panel A: Pre-Decimalization 2000/10/2-2001/1/28				
SPY	6622.49	8,115,591	0.105%	0.237%
QQQ	117.85	48,538,613	0.186%	-0.196%
Panel B: Post-Decimalization 2001/1/29-2001/5/29				
SPY	3256.06	11,433,180	0.104%	0.270%
QQQ	117.19	70,978,470	0.148%	-0.256%

Note. Average percentage bid-ask spread is calculated by $100\% \times 2 \times (Ask - Bid)/(Bid + Ask)$. And the discount percentage is estimated by using the middle price between bid and ask price $((Bid + Ask)/2)$ as the proxy of ETF trade prices and following the equation of $100\% \times (ETF \times c - Index)/Index$, where c stands for index factor.

TABLE 2

Realized Volatility

	ES	NQ	SP	ND	SPY	QQQ
Panel A: Pre-decimalization 2000/9/28~2001/1/28						
	0.0127	0.0342	0.0117	0.0326	0.0144	0.0369
Panel B: Post-decimalization 2001/1/29~2001/5/29						
	0.0120	0.0304	0.0111	0.0290	0.0133	0.0308

Note: The realized volatility for trading day t, from the close on day t-1 to the close on day t, is defined by

$$s_t = \sqrt{\sum_{i=1}^{n} r_{t,i}^2} \quad , where \quad 0 \le i \le n$$

where $r_{t,i}$ represent a set of n intraday returns for day t, and when $i = 1$ represents the five minutes commencing at the open, and concluding with the five minutes at the end when $i = n$.

[4] When the market tends to overprice SPDRs, it may cause the theoretical futures prices estimated by using SPDRs quotes higher than using S&P 500 index, and futures prices are hard to penetrate upper bond, and vice versa.

Table 2 shows the change of the realized volatility of the data set in this study for the pre-decimalization period and the post-decimalization period. We can see there has no significant decrease after decimalization.

4.1. Ex-post Boundary Violations

Table 3 provides the summarized results for the size, frequency, and length of futures ex-post boundary violations before (panel A) and after (panel B) decimalization. Boundary violations are identified according to Equation 6 for SPDRs and Equation 7 for QQQs for various levels of two-way transaction costs ranging from 0.20 to 0.40% of the theoretical futures prices.

Column 1 reports the number of matched pairs in each subperiod. The overall frequency of boundary violations and percentage of upper bound and percentage lower bound violations are presented in columns 3 through 5. Because boundary violations tend to occur in clusters, the total number of violations overestimates the actual arbitrage opportunity.[5] Using an "occurrence" of boundary violation as a series of same-side violations follows Chu and Hsieh (2002) so that any two adjacent violations in the same occurrence occur within a 20-min interval. In other words, a new boundary violation occurrence is recognized only when the direction of mispricing changes or when a mispricing occurs 20 min apart from the previous one. Integrating persistent mispricing into a single occurrence of boundary violation avoids the problem of overestimating actual arbitrage opportunity. [6]As transaction costs increase and the no-arbitrage bounds widen, the number of mispricing events drops in both periods.

Columns 6 through 8 report the average number of subsequent violations occurring

[5] If boundary violation persists for a period of time, say 5 min, then every matched pair in the 5-min interval immediately after the first mispricing signal also exhibits boundary violations. As Chung (1991) warns, an arbitrageur subject to capital rationing can execute only one arbitrage in response to the first (or second) mispricing signal but not to subsequent violations. The total number of violations therefore overestimates the actual arbitrage opportunities.

[6] Twenty minutes is an arbitrary time horizon. The results are the same when using 10- or 30-min intervals.

within a 20-min interval after the first mispricing signal. For example, in the pre-decimalization period with the 0.2% transaction costs category, there is an average of 6.22 subsequent violations following a new occurrence of boundary violation, 1.79 penetrating the upper bound, and 6.38 violating the lower bond.

Columns 9 through 11 present the average time span of boundary violations. Results suggest that the subsequent violations usually diminish within a short time period. For instance, for violations in the 0.2% transaction costs category in the pre-decimalization period lasts an average of 56 s. The lower boundary violations (0 min and 58 s) persist longer then the upper boundary violations (0 min and 13 s). The short duration of each cluster of violations indicates that the S&P 500 E-mini price is closely linked to SPDR. More important, arbitrage with transaction lags longer than the time span of violations is subject to uncertainty and may not be profitable, as the ex-ante analysis shows.

TABLE 3

Ex-Post Violations of S&P 500 E-mini Price Boundaries Using SPDRs as a Cash-Market Proxy

Number of Matches	Transaction Costs (%)	Occurrence of Boundary Violations			Average Number of Subsequent Violations			Average Time Span of an Occurrence (mm:ss)		
		Total Number	Upper %	Lower %	Overall	Upper	Lower	Overall	Upper	Lower
Panel A: Pre-Decimalization 2000/10/2-2001/1/28										
206,622	0.20	3,399	4%	96%	6.22	1.79	6.38	0:56	0:13	0:58
	0.30	1,154	1%	99%	1.91	3.45	1.89	0:13	0:49	0:13
	0.40	71	7%	93%	1.75	3.40	1.62	0:12	0:40	0:10
Panel B: Post-Decimalization 2001/1/29-2001/5/29										
224,602	0.20	6,779	<0.1%	>99.9%	10.44	3.00	10.44	1:40	0:31	1:40
	0.30	4,676	<0.1%	>99.9%	2.49	1.25	2.49	0:21	0:11	0:21
	0.40	178	1%	99%	0.67	1.00	0.67	0:04	0:10	0:04

Note. The ex-post tests focus on the frequency and persistence of boundary violation. No-arbitrage bands are constructed on the basis of quote prices of SPDRs

$$10 \times SPDR(t)_{bid}\, e^{(r-d)(T-t)} - C_c < F(t) < 10 \times SPDR(t)_{ask}\, e^{(r-d)(T-t)} + C_c$$

Transaction costs are measured in percentages of the theoretical futures value. An occurrence of boundary violation is defined as a series of same-side violations such that any two adjacent violations are apart by less than 20 min. Average number of subsequent violations and time span of violations measure the frequency of observed mispricing in an occurrence of violation and the time length of the occurrence, respectively.

In the pre-decimalization period, mispricings are asymmetric for the upper and lower bounds, suggesting that the market tends to underprice E-minis' prices in this period. Moreover, the larger lower bound violations tend to persist for longer periods of time and are followed by more subsequence violations as the result of the difference between ETF & index in Table 1.

In the Panel B, the number of occurrence of boundary violations significantly increases, showing that after the decimalization because smaller tick size improves to decrease bid-ask spread and then to decrease transaction costs. Boundary violations occur asymmetrically with fewer violations at upper than lower bounds. From the results in Table 1 found that SPDRs are slightly overvalued relative to index in the sampling period. The overvalued SPDRs overestimate the theoretical futures price and both boundaries.

Columns 6 through 8 reports that number of subsequent violations in the

TABLE 4

Ex-Post Violations of NASDAQ 100 E-mini Price Boundaries Using QQQs as a Cash-Market Proxy

Number of Matches	Transaction Costs (%)	Occurrence of Boundary Violations			Average Number of Subsequent Violations			Average Time Span of an Occurrence (mm:ss)		
		Total Number	Upper %	Lower %	Overall	Upper	Lower	Overall	Upper	Lower
Panel A: Pre-Decimalization 2000/10/2-2001/1/28										
237,594	0.20	18,010	>99.9%	<0.1%	7.24	7.25	0.54	0:52	0:52	0:06
	0.30	16,960	>99.9%	<0.1%	3.83	3.83	0.78	0:26	0:26	0:08
	0.40	10,011	>99.9%	<0.1%	2.32	2.32	0.43	0:15	0:15	0:09
Panel B: Post-Decimalization 2001/1/29-2001/5/29										
291,020	0.20	15,474	>99.9%	<0.1%	13.27	13.28	1.58	1:24	1:24	0:11
	0.30	20,414	>99.9%	<0.1%	5.85	5.85	1.78	0:35	0:35	0:14
	0.40	14,407	>99.9%	<0.1%	3.22	3.22	1.67	0:18	0:18	0:14

Note. The ex-post tests focus on the frequency and persistence of boundary violation. No-arbitrage bands are constructed on the basis of quote prices of QQQs

$$40 \times QQQ(t)_{bid} e^{(r-d)(T-t)} - C_c < F(t) < 40 \times QQQ(t)_{ask} e^{(r-d)(T-t)} + C_c$$

Transaction costs are measured in percentages of the theoretical futures value. An occurrence of boundary violation is defined as a series of same-side violations such that any two adjacent violations are apart by less than 20 min. Average number of subsequent violations and time span of violations measure the frequency of observed mispricing in an occurrence of violation and the time length of the occurrence, respectively.

post-decimalization are larger than in pre-decimalization period for every level of transaction cost. Column 9 shows that most of the violations do not last very long—an average of 0 min and 56 s and 1 min and 40 s for 0.2% transaction costs for the pre-decimalization and the post-decimalization period.

For NASADAQ 100, Table 4 shows the result of ex-post test before and after the decimalization. Note that in the post-decimalization period, occurrence of boundary violations in the 0.30% transaction cost is less than in the 0.20% one. This may be because while the transaction costs move from 0.20% to 0.30%, one long-persisted violation broke into several small ones. This circumstance also can be explained by there are larger numbers of subsequent violations in 0.20% than 0.30% transaction costs.

It is similar to the findings of the S&P 500, except for the percentage of violating upper bound is larger than the percentage of lower one, almost all violations are in the long arbitrage. It may because over the period, market tends to overprice SPDRs and underprice QQQs values.

In summary, comparisons of pre- and post-decimalization periods find that with every level of transaction costs, after decimalization, there is significant addition in occurrence of boundary, average number of subsequent violations, and average time span of an occurrence, showing that decimalization improve to increase arbitrage opportunities between ETFs and their E-minis.

4.2. Ex-Ante Arbitrage Profit

Assuming that arbitrageurs can trade at the next futures trade price and the SPDR quote prices immediately after observing mispricing. Panel A of Table 5 and 6 reposts ex-ante arbitrage profits between SPDRs and S&P 500 E-minis in the pre-decimalization period and the post-decimalization for Panel B. The frequency of mispricing signals, the ex-ante mean profit, and standard deviation for all arbitrage profits are presented in columns 2 and 3. The occurrence of ex-ante arbitrage opportunity is slightly less frequent than the number of boundary violations reported in Table 2 and 3 because some boundary violations occurred near closing time and left no time for traders to initiate arbitrage.

To better identify the source of arbitrage profit and loss, Table 5 and 7 divide results into long arbitrage and short arbitrage in columns 4 through 9 following Chu and Hsieh (2002). The average signal size measuring the ex-post profit defined as the difference between the future price and the appropriate upper or lower boundary at first mispricing signal. Table 5 also showed that a larger ex-post signal size does not guarantee arbitrage profit. It seems that larger deviations tend to reverse more quickly and leave little profit opportunity.

The finding of Table 5 revealed that although frequency of arbitrage opportunity in pre-decimalization period was larger than in post-decimalization period, the

TABLE 5

Ex-Ante Arbitrage Profit Using SPDRs Against S&P 500 E-mini

	All Arbitrage		Long Arbitrage			Short Arbitrage		
Transaction Costs (%)	Frequency	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)
Panel A: Pre-Decimalization 2000/10/2-2001/1/28								
0.20	3,398	0.197(0.667)	120	0.361	-0.040(1.866)	3,278	0.300	0.206(0.576)
0.30	1,154	0.020(0.800)	11	1.205	0.283(5.715)	1,143	0.265	0.017(0.600)
0.40	71	0.431(2.748)	5	2.124	2.602(4.965)	66	0.592	0.266(2.495)
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	6,774	0.210(0.495)	7	0.589	0.513(1.507)	6,767	0.283	0.210(0.493)
0.30	4,675	0.077(0.470)	4	0.895	-2.237(4.926)	4,671	0.225	0.079(0.448)
0.40	178	-0.231(1.244)	2	0.560	-2.442(10.570)	176	0.218	-0.206(0.933)

Note. The ex-ante test assumes trading SPDRs at prevailing quote prices immediately after observing boundary violations. A long arbitrage, triggered by futures overpricing, buys SPDRs and shorts futures after observing an upper-boundary violation, whereas a short arbitrage, triggered by futures underpricing, performs opposite transactions. Profits for long and short arbitrage are measured as follows

$$AP_L = F(t^+) - [10 \times SPDR(t^+)_{ask} e^{(r-d)(T-t)} + C_c]$$

$$AP_S = [10 \times SPDR(t^+)_{bid} e^{(r-d)(T-t)} - C_c] - F(t^+)$$

Ex-ante mean profit measures the profit/loss after considering transaction lag. Signal size stands for the ex-post profit. "NA" stands for not available. "STD" in parentheses means standard deviation.

TABLE 6

Ex-ante Arbitrages by Type and Profitability of Arbitrages Using SPDRs Against S&P 500 E-mini

	Long Arbitrage				Short Arbitrage			
	Profitable		Unprofitable		Profitable		Unprofitable	
Transaction costs (%)	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit
Panel A: Pre-Decimalization 2000/10/2-2001/1/28								
0.20	57	0.742	63	-0.747	2,197	0.484	1,081	-0.359
0.30	4	4.817	7	-2.308	617	0.380	526	-0.409
0.40	4	3.903	1	-2.603	27	1.491	39	-0.582
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	6	0.870	1	-1.628	4,687	0.429	2,080	-0.284
0.30	2	1.591	2	-6.065	2,848	0.337	1,823	-0.323
0.40	1	5.033	1	-9.916	66	0.510	110	-0.635

Note. The ex-ante test assumes trading SPDRs at prevailing quote prices immediately after observing boundary violations. A long arbitrage buys cash SPDRs and short S&P 500 E-mini after observing an upper-boundary violation. A short arbitrage performs opposite transactions. "NA" stands for not available.

ex-ante mean profit decreased for 0.40% transaction cost level. This means that after decimalization, smaller bid-ask spread reduced transaction costs to improve arbitrage opportunities, and strength the pricing efficiency between E-minis and ETFs. The result of Table 5 also found that overall intraday return volatility at any cost level decreased after decimalization consistent to Bessembinder (2003).

Table 6 looks into the arbitrage outcomes by dividing long and short arbitrage into profitable and unprofitable transactions. In summary, the ex-ante tests show higher arbitrage profit for trading SPDRs against futures than using programming trading (see the Appendix). The advantage of trading SPDRs for index arbitrage may have enhanced the pricing efficiency of the spot-index market, as shown in the pre- and post-decimalization comparison.

As the result of ex-ante test between SPDRs and their E-minis, the behaviors in the ex-ante test using QQQs and NASDAQ 100 E-minis are almost in the same pattern in Table 7 and 8. We also can see that the ex-ante profits after the decimalization for every level of transaction costs are decreased. The intraday return volatility for both long and

TABLE 7

Ex-Ante Arbitrage Profit Using QQQs Against NASDAQ 100 E-mini

	All Arbitrage		Long Arbitrage			Short Arbitrage		
Transaction Costs (%)	Frequency	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)
Panel A: Pre-Decimalization 2000/10/2-2001/1/28								
0.20	18,002	1.673(2.882)	17,989	1.911	1.676(2.837)	13	6.658	-1.400(19.629)
0.30	16,953	0.951(2.765)	16,944	1.553	0.952(2.720)	9	6.432	-0.536(22.869)
0.40	10,005	0.426(2.916)	9,998	1.378	0.428(2.840)	7	7.057	-2.500(27.023)
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	15,467	1.216(1.862)	15,455	1.273	1.219(1.812)	12	10.802	-2.698(15.500)
0.30	20,408	0.727(1.613)	20,399	0.942	0.730(1.566)	9	12.143	-5.650(18.245)
0.40	14,406	0.413(1.641)	14,397	0.808	0.419(1.569)	9	10.478	-8.695(18.166)

Note. The ex-ante test assumes trading QQQs at prevailing quote prices immediately after observing boundary violations. A long arbitrage, triggered by futures overpricing, buys QQQs and shorts futures after observing an upper-boundary violation, whereas a short arbitrage, triggered by futures underpricing, performs opposite transactions. Profits for long and short arbitrage are measured as follows

$$AP_L = F(t^+) - [40 \times QQQ(t^+)_{ask} e^{(r-d)(T-t)} + C_c]$$

$$AP_S = [40 \times QQQ(t^+)_{bid} e^{(r-d)(T-t)} - C_c] - F(t^+)$$

Ex-ante mean profit measures the profit/loss after considering transaction lag. Signal size stands for the ex-post profit. "NA" stands for not available. "STD" in parentheses means standard deviation.

TABLE 8

Ex-ante Arbitrages by Type and Profitability of Arbitrages Using QQQs Against NASDAQ 100 E-mini

	Long Arbitrage				Short Arbitrage			
	Profitable		Unprofitable		Profitable		Unprofitable	
Transaction costs (%)	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit
Panel A: Pre-Decimalization 2000/10/2-2001/1/28								
0.20	13,721	2.699	4,268	-1.613	4	20.321	9	-11.053
0.30	11,521	2.240	5,423	-1.787	4	17.648	5	-15.082
0.40	6,109	2.009	3,889	-2.056	2	31.246	5	-15.999
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	12,365	1.760	3,090	-0.947	8	4.792	4	-17.679
0.30	14,856	1.353	5,543	-0.940	5	4.997	4	-18.959
0.40	9,618	1.157	4,779	-1.067	4	3.563	5	-18.501

Note. The ex-ante test assumes trading QQQs at prevailing quote prices immediately after observing boundary violations. A long arbitrage buys cash QQQs and short NASDAQ 100 E-mini after observing an upper-boundary violation. A short arbitrage performs opposite transactions. "NA" stands for not available.

short arbitrage also reduced after decimalization. These empirical results are consistent with pricing efficiency between ETFs and their E-minis.

5. SUMMARY AND CONCLUSIONS

This article finds that after the decimalization on January 29, 2001, there is a significant increase in the number of arbitrage opportunities. These findings are consistent with the literature that reports that transaction costs and quoted depth decreased after the decimalization. Reductions in the minimum price increment reduce the effects of price discreteness and therefore market friction. Taken together with the evidence provided in this paper conclude that arbitrage link between ETFs and their E-minis have strengthened with the decimalization.

Test of ex-post boundary violations indicate that after decimalization, there are significant addition in occurrence of boundary, average number of subsequent violations, and average time span of an occurrence, showing that decimalization improve to increase arbitrage opportunities between ETFs and their E-minis.

This investigation found a surprisingly close price relationship between ETFs and E-minis. Ex-ante analyses of showed that show higher arbitrage profit for trading ETFs against futures than using programming trading. The advantage of trading ETFs for index arbitrage may have enhanced the pricing efficiency of the spot-index market, as shown in the pre- and post-decimalization comparison.

APPENDIX

A.1. Ex-Post Boundary Violations

Table 9 summarizes the size, frequency, and length of E-minis ex-post boundary violations before (panel A) and after (panel B) the decimalization. Boundary violations are identified according to Equation 3 for various levels of two-way transaction costs ranging from 0.20 to 0.40% of the theoretical futures price.

Column 6 through 8 reports the average number of subsequent violations occurring within a 20-min interval after the first mispricing signal. For example, in the pre-decimalization period with the 0.2% transaction costs category, there is an average of 5.69 subsequent violations following a new occurrence of boundary violation, 5.69 penetrating the upper bound, and 0.60 violating the lower bond.

TABLE 9

Ex-Post Violations of S&P 500 E-mini Price Boundaries Using S&P 500 Index as a Cash-Market Proxy

Number of Matches	Transaction Costs (%)	Occurrence of Boundary Violations			Average Number of Subsequent Violations			Average Time Span of an Occurrence (mm:ss)		
		Total Number	Upper %	Lower %	Overall	Upper	Lower	Overall	Upper	Lower
Panel A: Pre-Decimalization 2000/9/28-2001/1/28										
104,788	0.20	4,496	>99.9%	<0.1%	5.69	5.69	0.60	1:36	1:36	0:09
	0.30	1,730	>99.9%	<0.1%	3.76	3.76	0.00	1:04	1:04	0:00
	0.40	294	>99.9%	<0.1%	0.84	0.84	0.00	0:14	0:14	0:00
Panel B: Post-Decimalization 2001/1/29-2001/5/29										
107,904	0.20	3,090	99%	1%	2.83	2.85	0.18	0:46	0:47	0:04
	0.30	334	99%	1%	0.57	0.57	0.33	0:11	0:11	0:10
	0.40	15	87%	13%	2.20	2.54	0.00	0:39	0:45	0:00

Note. The ex-post tests focus on the frequency and persistence of boundary violation. No-arbitrage bands are constructed on the basis of the spot index

$$IDX_{SP}(t)e^{(r-d)(T-t)} - C_{c+m} < F(t) < IDX_{SP}(t)e^{(r-d)(T-t)} + C_{c+m}$$

Transaction costs are measured in percentages of the theoretical futures value. An occurrence of boundary violation is defined as a series of same-side violations such that any two adjacent violations are apart by less than 20 min. Average number of subsequent violations and time span of violations measure the frequency of observed mispricing in an occurrence of violation and the time length of the occurrence, respectively.

Columns 9 through 11 present the average time span of boundary violations. Results suggest that the subsequent violations usually diminish within a short time period. For instance, for violations in the 0.2% transaction costs category in the pre-decimalization period last an average of 1 min and 36 s. The upper boundaryviolations (1 min and 36 s) persist longer then the lower boundary violations (0 min and 9 s). The short duration of each cluster of violations indicates that the S&P 500 E-mini price is closely linked to the underlying index. More important, arbitrage with transaction lags longer than the time span of violations is subject to uncertainty and may not be profitable, as the ex-ante analysis shows.

In the pre-decimalization period, mispricings are asymmetric for the upper and lower bounds. When transaction costs exceed 0.2%, there are no lower bound violations, but there are upper bound ones, suggesting that the market tends to overprice E-minis' prices in this period. Moreover, the larger upper bound violations tend to persist for longer periods of time and are followed by more subsequence violations as the result of the difference between ETF & index in Table 1.

Table 10 generating the result of ex-post analysis on NASDAQ 100 index also shows the same pattern with S&P 500 index. We also can find that after decimalization, occurrence of boundary violations, subsequent violations, and time span all decreased at any cost level, different with the result using ETFs as cash-market proxy. It seems to that after decimalization, the smaller bid-ask spread improve to trade at the true values of the component stocks form the index. Therefore, we can conjecture that decimalization strengthen the pricing efficiency between E-minis and ETFs. On the other hand, this study here doesn't consider the true bid and ask price of every component stock and we can't see the true arbitrage opportunities.

TABLE 10

Ex-Post Violations of NASDAQ 100 E-mini Price Boundaries Using NASDAQ 100 Index as a Cash-Market Proxy

Number of Matches	Transaction Costs (%)	Occurrence of Boundary Violations			Average Number of Subsequent Violations			Average Time Span of an Occurrence (mm:ss)		
		Total Number	Upper %	Lower %	Overall	Upper	Lower	Overall	Upper	Lower
Panel A: Pre-Decimalization 2000/9/28-2001/1/28										
109,706	0.20	9,090	98%	2%	2.54	2.59	0.26	0:41	0:42	0:04
	0.30	4,257	99%	1%	1.97	1.98	0.31	0:32	0:32	0:05
	0.40	1,892	99%	1%	1.18	1.19	0.67	0:20	0:20	0:11
Panel B: Post-Decimalization 2001/1/29-2001/5/29										
113,592	0.20	6,824	97%	3%	2.29	2.36	0.22	0:37	0:38	0:03
	0.30	3,391	99%	1%	1.07	1.08	0.54	0:17	0:17	0:09
	0.40	798	99%	1%	0.45	0.45	0.78	0:08	0:08	0:12

Note. The ex-post tests focus on the frequency and persistence of boundary violation. No-arbitrage bands are constructed on the basis of the spot index

$$IDX_{ND}(t)e^{(r-d)(T-t)} - C_{c+m} < F(t) < IDX_{ND}(t)e^{(r-d)(T-t)} + C_{c+m}$$

Transaction costs are measured in percentages of the theoretical futures value. An occurrence of boundary violation is defined as a series of same-side violations such that any two adjacent violations are apart by less than 20 min. Average number of subsequent violations and time span of violations measure the frequency of observed mispricing in an occurrence of violation and the time length of the occurrence, respectively.

A.2. Ex-Ante Arbitrage Profit

Table 11 summarizes results for ex-ante arbitrage profit assuming a 5-min transaction lag for a trading spot portfolio. Panel A reports negative mean arbitrage profit for the various levels of transaction costs in the pre-decimalization period. For example, although traders in the 0.20% transaction costs category face 4,427 arbitrage opportunities, executing these arbitrage opportunities results in an average losses of 0.139 index points. The mean arbitrage losses are even greater for higher transaction cost traders, with -0.345 at 0.30% and -0.916 at 0.40% transaction costs. Further investigation shows that neither long nor short arbitrage is profitable at any cost level, as shown in columns 4 through 9.

Comparison of the two subperiods provides one insight. We found that index arbitrage using program trading results in negative mean profits in both subperiods, indicating that the market is ex-ante efficient.

TABLE 11

Ex-Ante Arbitrage Profit Using Program Trading
(Reported Index with Time Lag)

	All Arbitrage		Long Arbitrage			Short Arbitrage		
Transaction Costs (%)	Frequency	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)
Panel A: Pre-Decimalization 2000/9/28-2001/1/28								
0.20	4,427	-0.139(0.987)	4,422	0.355	-0.135(0.982)	5	0.471	-3.468(0.317)
0.30	1,712	-0.345(1.408)	1,711	0.295	-0.343(1.404)	1	0.390	-4.917(0.000)
0.40	287	-0.916(1.518)	287	0.315	-0.916(1.518)	0	NA	NA(NA)
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	3,035	-0.264(0.817)	3,020	0.276	-0.254(0.801)	15	0.977	-2.265(1.391)
0.30	327	-1.185(1.130)	324	0.252	-1.165(1.088)	3	2.371	-3.344(3.125)
0.40	14	-2.676(3.368)	12	1.626	-2.250(3.249)	2	1.996	-5.232(4.017)

Note. The ex-ante test imposes a 5-min execution lag for trading underlying stocks (program trading) against futures. A long arbitrage, triggered by futures overpricing, buys a basket of S&P 500 stocks and shorts futures after observing an upper-boundary violation, whereas a short arbitrage, triggered by futures underpricing, performs the reverse transactions. Profits for long and short arbitrage are measured as follows

$$AP_L = F(t^+) - [IDX_{SP}(t^+)e^{(r-d)(T-t)} + C_{c+m}]$$
$$AP_S = [IDX_{SP}(t^+)e^{(r-d)(T-t)} - C_{c+m}] - F(t^+)$$

Ex-ante mean profit measures the profit/loss after considering transaction lag. Signal size stands for the ex-post profit. "NA" stands for not available. "STD" in parentheses means standard deviation.

TABLE 12

Ex-ante Arbitrages by Type and Profitability of Arbitrages Using Program Trading Against S&P 500 E-mini

	Long Arbitrage				Short Arbitrage			
	Profitable		Unprofitable		Profitable		Unprofitable	
Transaction costs (%)	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit
Panel A: Pre-Decimalization 2000/9/28-2001/1/28								
0.20	1,975	0.688	2,447	-0.800	NA	NA	5	-3.468
0.30	640	0.662	1,071	-0.943	NA	NA	1	-4.917
0.40	27	0.984	260	-1.113	NA	NA	NA	NA
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	1,194	0.473	1,826	-0.729	1	0.375	14	-2.453
0.30	16	1.113	308	-1.283	NA	NA	3	-3.344
0.40	1	7.256	11	-3.114	NA	NA	2	-5.232

Note. The ex-ante tests impose a 5-min execution lag for trading underlying stocks (program trading) against S&P 500 E-mini. A long arbitrage buys a basket of S&P 500 stocks and short S&P 500 E-mini after observing an upper-boundary violation. A short arbitrage performs opposite transactions. "NA" stands for not available.

TABLE 13

Ex-Ante Arbitrage Profit Using Program Trading (Reported Index with Time Lag)

	All Arbitrage		Long Arbitrage			Short Arbitrage		
Transaction Costs (%)	Frequency	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)	Frequency	Average Signal Size	Ex-Ante Mean Profit (STD)
Panel A: Pre-Decimalization 2000/9/28-2001/1/28								
0.20	8,951	-1.443(4.435)	8,777	1.412	-1.318(4.339)	174	1.430	-7.720(4.680)
0.30	4,188	-2.044(6.544)	4,161	1.386	-1.976(6.496)	27	2.777	-12.461(5.711)
0.40	1,846	-2.667(8.063)	1,836	1.374	-2.588(7.998)	10	2.851	-17.188(7.120)
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	6,729	-0.837(2.491)	6,538	0.826	-0.733(2.409)	191	1.031	-4.386(2.650)
0.30	3,343	-1.354(2.148)	3,323	0.723	-1.317(2.085)	20	3.444	-7.383(3.606)
0.40	791	-2.298(2.574)	782	0.638	-2.215(2.438)	9	4.860	-9.528(3.771)

Note. The ex-ante test imposes a 5-min execution lag for trading underlying stocks (program trading) against futures. A long arbitrage, triggered by futures overpricing, buys a basket of NASDAQ 100 stocks and shorts futures after observing an upper-boundary violation, whereas a short arbitrage, triggered by futures underpricing, performs the reverse transactions. Profits for long and short arbitrage are measured as follows

$$AP_L = F(t^+) - [IDX_{ND}(t^+)e^{(r-d)(T-t)} + C_{c+m}]$$

$$AP_S = [IDX_{ND}(t^+)e^{(r-d)(T-t)} - C_{c+m}] - F(t^+)$$

Ex-ante mean profit measures the profit/loss after considering transaction lag. Signal size stands for the ex-post profit. "NA" stands for not available. "STD" in parentheses means standard deviation.

TABLE 14

Ex-ante Arbitrages by Type and Profitability of Arbitrages Using Program Trading Against NASDAQ 100 E-mini

	Long Arbitrage				Short Arbitrage			
	Profitable		Unprofitable		Profitable		Unprofitable	
Transaction costs (%)	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit	Frequency	Ex-ante Mean Profit
Panel A: Pre-Decimalization 2000/9/28-2001/1/28								
0.20	3,070	2.584	5,707	-3.417	5	1.400	169	-7.989
0.30	1,252	2.643	2,909	-3.964	NA	NA	27	-12.461
0.40	390	2.886	1446	-4.065	NA	NA	10	-17.188
Panel B: Post-Decimalization 2001/1/29-2001/5/29								
0.20	2,430	1.415	4,108	-2.004	9	1.438	182	-4.674
0.30	827	1.054	2,496	-2.103	NA	NA	20	-7.383
0.40	81	1.204	701	-2.610	NA	NA	9	-9.528

Note. The ex-ante tests impose a 5-min execution lag for trading underlying stocks (program trading) against NASDAQ 100 E-mini. A long arbitrage buys a basket of NASDAQ 100 stocks and short NASDAQ 100 E-mini after observing an upper-boundary violation. A short arbitrage performs opposite transactions. "NA" stands for not available.

Table 12 analyzes the arbitrage outcomes by dividing long and short arbitrage further into profitable and unprofitable transactions. For both types of arbitrage, unprofitable arbitrage consistently dominates profitable arbitrage in both subperiods.

For NASDAQ 100, we can see similar result in Table 13 and 14 and find that the performance of NASDAQ 100 is more significant than S&P 500.

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