When Does the Tick Size Help or Harm Market Quality? Evidence from the Tick Size Pilot*

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Abstract

Tick sizes provide a market quality tradeoff between pricing fidelity and undercutting — suggesting that the same tick size change may affect narrow and wide-spread stocks differently. Using comprehensive depth-of-book data we study the imposition and conclusion of the Tick Size Pilot (TSP) across a broad spectrum of stocks and many market quality dimensions. For TSP stocks with quoted spreads less (more) than 9¢ (15¢) the TSP *harmed* (*improved*) market quality. Our methodology contrasts with existing TSP studies which treat all non-tick constrained stocks the same and our analysis suggests care when using the TSP as an exogenous shock to liquidity.

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1 Introduction

Tick sizes affect many aspects of market quality and regulators around the globe are paying increased attention to them.[1] The Tick Size Pilot (TSP), which increased the tick size from 1¢ to 5¢ for some US stocks, provides a prime opportunity to study the causal effects of a tick size change on market quality, and numerous studies have used the TSP to do just that (see e.g. Hu, Hughes, Ritter, Vegella, and Zhang (2018), Griffith and Roseman (2019), Rindi and Werner (2019), and Chung, Lee, and Rösch (2020) among others). While this literature consistently finds that the TSP harmed liquidity for stocks that became tick constrained by the TSP,[2] for non-tick constrained stocks, which comprise the vast majority of listed stocks, the literature offers virtually no consistent results.[3] Using MIDAS depth of book data and other sources, we present robust empirical evidence that the TSP harmed market quality for stocks with average quoted spreads less than 9¢ and improved it for stocks with quoted spreads greater than 15¢.

To frame our analysis we characterize tick sizes as offering a market quality tradeoff between pricing fidelity and undercutting concerns similar to Werner, Rindi, Buti, and Wen (2022). Pricing fidelity refers to how accurately realized prices can reflect fundamental values. A smaller tick increases pricing fidelity by creating a finer price lattice on which the market can establish prices (Harris (1991), Harris (1996)). This effect improves market quality by allowing prices to more accurately equate liquidity supply and demand which in turn limits distortions that can occur when the tick size forces the bid-ask spread to be too wide relative to fundamentals.[4] However, a smaller tick reduces the cost of undercutting — referred to as pennying in industry. Undercutting occurs when a market participant cuts to the front of the queue by posting a quote that offers economically trivial price improvement. Undercutting behavior has been shown to harm market quality by mak-

[1] For example, in December 2022, the US Securities and Exchange Commission proposed the first update to US tick sizes in 20 years(https://www.sec.gov/rules/proposed/2022/34-96494.pdf). In Europe, MIFID II, adopted in 2018, updated the tick sizes for European markets. The Korean Stock Exchange modified tick sizes in 2010 and is again in January 2023. The Japanese Stock Exchange modified their tick size in 2014.

[2] A stock is tick constrained when it is consistently trading with a quoted spread that equals the minimum tick. This situation indicates that the stock would likely trade with a narrower spread if the tick size constraint were relaxed. In the context of the TSP, stocks with pre-TSP quoted spreads less than 5¢ are considered to have been tick constrained by the TSP because their prevailing quoted spread with a 1¢ tick was lower than the imposed 5¢ tick. For the TSP conclusion we characterize tick constrained stocks as those with average quoted spreads of 5.5¢.

[3] We review this literature in greater detail in Section 2.

[4] When the tick size forces spreads to be wider than is justified by stock fundamentals, the price of liquidity is too high and there can be an oversupply of liquidity leading to longer queues for limit orders, lower fill rates, and an increasing importance of speed to get to the front of the queue. See e.g., Yao and Ye (2018), Rindi and Werner (2019), and Mackintosh (2022)

ing market participants less willing to post displayed liquidity, by making inventory management more difficult, and potentially increasing adverse selection for slower liquidity providers - effects which can discourage liquidity provision (Werner et al. (2022), Foley, Dyhrberg, and Svec (2022), and Edwards, Hughes, Ritter, Vegella, and Zhang (2021)).[5] We refer to these competing effects as the tick size tradeoff.

This tradeoff suggests that the same tick size change will impact stocks differently depending on which force plays a bigger role. Following this intuition, stocks with narrower spreads should see pricing fidelity predominate, meaning that a larger tick worsens market quality. In contrast, stocks with wider spreads should see undercutting predominate. For these wider spread stocks, a larger tick improves market quality by reducing the number of price levels and so decreasing the role of undercutting. This is exactly what we find.

Understanding the empirical implications of this tradeoff is critical for two reasons. First, as we show, near-tick constrained stocks and those with wide spreads, while both technically not tick constrained, had liquidity affected in opposite directions by the TSP. Thus, combining all non-tick constrained stocks into one group, as is prevailing practice, muddles empirical inference by essentially averaging the market quality effects of stocks that were positively and negatively impacted by the TSP. Second, there is a growing literature that uses the TSP as an exogenous shock — usually to liquidity — to make inference in a wide range of settings.[6] In empirical design, this literature generally assumes, implicitly, that the TSP affected all test stocks the same. This is not the case. Studies that use the TSP as an exogenous shock could benefit by addressing this heterogeneity, perhaps by limiting their sample to only tick or near-tick constrained stocks. In this regard our analysis compliments the message of Heath, Ringgenberg, Samadi, and Werner (2020) in arguing that when using, or re-using, natural experiments, particularly in settings outside the designed intent of the natural experiment, caution needs to be used to ensure that the resulting inference is valid.

To measure the market quality impact of the TSP, our empirical methodology advances what is learned from the TSP about the impact of tick sizes on market quality in four key ways. First, like

[5]While not directly attributing their result to undercutting, Allena and Chordia (2021) document that the TSP lowered inventory risk, which is consistent with lower undercutting risk.

[6]Prominent published and working papers in this vein include Ahmed, Li, and Xu (2020), Lee and Watts (2021), Li and Xia (2021), Hope and Liu (2022), Ye, Zheng, and Zhu (2022), Cheng, Huang, and Yin (2022), Chen, Ng, Ofosu, and Yang (2022), Deng, Lin, and Zhou (2022), Lin, Yao, and Zou (2022) among others.

prior TSP studies, we use a difference-in-difference (DD) setup to measure the effect of the TSP on treated stocks. However, in important contrast to prior studies, we place stocks into four bins labeled tick constrained, near-tick constrained, intermediate spread, and wide spread stocks based on the stock's prevailing quoted spread relative to the 5¢ tick size. This segregation of non-tick constrained stocks into three groups is key because it allows us to clearly identify which stocks were positively and negatively affected by the tick size change.

Second, we have access to data sources not available to most prior studies. In addition to standard measures of liquidity and price efficiency, we use data from MIDAS, which allows us to view the entire order book at any given point in time and thus study the effect of the TSP on depth beyond the top of the book and on outcomes whose construction require depth-of-book data.[7]

Third, our study improves on prior studies by performing DD regressions on both the TSP imposition and conclusion. Since these events were separated by two years, the results obtained for both events can capture robust effects of the TSP. A further virtue of studying the TSP conclusion is that the market had two years to adapt to the larger tick size and was thus familiar with both the 5¢ tick regime and the 1¢ tick regime. As a consequence, results obtaining from the TSP conclusion are less likely to reflect transient changes that may affect analysis of the imposition of the TSP as market participants adapted their behavior to the larger tick.

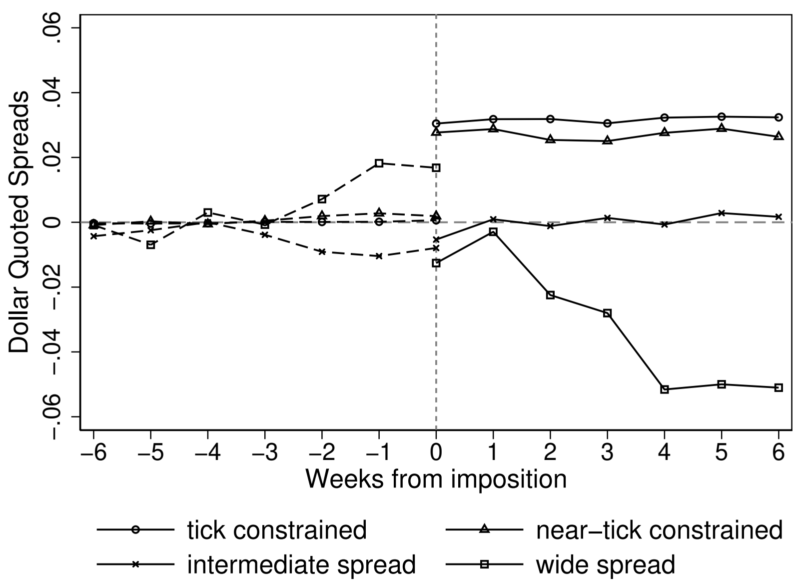
A fourth innovation is our use of quantile regressions in our main specifications. Microstructure outcome variables are notoriously sensitive to outliers, and OLS regression outcomes can be sensitive to how researchers deal with outliers. Thus, while we use OLS regressions as a robustness check and to connect with prior literature, our main analysis focuses on quantile (median) regressions, which do not suffer from the same outlier sensitivities.

Turning to empirical results, Figure 1 provides a succinct description of our overall empirical message. This figure plots the effect of the imposition of the TSP on quoted spreads for four categories of stocks: tick constrained, near-tick constrained, intermediate-spread, and wide-spread stocks. For stocks that became tick or near-tick constrained by the imposition of a 5¢ tick, quoted spreads widened by about 3¢. For stocks with intermediate pre-TSP quoted spreads (10¢-15¢), a

[7] To our knowledge only Chung et al. (2020) uses comparable data although they combine all non-tick constrained stocks together and their results for non-tick constrained stocks are unclear. They also examine depth at a limited number of levels. Griffith and Roseman (2019) and Penalva and Tapia (2017) also have order book data, but it comes from the Nasdaq ITCH data set and thus only covers Nasdaq exchanges.

5¢ tick had no visually discernible impact on quoted spreads. For stocks with very wide spreads (15¢+), moving from 1¢ to 5¢ narrowed quoted spreads by about 4¢. This pattern reflects the expectation that for stocks with already narrow spreads, an increase in the tick size harms market quality by making it more difficult for prices to find equilibrium. However, for stocks with very wide spreads, a larger tick may help mitigate undercutting concerns leading to better market quality.

Figure 1. Quoted Spread's Response to a Minimum Tick Size Increase.
The figure presents visual evidence of the causal impacts of an exogenous increase in the tick size associated with the TSP for differentially tick constrained stocks. Stocks are classified into four tick constraint bins based on their average May and June 2016 quoted spreads: tick constrained (bin 1), no more than 5¢; near-tick constrained (bin 2), 5¢ to 10¢; intermediate spread (bin 3), 10¢ to 15¢; and wide spread (bin 4), above 15¢. Each week, median quoted spread is calculated by tick constraint bin for control and pilot stocks after controlling for date fixed effects. The time-series of the difference in medians of control and pilot firms are plotted against weeks from the day of increase in tick size, with 08/12/2016-09/30/2016 and 10/24/2016-12/14/2016 used as pre- and post-event intervals, respectively.



An overview of our remaining empirical results follows. We first look for evidence of trading behavior consistent with less undercutting with a wider tick. When undercutting concerns are prominent, we expect traders to manage posted quotes more aggressively—increasing the cancel-to-trade ratio. They will use more hidden orders to avoid being undercut—increasing the hidden ratio. They will shred trades into a larger number of child orders—increasing the odd-lot ratio. They will also use intermarket sweep orders (ISOs) more. If a larger tick size decreases undercutting concerns, we would expect that all four metrics would decrease during the TSP and then increase again after the TSP is concluded. This pattern is exactly what we observe. Collectively, our findings provide compelling evidence for the tick size tradeoff.

Turning to market quality, results for effective spread mirror the pattern presented in Figure 1 for quoted spread. For tick and near-tick constrained stocks, the TSP significantly increased effective spreads and when the TSP ended effective spreads declined. For stocks with very wide spreads, the 5¢ tick appeared to offer superior market quality to a 1¢ tick as effective spreads declined when the TSP was imposed and then increased at the conclusion of the TSP.

We next consider the TSP's impact on depth across the quoted spread spectrum. Consistent with prior studies, a larger tick size is associated with increased depth at the National Best Bid and Offer (NBBO) for all quoted spread groups—with the biggest effect for tick and near-tick constrained stocks. This finding is consistent with the idea that a larger tick forces quotes that would have spread out over multiple price levels to instead concentrate onto fewer discrete prices. Looking beyond the top of the book with MIDAS data, we find that that cumulative depth across all exchanges increased but that the pattern of the increase is different for tick constrained stocks and those with wide spreads. For stocks that were tick constrained by the 5¢ tick, the increase in cumulative depth is felt deeper in the book, at 25¢ from the NBBO and deeper, while the exact opposite pattern obtains for stocks featuring wide spreads, with most of the increase in cumulative depth occurring closer to the quote midpoints.

An increase in cumulative depth need not translate directly into a lower cost of trading, which, in part, reflects how the increased depth is spread across the various price levels. We study the effect of the TSP on trading costs using cumulative round trip costs to trade (CRT) for a broad spectrum of trade sizes. These CRT measures are similar to those employed by Griffith and Roseman (2019), Chung et al. (2020), and Domowitz, Hansch, and Wang (2005). They are measured as the absolute difference between the average cost per share when walking the book until a given number of shares are purchased averaged across both sides of the market. Two key results characterize our CRT findings. First, the effect of the TSP on trading costs becomes less negative (or more positive) the larger the CRT share level considered. Second, the effect of the TSP on CRTs becomes less negative (or more positive) for stocks with wider spreads. We view both patterns as consistent with two effects. First, by limiting undercutting the TSP induced additional liquidity provision, consistent with the findings of Foley et al. (2022) and Foley, Meling, and Ødegaard (2021). Second, because a wider tick decreases the role of time priority liquidity providers may feel induced to maintain orders at various price levels to ensure their queue priority should prices change. These two effects combined would cause the two patterns observed in the data.

We next evaluate the effect of the TSP on price efficiency. Existing TSP research on price efficiency generate conflicting results, with different studies showing increases, decreases, or no effect on price efficiency. We predict that the effect of the TSP on price efficiency will depend on the time horizon used to measure price efficiency. Intra-day measures of price efficiency based on return autocorrelation or variance ratios will likely show a decrease in price efficiency because a larger tick will mechanically limit market participants' abilities to arbitrage return patterns that exist within the tick size. However, longer term price efficiency measures, such as daily autocorrelations, are less likely to be affected by these small price movement effects and are likely more indicative of the behavior of fundamental investors trading on information. Some have argued that a larger tick inhibits HFT behavior making it easier to implement a trade for a non-HFT, which will improve price efficiency by leading to more information acquisition (Lee and Watts (2021) and Ahmed et al. (2020)). Others have argued that, to the extent that a larger tick makes it more expensive to transact, it will discourage gathering and trading on information (Li and Xia (2021)). Consequently, the existing literature does not provide clear guidance regarding the effect of the TSP on longer horizon measures of price efficiency. Consistent with our prediction for intra-day price efficiency measures, we find that both autocorrelation and variance ratio price efficiency measures based on intra-day prices suggest a decline in price efficiency associated with the TSP - particularly for tick constrained stocks. However, our longer horizon price efficiency results using daily return autocorrelation suggest that the TSP had no effect on price efficiency.

A natural concern relating to the TSP is its generalizability because the TSP focused on small-cap stocks. Thus, there is concern that findings from the TSP may not generalize outside of small-cap stocks. We address this by exploring the robustness of our findings in various ways. We re-run key analysis on only the top half of TSP stocks in terms of average trading volume, we include a robust set of stock characteristic control variables, we exclude penny stocks, and we estimate quartile regressions at the first and third quartiles. Our main results are robust to these tests.

Finally, we attempt to identify with greater precision the thresholds in terms of ticks intra-spread where the TSP stocks traded with more liquidity with either a 5¢ or 1¢ tick size. To accomplish this, we estimate quantile regressions with rolling bins across the quoted spread spectrum for both the TSP imposition and conclusion and across many market quality measures. This methodology will inherently limit the power of the tests relative to the main tests in the study by limiting the sample size. Consequently, we use a rule of thumb to determine where on the quoted spectrum the TSP transitioned from harmful to benign to beneficial. Specifically, we identify a quoted spread range as having been affected by the TSP if both the TSP imposition and conclusion results agree in sign and at least one set of tests is statistically significant. If not, we label the range as undetermined. This analysis indicates that across most market quality metrics, stocks with quoted spreads less than 9¢ generally traded better with the 1¢ tick—which produced 1-9 ticks intra-spread—than with the 5¢ tick—which produced less than 2 ticks intra-spread. On the other end, stocks with prevailing quoted spreads greater than 15¢ generally traded better with the 5¢ tick size.

2 Background and Related Literature

2.1 The Tick Size Tradeoff

Tick sizes have been discussed in the academic literature as presenting a market quality tradeoff of some sort going back to at least Grossman and Miller (1988) who argue that a tick size, by establishing the minimum bid ask spread, needs to be large enough to ensure adequate compensation to market makers, but not so large that it discourages participation in the market by fundamental traders. Harris (1991) also characterizes tick sizes as providing a tradeoff in terms of bargaining costs and transaction costs. Harris (1991) also points out that tick sizes need to be non-zero for time priority to play a meaningful role in financial markets. Seppi (1997) and Portniaguina, Bernhardt, and Hughson (2006) model tick sizes as providing a tradeoff between spread size and undercutting. A smaller tick narrows spreads but also allows a specialist to more easily undercut other traders, while a larger tick can widen spreads but limits undercutting behavior and promotes depth.[8]

[8]While not explicitly discussing tick sizes as providing a tradeoff, the notion that a tick size change will affect stocks differently depending on the characteristics of the stocks is also well established in the literature. Bonart (2017) conducts a cross-sectional analyses examining relative tick sizes on NASDAQ and finds that execution costs fall with a decreasing relative tick size up to a point after which they start to rise. The literature on decimalization provides additional support for the notion that the same change in tick size will not affect all stocks the same. While most studies examining the process of decimalization found positive results (e.g., Bacidore, Battalio, and Jennings (2003), Chordia, Roll, and Subrahmanyam (2008), and Zhao and Chung (2006)), Bessembinder (2003) finds that

These studies generally discuss tick sizes in the context of a non-computerized market where most trading takes place face-to-face. In today's markets, we believe that tick sizes should be characterized as providing a market quality tradeoff between pricing fidelity on the one hand and concerns relating to undercutting on the other, a view supported by the theoretical model of Werner et al. (2022).[9] Pricing fidelity refers to the ability of markets to establish equilibrium prices. A tick size that is too large constrains the bid-ask spread to a level greater than what it would otherwise be. When this occurs, there will be an oversupply of liquidity relative to the amount demanded at that price and a smaller tick would allow spreads to close in on the narrower latent spread (Harris (1994)). Existing research indicates that when spreads are constrained by tick sizes, market quality deteriorates: transaction costs in the form of quoted and effective spreads increase, queue lengths are longer, fill rates are lower, and the relative importance of speed for liquidity providers increases (Yao and Ye (2018), Rindi and Werner (2019), and Mackintosh (2022)).

On the other hand, a stock that has too many ticks intra-spread can see market quality decline due to undercutting concerns. A smaller tick increases undercutting by weakening time priority and making it easier to get to the front of the queue by submitting a limit order that, while technically superior to existing orders, offers economically trivial price improvement (Harris (1991)). Undercutting increases the cost of providing liquidity for many reasons. First, undercutting discourages posting displayed liquidity (Werner et al. (2022), Foley et al. (2022)). A market participant who posts a displayed quote is broadcasting the measure that an undercutter needs to beat in order to get to the front of the queue. Hidden orders at superior prices will execute before displayed orders at inferior prices and so they can be used as a defense against undercutting. However, hidden orders are not costless: they are more expensive than displayed orders in terms of exchange fees, have higher uncertainty regarding whether they will be executed, and hidden orders can decrease the likelihood that an exchange is at the NBBO and so receives an order. Increased use of hidden orders is also associated with worse market quality on numerous dimensions (Edwards et al. (2021)). Undercutting increases adverse selection for slower traders because if a slower liquidity provider has a

when the tick in US markets moved from $\$\frac{1}{16}$ to 1¢, liquidity and spreads improved for the market as a whole with the most substantial improvements being in heavily traded stocks. Lastly, Angel (1997) argues that firms use stock splits to increase their relative tick size which benefits market makers to promote liquidity provision while balancing the costs a wider spread has on investors.

[9] Li and Ye (2021) model the optimal number of ticks intra-spread and find that approximately two ticks provides a theoretically optimal number. However, their model abstracts away from undercutting concerns.

trade execute, it could be simply be because a faster liquidity provider received a signal that prices were going to move against the posted quote and so they chose not to undercut—a behavior akin to sniping (Li, Wang, and Ye (2021), O'Hara, Saar, and Zhong (2019)). Less certainty regarding whether a given order will execute due to undercutting concerns can increase the cost of inventory management and is empirically associated with less liquidity provision (Foley et al. (2022), Foley et al. (2021)). Less competition for liquidity provision is empirically associated with worse market quality (Brogaard and Garriott (2019)).

Many ticks intra-spread can also potentially increase the cost of providing liquidity by making liquidity spread out over many price levels and potentially many exchanges, requiring increased data and connectivity expenses as well as computer processing power. These costs can be particularly salient in the United States because of the Order Protection Rule (OPR), Rule 611 of Regulation NMS. This rule prevents stocks from trading at prices that are not the protected NBBO price. Because of the OPR, an order cannot walk the book on one exchange if doing so would trade through a protected quote on another exchange. For example, if exchange A has 100 shares offered at \$10.00 and 100 shares offered at \$10.01, and exchange B has 100 shares offered at \$10.00, a trader wishing to buy 200 shares could not simply submit a 200 share order to exchange A, even if the trader does not have connectivity to exchange B. Such an order would violate the OPR because the protected price in this case is \$10.00, and so it would be illegal for the trader to execute the 100 shares on exchange A for \$10.01 without first executing the shares at the protected price level of \$10.00 at exchange B. If Exchange A were to receive an order for 200 shares, it would execute 100 shares at the protected price and then re-route the remaining 100 shares to exchange B, and the trader would be charged a re-routing fee in addition to any transaction fee charged. Alternatively, the trader could submit an order for 100 shares directly to both exchanges. However, doing so would require data and connectivity to both exchanges as well as the technical capacity to monitor both exchanges and relevant price levels. As the number of price levels increases, this process becomes more costly.

Pricing fidelity concerns are most salient for stocks with relatively narrow spreads and undercutting concerns become more salient as spreads widen. For narrow spread stocks, the tick size is most binding in terms of preventing market participants from improving prices to levels more reflective of liquidity supply and demand. For example, in a stock with a 2¢ spread, a trader wishing to improve the price would have to cut the quoted spread in half to do so. For stocks with wider spreads, this is not the case and the relative cost to improve the spread is lower. For narrow spread stocks, a larger tick could harm market quality by exacerbating pricing fidelity concerns. For wide spread stocks the cost of improving the spread is smaller and the degrees of freedom which market participants have to post quotes is larger. Thus, undercutting is easier among stocks with wider relative spreads (Werner et al. (2022)). For these stocks, a larger tick could improve market quality by mitigating undercutting concerns.

2.2 The Tick Size Pilot

In May 2015, the SEC approved a National Market System (NMS) plan that would implement a two-year tick size pilot (TSP) that would increase the tick size to 5¢ for some stocks. Participation in the TSP was limited to stocks with a market capitalization less than $3 billion. The TSP applied to approximately 2,400 securities, of which approximately 1,200 were control stocks. The remaining 1,200 were divided into three test groups, 400 in each group, which we label G1, G2, and G3. The imposition of the TSP was staggered through the month of October 2016, with the TSP going live for the first set of stocks on October 3 and the last set of stocks on October 31.[10]

Stocks in G1 received a 5¢ tick that only applied to quoting but not to trading. For these stocks, the TSP acted in a manner similar to the way Rule 612 of Reg NMS, which establishes the 1¢ tick in US markets, currently operates. In practice, however, because most exchanges and ATSs run crossing networks, the 5¢ tick applying to quotes meant that the majority of trades in this test group occurred in increments of 5¢. Exceptions include trades that executed via midpoint or benchmark trades like Volume Weighted Average Price (VWAP) or Time Weighted Average Price (TWAP) trades, as well as trades that were internalized by wholesalers.

Stocks in G2 had the 5¢ apply to both trading and quoting. However, in practice, there was functionally very little difference between G1 and G2 because G2 offered exceptions to the requirement to trade in units of the 5¢ tick for midpoint and benchmark trades, like VWAP or TWAP trades, as well as for retail trades that receive price improvement of at least a half a cent. Thus, the only functional difference between G1 and G2 was that G2 would apply the 5¢ trading

[10]See Griffith and Roseman (2019) Section 2 for additional details on the timelines for the imposition of the TSP. The TSP concluded on October 1, 2018 for all stocks.

increment to internalized retail trades that did not receive a half cent of price improvement and potentially non-retail trades that could be internalized by wholesalers. While there is no clear data on the total volume of these securities, they were likely a very small fraction of total trading volume. Consequently, Hu et al. (2018), who provide an exhaustive analysis of the differences between the test groups, find no reliable differences between how stocks in G1 and G2 responded to the TSP.

Stocks in G3 had the same restrictions as those in G2 but they also had a trade-at rule applied. A trade-at rule would require trading centers that do not currently have quotes posted at the NBBO to either improve the price relative to the NBBO when executing an incoming order, or to route the order to an exchange posting at the NBBO. The trading center couldn't simply match the existing NBBO. A trade-at rule would, for example, prevent an exchange that had a hidden order at the NBBO from executing unless the exchange was also posting a displayed quote at the protected price. Most studies, including Hu et al. (2018), find that G3 responded significantly differently to the TSP relative to G1 and G2 on many dimensions. Comerton-Forde, Grégoire, and Zhong (2019) and Farley, Kelley, and Puckett (2018) also document that the trade-at rule led to a significant redistribution of trading volume across maker-taker and inverted exchanges.

2.3 Existing TSP Literature

Numerous studies have used the TSP to study the effects of a tick size change on market quality. Prominent studies in this vein include Hu et al. (2018), Rindi and Werner (2019), Penalva and Tapia (2017), Chung et al. (2020), and Griffith and Roseman (2019). In this review, we focus our discussion on results in the literature for G1 and G2. This is because the focus of our study is on the effect of tick sizes on market quality and not on the trade-at rule.

Existing studies generally agree as to the effect of the TSP on stocks that became tick constrained by the larger tick—i.e., stocks that had pre-TSP prevailing quoted spreads less than or equal to 5¢. Consistent with pricing fidelity playing a primary role among these stocks, the literature is consistent in finding that the TSP generally harmed market quality. For example, one consistent finding is that depth at the top of the book increases with the 5¢ tick, which could be indicative of improved market quality. However, this increase in depth is not enough to compensate for the mechanically wider spreads imposed by the 5¢ tick. All studies that we are aware of find that for tick constrained stocks, the TSP increased both quoted and effective spreads. Chung et al.

(2020) and Griffith and Roseman (2019) study liquidity beyond the top of the book and generally report that the TSP was harmful to market quality deeper in the book for tick constrained stocks.[11] In a related study Allena and Chordia (2021) develop a big data methodology to estimate the liquidity effects of the TSP and find that the TSP, on average, lowers liquidity across all TSP stocks.

The consistency of results documented in the TSP literature for tick constrained stocks does not extend to non-tick constrained stocks. Non-tick constrained stocks comprise the vast majority of listed securities and accounted for approximately 80% (50%) of dollar (share) volume in the first six months of 2022. For these stocks, the existing research examining the effects of the TSP on market quality is quite muddled. For example, Hu et al. (2018) find that for non-tick constrained stocks, increasing the tick size largely had no effect on either quoted or effective spreads. Rindi and Werner (2019), in contrast, find that quoted spreads go up but effective spreads go down for non-tick constrained stocks. Chung et al. (2020) find that quoted spreads decrease for non-tick constrained stocks. The confusion extends beyond analysis of trade based on top of the book-based measures of liquidity. Chung et al. (2020) find that for non-tick constrained stocks, the cost of transacting large quantities fell with a larger tick. In contrast, Griffith and Roseman (2019) use different data and methods and find that for non-tick constrained stocks, increasing the tick size led to either no effect or an increase in the cost of executing a large trade.

The literature is not just muddled regarding the effect of the TSP on standard measures of liquidity for non-tick constrained stocks, it also has produced results running the spectrum in terms of the effect of the TSP on price efficiency. Hu et al. (2018) find for tick constrained stocks that price efficiency diminishes and, depending on the measure used, for non-tick constrained stocks that price efficiency is either unchanged or declines. Chung et al. (2020) present evidence suggesting that price efficiency broadly increased. Li and Xia (2021) present results arguing that price efficiency was harmed across all stocks and they argue that the mechanism was lower liquidity, discouraging investors from gathering information in pilot stocks. In contrast, Lee and Watts (2021) and Ahmed et al. (2020) take the exact opposite position. Both studies argue that the TSP improved information gathering opportunities by discouraging high-frequency traders. Further,

[11] In rare disagreement, Chung et al. (2020) find when analyzing liquidity very deep in the book (e.g. 5,000 shares) that the TSP improved liquidity for tick constrained stocks while Griffith and Roseman (2019) observe the opposite effect.

Albuquerque, Song, and Yao (2020) document significant pricing effects of the TSP specifically for tick constrained stocks while Pachare and Rainer (2018) find no such effect.

While the studies here differ in terms of methodologies used, they all share a few common characteristics. With one exception, existing studies focus their analysis on the introduction of the TSP.[12] Additionally, the studies mentioned here divide stocks into at most two groups, tick and non-tick constrained, and some don't do that, for their analysis. As discussed previously, combining all non-tick constrained stocks together for analysis likely muddles the effect of the TSP for these stocks as we expect that stocks that are near-tick constrained, where pricing fidelity concerns predominate, may respond to the larger tick size differently from those stocks with very wide spreads, where undercutting concerns may predominate. The current state of the TSP literature leaves individuals seeking to understand how the TSP may have affected market quality at a loss—exposing a significant gap in the current understanding of the empirical effect of a tick size change on market quality.

3 Data and Methodology

3.1 Data

Our empirical analysis focuses on the TSP, and Section 2.2 provides an overview of the structure of the TSP. We study two event windows: one around the imposition of TSP and the other around its conclusion. For our analysis of the imposition of the TSP, we examine the time window of 08/11/2016 through 12/15/2016. We follow Griffith and Roseman (2019) and exclude from this window the trading days spanning the staggered imposition of the TSP which comprise 10/03/2016–10/23/2016.[13] Our analysis of the imposition of the TSP has a pre-period where both the pilot and control stocks had a tick of 1¢, running from 8/11/2016 to 10/02/2016, and a treatment period where pilot stocks had a 5¢ tick and control stocks had a 1¢ tick, running from 10/24/2016 to 12/15/2016. Our analysis of the conclusion of the TSP runs from 08/07/2018 through 11/20/2018, during which the minimum tick size for stocks in TSP Test Groups was simultaneously reduced

[12] Albuquerque et al. (2020) examine both the imposition and conclusion of the TSP.

[13] Some effects related to the tick size change may not occur instantaneously as market participants may need time to optimize systems and adapt behavior. Excluding the imposition period helps mitigate some of this noise that may muddle inference of the steady state effects of the tick size change.

from 5¢ to 1¢ on 10/01/2018.[14]

This study compares microstructure outcomes of control stocks, denoted C, to those of TSP Test Groups 1 and 2, denoted G1 and G2, respectively. Because of the similarities between G1 and G2 discussed in Section 2.2, and to increase the power of our tests, we combine G1 and G2 stocks together for all analysis.[15] We use the "`tick size pilot indicator`" flag in TAQ data to identify control and pilot stocks as well as the exact dates tick size changes were enforced for each stock in the experiment. This allows us to identify exact actual enforcement dates for the few stocks whose TSP restrictions where enforced or lifted with delays relative to the dates intended by the program. Stocks that changed test groups or that were removed from the TSP, for any reason, are excluded from all analysis.[16]

We construct daily measures of time-weighted average quoted spreads and size-weighted average effective spreads during regular trading hours from Daily TAQ data following the procedure described in Holden and Jacobsen (2014). Additionally, we construct daily measures of size-weighted average realized spreads and price impacts by comparing transaction prices of signed trades with the quote midpoints x seconds forward, with $x \in \{15, 60, 300\}$, reflecting the findings of Conrad and Wahal (2020). From WRDS Intraday Indicators, we obtain daily measures of time-weighted quoted depth at the National Best Bid and Offer prices (NBBO); total trading volume; and share of ISO trading volume in daily volume, constructed using information from regular trading hours.

To study market quality deeper in the book, we use data from MIDAS. Among other things, MIDAS data allows us to take snapshots of the entire order book across all exchanges and at any point in time. From MIDAS data, we obtain daily measures of cancel-to-trade ratio, which divides the daily number of canceled orders by the total daily number of trades; hidden ratio, which divides the daily number of trades involving hidden orders by the total daily number of

[14] Following Rindi and Werner (2019), we remove trading days coinciding with Labor Day, Thanksgiving, and Black Friday from our sample. We also do not omit the period surrounding the conclusion of the TSP as we do with the imposition of the TSP because nearly all TSP stocks returned to a 1¢ tick simultaneously, with market participants returning to a familiar trading environment, i.e., one that had continued to operate on the majority of stocks. For these reasons, we generally view the conclusion of the TSP as a cleaner test than the TSP imposition.

[15] Although we do not perform any analysis on G3 stocks in the main body of the paper because our focus is on tick size changes and not the trade-at rule, the appendix provides results from our primary tests for each of the three test groups independently—including G3 stocks.

[16] If a stock's price closes lower than $1.00 on any trading day, then the following trading day the stock is removed from the TSP and placed into the control group with a 1¢ tick. Removing such stocks from our analysis prevents such outcomes from contaminating the analysis. In Section 4.6 we repeat our main analysis excluding all stocks with closing prices below $5.00 and document similar results as our main tests.

trades; and odd-lot ratio, which divides the daily number trades involving odd-lot orders by the total daily number of trades. From MIDAS, we also extract measures of cumulative depth in the order book as well as the the per share cost (in dollars) associated with round-trip trades. For each stock day in our sample, we take snapshots of the entire order book every 15 minutes from 9:45am through 3:45pm. Across these snapshots, we calculate the average cumulative depth on the ask and bid sides of the order book at z cents away from the corresponding midpoint, with $z \in \{-60, -40, -25, -15, -10, 10, 15, 25, 40, 60\}$.[17] We also calculate the hypothetical round-trip per share cost associated executing y-round-lot orders, with $y \in \{1, 2.5, 5, 10, 25, 50, 100\}$ following the same procedure used by Chung et al. (2020) and Griffith and Roseman (2019). This procedure essentially walks the book on both sides of the market until y round lots are purchased. We then compute the absolute difference between the average per share purchase price and the midpoint for both sides of the market and take the average of the two. This procedure is computed for every 15 minute snapshot and then the average across the entire trading day is computed for a stock to give the average cost of a round trip trade for a trade of y round lots for that stock that day. We refer to the cost of a round trip trade as $CRT_{y,i,t}$ where y identifies the number of round lots, i indexes the stock, and t indexes the day.[18]

Using Quote and NBBO files from Daily TAQ, we construct high-frequency measures of price efficiency. After identifying NBBO prices, we construct 5-minute returns of each stock using NBBO midpoints. We estimate AR(1) models of these returns by stock and day, storing the respective AR(1) coefficients as measures of price efficiency—full price efficiency, i.e., a martingale price process, translates into AR(1) coefficients that equal zero. From WRDS Intraday Indicators, we also obtain return variance ratios for horizons 15 seconds to 3×5 seconds and 5 minutes to 5×1 minute. The absolute values of the differences between these ratios and unity measure price efficiency, with a quantity of zero capturing fully efficient prices. Hence, reflecting the extent of auto-correlation in returns, variance ratios rise when intra-day returns become more strongly auto-correlated.

[17] We use natural logs of all depth variables to provide a percentage DiD estimate for treatment effect, and we replace the natural log of depth with zero when the respective depth quantity is zero, i.e., we assume a depth of zero is equivalent to a depth of one share.

[18] A missing value is assigned to cumulative depth when the quoted price in the order book falls below $1. Similarly a missing value is assigned to round-trip costs when there is not enough depth available to fill a y-round-lot order.

3.2 Empirical Method

Our primary empirical methodology used throughout this study employs difference-in-difference quantile regressions to measure the effect of the TSP on G1 and G2 stocks compared to control stocks. For this analysis, TSP stocks in G1 and G2 as well as control stocks are partitioned into one of four bins based on their prevailing time-weighted quoted spread prior to the imposition and conclusion of the TSP. Our bin assignments are guided by two objectives: (i) distinguishing stocks based on the number of intra-spread ticks under a 5¢-tick regime; and (ii) maintaining comparable test power across bins. For the imposition window, stocks are classified into bins according to their time-weighted average quoted spreads in May and June of 2016.[19] For the imposition phase of the analysis, stocks are assigned to the following four groups: bin 1 (tick constrained) 5¢ or less quoted spread, bin 2 (near-tick constrained) greater than 5¢ but less than 10¢, bin 3 (intermediate spread) greater than 10¢ but less than 15¢, and bin 4 (wide spread) greater than 15¢. These bins correspond to stocks for which a 5¢ tick would result in one or fewer, one to two, two to three, or more than three ticks intra-spread.

For the conclusion of the TSP, stocks are similarly assigned to bins based on average quoted spreads in May and June 2018 with slight modifications to the bins as follows: bin 1 (tick constrained) less than 5.5¢, bin 2 (near-tick constrained) greater than 5.5¢ but less than 10¢, bin 3 (intermediate spread) greater than 10¢ but less than 15¢, and bin 4 (wide spread) greater than 15¢. This slight modification of bin 1's threshold reflects the restrictions put in place by the TSP. The 5¢ tick size creates a floor on quoted spreads making it all but impossible for a TSP stock to have a time-weighted quoted spread less than 5¢, thus the threshold for tick constrained stocks is 5.5¢ for the conclusion of the TSP.[20]

Table 1 reports the distribution of control and treated stocks across the four bins for the TSP imposition (Panel A) and the TSP Conclusion (Panel B). Treated stocks comprise 18-60% of the stocks falling in each tick constraint category, providing meaningfully large treatment groups. In addition, the table indicates no statistically significant differences in market capitalization, dollar

[19] Specifically we use WRDS Intraday Indicators data for time-weighted average quoted spread for each stock during regular trading hours and compute a simple average across all trading days in May and June 2016.

[20] A quoted spread less than 5¢ could occur for TSP stocks whose prices dropped below $1.00 at which point the minimum tick would revert to the standard $0.0001 that applies to all stocks priced below $1.00 by Rule 612 of Reg NMS. This effect likely does not impact our analysis because if the stock closes priced less than $1.00, the stock would be removed from the TSP and also would be removed from all analysis based on the filters presented above.

volume, and return volatility across control and treated stocks in any of the categories. Quoted spreads of control and treated stocks in Groups 1 & 2 of the TSP conclusion window are statistically different. This is a consequence of the TSP experiment design where treated stocks must trade at quoted spreads at or above the 5¢ tick, while for control stocks this is not the case. As such, consistent with the design of TSP, any significant effect associated with a change in tick size within our tick constrained categories may not be attributed to non-random differences in these firm characteristics.

Table 1 also presents the correlations between quoted spreads in May-June of 2016 for the imposition and 2018 for the conclusion and average share price, market cap, daily dollar volume and volatility over the same period. All variables are converted to percentiles to account for non-linearity in the data. This analysis indicates that quoted spreads are positively associated with share price, but negatively associated with dollar volume and volatility. There is also a negative association with market cap, but the association appears weak, particularly for the TSP conclusion.

[Insert Table 1 about here.]

We employ a difference-in-difference strategy to estimate the impacts of an exogenous change in tick size on a given outcome variable, Y_{jt}. We estimate

$$Y_{j,t} = \alpha_0 + \alpha_p Pilot_j + \alpha_e Event_{j,t} + \beta \left(Pilot_j \times Event_{j,t} \right) + u_t + \varepsilon_{j,t}, \tag{1}$$

where $Pilot_t$ is an indicator variable that equals 1 for treated stocks (G1 or G2) and equals 0 for control stocks; $Event_{j,t}$ of a treated stock equals 0 prior to a change in minimum tick size and equals 1 after the change, accounting for the enforcement date differences across stocks; $Event_{j,t}$ of a control stock in the imposition (conclusion) window equals zero before 10/03/2016 (10/01/2018) and equals 1 as of 10/24/2016 (10/01/2018); u_t is the date fixed effect; and $\varepsilon_{j,t}$ is the error term.

To estimate the treatment effect β, we fit equation (1) using quantile regressions, with median regressions underlying our main result. Microstructure variables are notoriously sensitive to outliers and results can change depending on how researchers choose to manage outliers. By using quantile median regressions, we sidestep outlier concerns in our analysis. For robustness and to connect with prior literature, we also fit standard OLS estimates after winsorizing each outcome variable,

Y_{jt}, at its 5^{th} and 95^{th} percentiles by tick constraint and treatment category.[21] All of our estimates control for date fixed effects and double-clustered standard errors at the stock-date level.[22]

4 Results

4.1 Undercutting

Foley et al. (2022) document that undercutting can be a profitable trading strategy. They also show that liquidity providers respond to undercutting by reducing the amount of time that they expose orders and by reducing the size of exposed orders (i.e. depth decreases). Their study is concentrated on a crypto exchange. On equity markets, this behavior—reducing the size and exposure time of liquidity providing orders—will manifest as increases in the cancel-to-trade ratio and the odd-lot ratio. The cancel-to-trade ratio is a MIDAS-based measure that captures the number of orders that are canceled relative to the number of trades that execute. An increase in the odd-lot ratio will indicate that liquidity providers are posting smaller individual quotes. Additionally, Werner et al. (2022) argue theoretically that when undercutting risk is higher, liquidity providers will respond by posting more hidden orders. Thus when the risk of undercutting is higher, the hidden ratio, which is the ratio of hidden orders to displayed orders, will increase. In addition to these measures, we also suggest that the risk of undercutting may lead to increased intermarket-sweep-orders. An ISO order allows traders to execute orders from the top of the book simultaneously across multiple venues even if an exchange is not currently priced at the NBBO. It is a way to circumvent the order protection rule. An ISO order allows market participants to trade relatively larger quantities in one shot thus making it more difficult for markets to anticipate the order and adjust prices against the user of the ISO (see Lohr (2021)). We view ISO usage as a response to potential adverse selection concerns associated with undercutting and the fact that there is less liquidity and less stable liquidity at the NBBO when undercutting risk is high.

[21] Winsorizing at the 1^{st} and 99^{th} percentiles has no material impact on our findings with the exception of OLS estimates for realized spreads and price impacts whose distributions feature very long tails.

[22] Because there is some variation in the dates when the TSP was implemented across TSP stocks, the variable $Event_{j,t}$ does not drop out of the regressions due to colinearity with the time fixed effect. The introduction of date fixed effects reflects the fact that for some stocks, the enforcement/lifting dates of TSP restrictions differ from the intended dates by the program. However, in unreported results, we verify robustness to, instead, the use of stock fixed effects or the use of both date and stock fixed effects. The consistency of results across fixed effect specifications is consistent with the findings of Rindi and Werner (2019), who also state that their results are virtually unchanged as they vary their fixed effects specifications.

If a larger tick mitigates undercutting risk, then an outcome consistent with this would be a decrease in all of these metrics. Thus, we hypothesize that across all metrics, moving from a 1¢ to a 5¢ tick will lead to a reduction in all four measures and that the conclusion of the TSP will see the opposite occur. To this end, we perform DD regressions examining the effect of the TSP on the cancle-to-trade ratio, the hidden ratio, the odd-lot ratio, and the ISO volume as a percent of total volume. These results are presented in Table 2.

Table 2 provides evidence consistent with our hypothesis. Analysis of the TSP imposition and conclusion uniformly suggest that a 5¢ tick led to lower cancel-to-trade ratios across all stocks. This finding is true for all spread bins but was most pronounced in the wide spread bin—where undercutting concerns would predominate. Table 2 also shows a significant decrease in the use of hidden orders associated with the larger tick size for all but tick constrained stocks—again with the largest effect on stocks with wider spreads. For tick constrained stocks, the results from the TSP imposition and conclusion disagree.[23] The 5¢ tick was also associated with a decrease in the use of odd-lot orders. Lastly, we find that ISO volume fell on the TSP imposition and then rose again upon its conclusion for tick and near-tick constrained stocks. For intermediate spread stocks and stocks with wide spreads, we find no consistent effect on ISO volume. These findings, while not causally indicative of undercutting, are consistent with prior literature and the predictions of theory concerning how market participants may respond when faced with undercutting risk.

[Insert Table 2 about here.]

4.2 Quoting Behavior

If the market for liquidity provision is competitive and there is a tick size, then the bid and ask prices will be set at the price just worse (from the liquidity demander's perspective) than the break even prices for the marginal liquidity provider. In this case, the tick size has two effects on the equilibrium quoted spread: it limits the lattice where bid and ask prices can be set, and it endogenously affects the cost of providing liquidity through undercutting. Consider a competitive market where liquidity providers would post quotes with a 2¢ spread (but not lower) that has a

[23] For tick constrained stocks the the imposition results are small and negative while the conclusion results are also negative and larger. We generally view the TSP conclusion as a cleaner test, so it is possible that the TSP may have lead to an increase in hidden order usage among tick constrained stocks — although the mechanism isn't immediately obvious.

5¢ tick restricting spreads to a {5¢,10¢,15¢,...} grid. In this case, 2¢ is not a feasible spread and so the spread would widen to 5¢, all else equal, resulting in a tick size induced distortion of 3¢. However, the price point at which LPs are willing to supply liquidity is itself affected by the pricing grid. If the pricing grid is set too fine, the cost of undercutting quotes falls and the spreads at which LPs supply liquidity may need to widen to provide compensation for the hazardous market structure. Put differently, the higher fidelity of a smaller tick size allows for spreads to narrow in on the equilibrium spread, up to a point, after which increased fidelity causes the equilibrium spread to widen as the market becomes more hazardous due to undercutting.

We hypothesize that for stocks with narrow spreads, a larger tick will lead to a wider quoted spread until a point whereupon spreads are sufficiently wide that a larger tick improves the trading environment by reducing the risk of undercutting.

The results provided in Table 3, which provide DD analysis of the effect of the TSP imposition and conclusion on time-weighted quoted spread for each of the four spread bins, are consistent with our hypothesis. For tick and near-tick constrained stocks, the imposition of the 5¢ tick increased quoted spread by between 2.2¢ and 5.2¢. For stocks with wide spreads, the TSP decreased spreads by between 3.9¢ and 9.9¢. For intermediate stocks, the effect is uncertain as the results from the imposition and conclusion disagree.

[Insert Table 3 about here.]

We next examine the percentage change in quoted depth at the NBBO as a result of a change in the tick size. Depth at the NBBO is important because of the order protection rule, which prohibits an exchange from executing an order at a price worse than the prevailing NBBO. Having significant liquidity at the NBBO makes it easier to source a larger number of shares directly.

We hypothesize that the 5¢ tick size will lead to an increase in depth at the NBBO—a result already demonstrated in prior literature. However, there are competing hypotheses regarding which bins will receive the largest relative increase in depth. First, a larger tick forces liquidity to congregate at fewer price points. This is true across all stocks. However, for stocks with very narrow spreads, the relative fraction of total depth that is forced to congregate at the larger tick price levels is greater than it is for stocks with wide spreads. This effect would suggest that narrower spread stocks will experience a larger increase in depth at the NBBO. Alternatively, Foley et al. (2022) document that market makers respond to undercutting risk by posting less liquidity. Undercutting risk is greatest among stocks with wider spreads, and so to the extent that the wider tick mitigates undercutting risk, it may lead to an increase in depth at the NBBO among stocks with wider spreads. Consequently, the net effect is an empirical question.

Our empirical analysis of depth at the NBBO presented in Table 4. This analysis finds that while quoted depth at the NBBO rises for all spread bins with the 5¢ tick, the relative increase varies significantly across these bins with the greatest increases occurring in tick and near-tick constrained stocks. As minimum tick size rises from 1¢ to 5¢, quoted NBBO depth of the median stock rises by 108%, 104%, 53%, and 20% for tick constrained, near-tick constrained, intermediate spread, and wide spread stocks respectively. For all quoted spread bins, the effect reverses upon the conclusion of the TSP, with the greatest declines in NBBO depth occurring in tick and near-tick constrained stocks.

[Insert Table 4 about here.]

We provide further evidence of the heterogeneous impacts of a tick size change on the cost of undercutting resting quotes by examining the effect of a tick size change on cumulative depth at different price levels in the order book. Using MIDAS data, we construct the log of average cumulative ask- and bid-side quoted depth at 10¢, 15¢, 25¢, 40¢, and 60¢ away from the midpoint for each stock-day. We then estimate the effect of a tick size increase (decrease) on cumulative depth measures using Equation (1) at the TSP imposition (conclusion). Figure 2 plots median regression point estimates and the corresponding 95% confidence intervals against the order book location relative to the midpoint—in unreported results, we find qualitatively similar patterns using OLS estimates.

[Insert Figure 2 about here.]

Our analysis indicates that while depth increased all along the order book, the effects of tick-size change on cumulative quoted depth follow strikingly different patterns across differently tick constrained stocks. For tick constrained stocks, these effects are largest deeper in the order book. For near-tick constrained stocks, the increased depth appears uniform across price levels. For intermediate and wide-spread stocks, effects are strongest closer to the midpoint. For stocks with wide spreads, the increase in depth near the NBBO is consistent with the wider spread mitigating undercutting risk and thus encouraging more liquidity provision near the NBBO. The finding that the cumulative depth increases for tick constrained stocks deeper in the book could reflect the coarser price lattice increasing time priority. When time priority is more important due to the wider tick, it is more important to get an order submitted to establish queue priority. Consequently, liquidity providers may post orders deeper in the book to establish queue priority in the event of a price change than they would with a smaller tick.

Our depth of book results are largely consistent with Chung et al. (2020) who likewise find an overall increase in depth deeper in the book and are less consistent with Griffith and Roseman (2019) who find lower depth for tick constrained stocks. However, the tick size tradeoff presents a possible reconciliation of Griffith and Roseman (2019) and Chung et al. (2020). Griffith and Roseman (2019) have data from only Nasdaq exchanges and limit their analysis to only Nasdaq listed securities while Chung et al. (2020) studies depth across all markets. A plausible response to heightened undercutting risk could be that liquidity providers may concentrate their liquidity provision on the listing exchange because it is too costly to post and manage liquidity across multiple venues and many price levels in the presence of heightened undercutting risk. When the TSP reduced the risk of undercutting, liquidity providers responded by spreading out their liquidity provision across more venues. Consequently, the total depth posted on the listing exchange declined while overall depth increased.

4.3 Trading Costs and Trading Activity

We next analyze the effects of a change in tick size on various measures of trading costs and trading activity. Our measures of trading costs include effective spreads as well as round-trip per share cost associated executing y-round-lot orders, with $y \in \{1, 2.5, 5, 10, 25, 50, 100\}$, constructed using MIDAS order book data.[24]

We hypothesize that we should observe the same overall pattern of results in terms of the effect of the TSP on effective spreads as we do with the effect of the TSP on quoted spreads: for narrow spread stocks, the larger tick will lead to higher transaction costs as pricing fidelity effects

[24]The total size of a round trip order of y round lots is a function of the price of the stock. In untabulated robustness analysis, we document qualitatively similar results based on the per-dollar round-trip execution costs of z-thousand-dollar positions, with $z \in \{1, 2.5, 5, 10, 25, 50, 100, 250\}$.

dominate. For wide spread stocks, we expect the opposite to occur as the larger tick reduces the risk of undercutting, leading to lower transaction costs.

Table 5 provides evidence consistent with this hypothesis. For stocks that were tick or near-tick constrained by the imposition of the 5¢ tick size, effective spreads increased by between 3.2¢ and 3.6¢ for tick constrained and 1.6¢ and 2.5¢ for near-tick constrained stocks. For wide spread stocks, the effect of the larger tick size was to reduce effective spreads by between 1.8¢ and 3.2¢. For intermediate stocks, the TSP imposition and conclusion results were not clear as they disagree on sign and statistical magnitude. In any case, the point estimates for the effect of the TSP on intermediate spread stocks indicate an effect less than 1¢. The muted results for intermediate spread stocks are consistent with the findings for quoted spread and suggest that at this level, pricing fidelity and undercutting concerns may largely offset.

[Insert Table 5 about here.]

Effective spreads can be mechanically affected by trade sizes, as larger trades may have to go deeper into the book to execute. We do document in Table 5 that average trade size increases by between 4 and 16%, with the largest increases in trade size associated with tick and near-tick constrained stocks. However, we do not believe that increased trade size is the key driver of increased effective spreads; rather, we view the increase in trade size as a natural response to the increase in depth at the NBBO. Additionally, the relative magnitude of the increase in effective spreads is significantly larger than the increase in trade size. For tick constrained stocks, which had pre-TSP average effective spreads of approximately 2.5¢, the TSP more than doubled effective spreads. For near-tick constrained stocks, which had pre-TSP average effective spreads of approximately 5¢, the imposition of the TSP increased effective spreads by approximately 50%. These magnitudes are significantly larger than the 7-10% increase in trade size.

In Table 5, we also examine the impact of the TSP on trading volume. Werner et al. (2022) argue theoretically that a tick size change could have competing effects on trading volume. In their specification, they predict that the effects of a tick size change on market quality will mirror overall market quality effects. Thus, where a tick size change negatively affects market quality, trading volume will decrease. The opposite is true when the tick size change improves market quality. We do not find strong evidence that the TSP affected volume one way or the other as the results are not statistically significant, and where they are significant, the TSP imposition and conclusion disagree concerning the effect. This effect coheres with the findings of O'Hara et al. (2019).

We next explore the cost of transacting deeper in the book using the cost of a round trip trade measure 'CRT'. Similar measures are employed by both Griffith and Roseman (2019) and Chung et al. (2020). These measures estimate the average per share cost to walk the book on both sides of the market up to a given level of shares. The order protection rule prevents trades from occurring at prices other than the NBBO, and thus it is not possible to submit an order that simply walks the book. However, executing a rapid succession of orders can produce a similar effect. For example, if the first order executes at the NBBO, the next best price then becomes the new NBBO and a subsequent order can execute against that quote. Thus by submitting a rapid succession of orders, a trader could do something akin to walking up the book to execute a large trade. We therefore believe it is useful to explore the average cost to transact a large order. Additionally, this analysis can help provide additional insight given that Griffith and Roseman (2019) and Chung et al. (2020) find conflicting results in their analysis.

The total trading cost associated with the execution of an order that removes liquidity deep in the order book reflects the net effect of two opposing factors: pricing and cumulative depth. Trading costs increase in the distance between the prices at which LPs quote and the NBBO midpoint, but they decrease in the cumulative depth that is available at any given price. While our prior results have established the effects of a tick size change on bid-ask spreads and cumulative depth, it is yet to be determined how these effects net out to determine trading costs deeper in the book.

Table 6 documents two distinct patterns that generally hold across CRT round lot sizes and for the imposition and the conclusion of the TSP. First, the effect of a larger tick size on CRT levels becomes less negative (or more positive) for stocks with wider spreads. The second pattern that emerges from this analysis is that as the trade size considered increases, a larger tick size becomes less harmful (or more beneficial) to CRT transaction costs. For example, for wide spread stocks and for one round lot, the imposition of the TSP decreased transaction costs by 3.8¢ for a one round lot trade and by 10¢ for a 25 round lot trade. Similarly, for tick constrained stocks, the TSP conclusion lowered one round lot CRTs by 9.5¢ and 18¢ for 25 round lot trades. We view both patterns as consistent with two effects. First, by limiting undercutting, the TSP may have induced additional liquidity provision that may not have otherwise been provided, or would have been provided via hidden orders, consistent with the findings of Foley et al. (2022) and Foley et al. (2021) and our analysis in Figure 2. Second, because a wider tick decreases the role of time priority, liquidity providers may feel induced to maintain orders at various price levels to ensure their queue priority should prices change—increasing posted liquidity deeper in the book. These effects would increase displayed depth, particularly for wider spread stocks.

[Insert Table 6 about here.]

4.4 Profits to Liquidity Provision

The tradeoff between pricing fidelity and undercutting also has implications for the profits to liquidity provision. The direct compensation for providing liquidity is the effective spread. The spread can be decomposed into two components: the realized spread and adverse selection components. The adverse selection component of the spread is measured as the proportional change in the midpoint between the time of the trade and some future time. It is the portion of the spread that compensates liquidity providers for their trading losses that accrue due to trading with others that are more informed than they are. The remainder of the spread, referred to as the realized spread, compensates liquidity providers for all non-adverse selection costs and also provides their profit.[25]

For tick constrained stocks, we expect the increase in the tick size to increase both effective and realized spread by mechanically widening the spread. Additionally, by de-emphasizing price in the price-time priority rules, an increase in the tick size inherently creates an environment that emphasizes speed in trading execution. This tilting of the playing field towards faster traders can increase adverse selection by increasing the role that sophisticated high speed traders play in markets. Thus, for narrow spread stocks, the exact balance between the relative effects of adverse selection and realized spread is an empirical question. For stocks with wider spreads, the TSP was shown to decrease effective spreads. Undercutting increases adverse selection and so we expect a reduction in adverse selection to be a prime driver of lower effective spreads among stocks with wider spreads.

Table 7 presents our empirical analysis of the effect of the tick size change on realized spread and adverse selection. While we present results using 15, 60, and 300 second horizons, following

[25] See Dixon (2021) appendix C for a more complete discussion of how the effective spread decomposes into realized spread and adverse selection components.

Conrad and Wahal (2020) we focus our discussion on results using a 60 second horizon because the TSP focused on small-cap stocks. For tick and near-tick constrained stocks, both the analysis of the TSP imposition and conclusion suggest that realized spread and adverse selection costs play a role in increasing effective spreads. However, the analysis suggests that adverse selection played the larger role with both the TSP imposition and conclusion results suggesting that adverse selection effects were twice as large as the realized spread effects. For wide spread stocks, the results are more balanced. Both the TSP imposition and conclusion suggest that these stocks had both lower realized spread and adverse selection costs with the 5¢ tick size, but the effect of the two channels appears more balanced with adverse selection exerting a moderately larger influence on effective spreads than realized spread. One reason realized spread could decline for wider spread stocks with a wider tick may relate to the lower costs incurred due to fewer price levels that market participants would need to monitor and respond to. Lastly, as with much of our other analysis, the results for intermediate spread stocks are ambiguous given that the results from the TSP imposition and conclusion do not always agree in terms of sign or statistical significance.

[Insert Table 7 about here.]

4.5 Price Efficiency

At a base level, a larger tick makes it harder for prices to realize their equilibrium levels, meaning that HFTs can only trade on a misspricing that is larger than the tick size—implying that misspricings or return patterns that are smaller than the tick size are more likely to persist with a wider tick. Consequently, a larger tick could inhibit specifically HFT trading strategies by constraining their activity to a coarser lattice.[26]. High-frequency traders are adept at trading on short-lived price changes, and thus they help reduce intra-day price predictability (see e.g. Brogaard, Hendershott, and Riordan (2014) among others). Consequently, we expect that price efficiency measures that are computed using intra-day variance ratios or auto-correlation patterns will likely show a decrease in price efficiency.

Another dimension of price efficiency relates to how much stock prices reflect knowable information and how quickly that that information is incorporated into stock prices. This dimension of

[26]This view is similar to that articulated by both Lee and Watts (2021) and Ahmed et al. (2020)

price efficiency relates more to the activities of individuals performing fundamental research and then choosing to purchase or sell stocks accordingly. This type of behavior will affect stock prices on horizons longer than intra-day. The effect of the TSP on this type of behavior is less clear. Research shows that when it becomes more difficult to trade on information, traders collect less information—leading to worse price efficiency (see e.g. Dixon (2021)). If, as Lee and Watts (2021) and Ahmed et al. (2020) argue, HFTs consume some of the profit of information gathering, then limiting HFTs will improve price efficiency. In contrast, if less liquidity makes it more expensive to transact, then there could be less information gathering as argued by Li and Xia (2021). The net effect is uncertain.

We examine price efficiency using both intra-day and day-to-day price efficiency measures. For intra-day price efficiency, we use two processes. The first is an AR(1) process that measures the auto-correlation of five minute midpoint returns. This estimation is measured each stock each day and the AR(1) coefficient from each regression is saved, producing a unique panel of autocorrelation coefficients for each stock each day. Our other intra-day price efficiency measure is 15 to 5 second variance ratios and 5 minute to 1 minute variance ratios. For both intra-day measures, we use the same DD procedure as in our prior tests with the various price efficiency measures as the dependent variable. To measure price efficiency at a longer horizon, we use an AR(1) panel regression. To avoid concerns relating to the opening and closing auctions (Bogousslavsky and Muravyev (2022)) we calculate 1pm-to-1pm returns and then estimate the following regression with these daily returns as our dependent variable,[27]

$$Y_{jt} = \rho_0 + \rho_1 R_{j,t-1} + \rho_2 Pilot_j R_{j,t-1} + \rho_3 Event_{jt} R_{j,t-1} + \rho_4 (Pilot_j \times Event_{jt}) R_{j,t-1} + u_{jt}. \quad (2)$$

Our results are presented in Table 8.

[Insert Table 8 about here.]

Table 8 indicates that price efficiency largely deteriorated at an intra-day level. Intuitively, this decline in efficiency appears to be strongest among tick and near-tick constrained stocks where the

[27] In untabulated tests, we find quantitatively similar results using open-to-open or close-to-close returns

5¢ tick size would have been most binding on HFT behavior. The quantile regressions indicate that intraday negative autocorrelation became stronger for tick and near-tick constrained stocks. For intermediate and wide spread stocks, intra-day autocorrelation was not affected by the larger tick. Further, variance ratios increase across all groups during the TSP indicating less price efficiency at an intra-day level.

Our results using 1pm-to-1pm autocorrelation indicate no change in price efficiency at the 24 hour level. This finding could be indicative of either no-effect, or of a lack of power in our test design. We believe that our results are more consistent with no-effect because the R_{t-1} coefficients often do not agree across the imposition and conclusion of the TSP and sometimes switch from spread bin to spread bin. In summary, our results indicate that the 5¢ tick decreased intra-day price efficiency which is consistent with the larger tick making it more difficult to trade on intra-day price patterns and thus allowing some of those patterns to persist. However, our null result using 24 hour autocorrelation suggests that the larger tick did not affect price efficiency at longer horizons—consistent with fundamental traders not being overly sensitive to the larger tick when determining how much information to gather and trade on.

4.6 Robustness

A natural concern using the TSP is generalizability. The TSP only included small-cap stocks and thus it is not clear how applicable results using the TSP are to the broad spectrum of stocks. There is no way to completely resolve this shortcoming of the TSP. However, we try and mitigate concerns about generalizability in multiple ways. We first estimate our main analysis using quartile regressions. This analysis lets us examine whether the patterns that we document occur across the distribution of the dependent variable—rather than just near the center. It is a way of asking whether a stock at the 25th or 75th percentile of the distribution of the dependent variable is affected in the same manner as one at the median. These results are presented in Table 9. The next way we address generalizability concerns is by bifurcating the TSP sample and estimating our key analysis using only stocks with higher than median trading volume among TSP and control stocks. Specifically, we evaluate trading volume in May of 2016 (for the TSP imposition) and May of 2018 (for the TSP conclusion) and eliminate from our analysis stocks that had below median trading volume in these months from our analysis. We then replicate key analyses exactly as before.

Results are presented in Table 10. Our third approach to addressing the generalizability of our analysis is to exclude all penny stocks from our analysis. Specifically, if a stock had an average closing price across all trading days in May and June of 2016 for the TSP imposition and 2018 for the TSP conclusion of less than $5, it was excluded from our sample. These results are presented in Table 11. Lastly, we estimate our analysis including a robust set of control variables.[28] These results are presented in Table Table 12

Across all robustness methodologies, we find that the basic patterns documented in the main tests. Quoted and effective spreads increase for tick and near-tick constrained stocks but decrease for stocks with wide spreads with a 5¢ tick size. We obtain the same patterns of realized spread and price impact. With one exception—1st quartile regressions on the TSP conclusion for tick constrained stocks—all robustness tests indicate an increase in depth at the NBBO. The patterns of realized spread and price impact remain: adverse selection point estimators are always larger than are realized spread point estimators. CRT trading costs for large orders increase for tick and near-tick constrained stocks but decrease for stocks with wide spread.

[Insert Table 9 about here.]

[Insert Table 10 about here.]

[Insert Table 11 about here.]

[Insert Table 12 about here.]

4.7 A More Granular Analysis of Trading Costs

The prior sections demonstrate evidence consistent with the notion that the same tick size adjustment will affect stocks differently depending on the stock's prevailing quoted spread consistent with the tick size tradeoff between pricing fidelity and undercutting. In this section, we attempt to more precisely identify thresholds in terms of prevailing quoted spread where the TSP tick size change was beneficial, harmful, or undetermined.

[28]Control variables include market capitalization, dollar volume, and volatility (from Daily CRSP) as well as time-weighted quoted spread (from WRDS Intraday Indicators). To construct the quantities of control variables for a stock, we average relevant daily observations from June of 2016 and June of 2018 for the TSP imposition and conclusion, respectively—volatility reflects the standard deviation of daily returns.

We sort TSP and control stocks into overlapping bins based on their pre-shock (i.e., pre imposition or conclusion) levels of quoted spreads; we use average quoted spread from May and June 2016 for the TSP imposition and from May and June 2018 for the TSP conclusion. Stock bins reflect overlapping intervals that increase by 1¢ in each bin of pre-shock quotes spreads $\{(0, 6¢), (1¢, 7¢), \ldots, (15¢, 21¢), (16¢, 22¢)\}$. We estimate Equation 1 using the data in each bin, and then plot the point estimates for the Equation 1 difference-in-difference coefficient along with the 95% confidence intervals where the horizontal axis indicates the mean pre-shock dollar quoted spread for a given bin and the vertical axis indicates the difference-in-difference coefficient.

To create our thresholds, we use the following rule of thumb: If point estimators between the TSP imposition and conclusion have opposite signs and at least one set of tests is statistically significant, then we count the bin as having a determinable effect. If both the TSP imposition and conclusion are statistically insignificant or the sign of the coefficients are in the same direction (indicating a lack of agreement as to the direction of the effect), then we label the effect of the TSP on market quality for that bin as undetermined.

Figure 3 presents results for this analysis for effective spreads and 500 share CRT. For effective spreads, both the TSP imposition and conclusion suggest that for stocks with average quoted spreads less than 10¢, the 5¢ tick imposed by the TSP increased effective spreads and that the effect was greater for stocks with narrower quoted spreads. On the other end, for stocks with quoted spreads greater than approximately 16¢, the 5¢ tick decreased effective spreads. In between, these ranges the effect of the TSP on effective spreads is unclear. For 500 share CRT, the thresholds are similar: For stocks with pre-shock average quoted spreads approximately 9¢ or less, the TSP increased the cost to trade, while for stocks with average quoted spreads greater than approximately 13¢, the TSP reduced trading costs.

Figure 4 presents this same analysis for CRT at the 100, 250, and 1000 share level. For 100 share CRT, the the analysis suggests that for stocks with average quoted spreads below approximately 9¢, the TSP increased transaction costs with the effect on spreads being greatest for stocks with the narrowest spreads and declining as spreads widen. For stocks with spreads above approximately 13¢, the TSP improved 100 share CRT with the effect being greatest for stocks with the widest spreads. In between these ranges the effect is not clear.

For 250 share CRT, the analysis suggests that for stocks with spreads below approximately 9¢, the TSP increased transaction costs with the effect on spreads being greatest for stocks with the narrowest spreads and declining as spreads widen. For stocks with spreads above approximately 14¢, the TSP improved 250 share CRT with the effect being greatest for stocks with the widest spreads. In between these ranges the effect is not clear.

For 1,000 share CRT, the analysis suggests that for stocks with spreads below approximately 7¢, the TSP increased transaction costs with the effect on spreads being greatest for stocks with the narrowest spreads and declining as spreads widen. For stocks with spreads above approximately 11¢, the TSP improved 1,000 share CRT with the effect being greatest for stocks with the widest spreads. In between these ranges the effect is not clear.

Figure 5 presents this same analysis for CRT for very large trades: at the 2,500, 5,000, and 10,000 share level. Consistent with Table 6, at virtually every price point (except perhaps for 2,500 share CRT for stocks with very narrow spreads), the TSP almost uniformly lowered transaction costs for these extremely large trades.

Trades larger than 1,000 shares are relatively rare, comprising less than 2% of total trades posted to TAQ.[29] Thus, focusing on the effective spread and CRT analysis for trades less than 1,000 shares (where the vast majority of trading occurs) suggests the following general result: For stocks with spreads equal to approximately 9¢ or less, the 1¢ tick size provided a superior trading environment. For these stocks, a 5¢ spread implied that they generally traded with fewer than two ticks intra-spread whereas with a 1¢ tick there were up to 9 ticks within the spread. On the other end, stocks with quoted spreads larger than approximately 15¢ generally had lower transaction costs with the 5¢ tick. For these stocks, a 5¢ tick provided 3+ ticks intra-spread whereas a 1¢ tick provided 15+ ticks intra-spread.

While this analysis cannot identify the theoretically optimal number of ticks intra-spread because it only compares two tick regimes, it does clearly indicate that for stocks with fewer than two ticks intra-spread, pricing fidelity concerns could justify a smaller tick; and for stocks with more than 15 ticks intra-spread, undercutting concerns suggest that a larger tick could be merited.

[29] Calculated by simply tabulating the number of normal trades in TAQ, i.e. those without trade codes in ABCDGHKLMNOPQRTUVWXZ1456789 and greater than 1,000 shares for 12/5/2022-12/9/2022 as a fraction of all trades.

5 Conclusion

This study characterizes tick sizes as offering a fundamental tradeoff between allowing markets to establish prices with greater fidelity on the one hand and undercutting concerns on the other. This tradeoff means that the same tick size change may affect stocks differently depending on which effect dominates. We find that for stocks that became tick or near-tick constrained by the 5¢ tick (those with quoted spreads less than 9¢), the TSP harmed liquidity. For stocks with wide spreads (15¢+), the TSP improved liquidity.

Understanding these heterogeneous effects is important for two reasons. First, because near-tick constrained stocks and those with wide spreads had liquidity affected in opposite directions by the TSP, studies that combine all non-tick constrained stocks together muddle empirical inference. Something we believe is a key driver of the disparate findings in the existing literature. Second, there is a growing literature that uses the TSP as an exogenous shock — usually to liquidity — to make inference in a wide range of settings. These studies should to address the heterogeneity shown in this study regarding how the TSP affected market quality — perhaps by limiting their analysis to tick and near-tick constrained stocks.

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Figures and Tables

Figure 2. Minimum Tick Size and Order Book Depth: Quantile Regression.
The figure presents visual evidence of the causal impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, for differentially tick constrained stocks. Stocks in the TSP imposition period 08/12/2016-12/14/2016, where tick size increased from 1¢ to 5¢ for pilot stocks, are classified into four tick constraint bins based on their average May and June 2016 quoted spreads: bin 1, no more than 5¢; bin 2, 5¢ to 10¢; bin 3, 10¢ to 15¢; and bin 4, greater than 15¢. Stocks in the TSP imposition period 08/08/2018-11/20/2018, where tick size decreased from 5¢ to 1¢ pilot stocks, are classified into four tick constraint bins based on their average May and June 2018 quoted spreads: bin 1, no more than 5.5¢; bin 2, 5.5¢ to 10¢; bin 3, 10¢ to 15¢; and bin 4, greater than 15¢. Average cumulative quoted depth on the bid and ask sides of the order book is measured at 10¢, 15¢, 25¢, and 40¢ away on each side of the midpoint price. The effect of a tick size change on the natural log of cumulative depth is estimated by Equation (1) using quantile (median) regressions that control for date fixed effects and double-cluster standard errors by stock and date. Point estimates of the treatment effects along with the corresponding 95% confidence intervals are plotted against the distance from the midpoint.

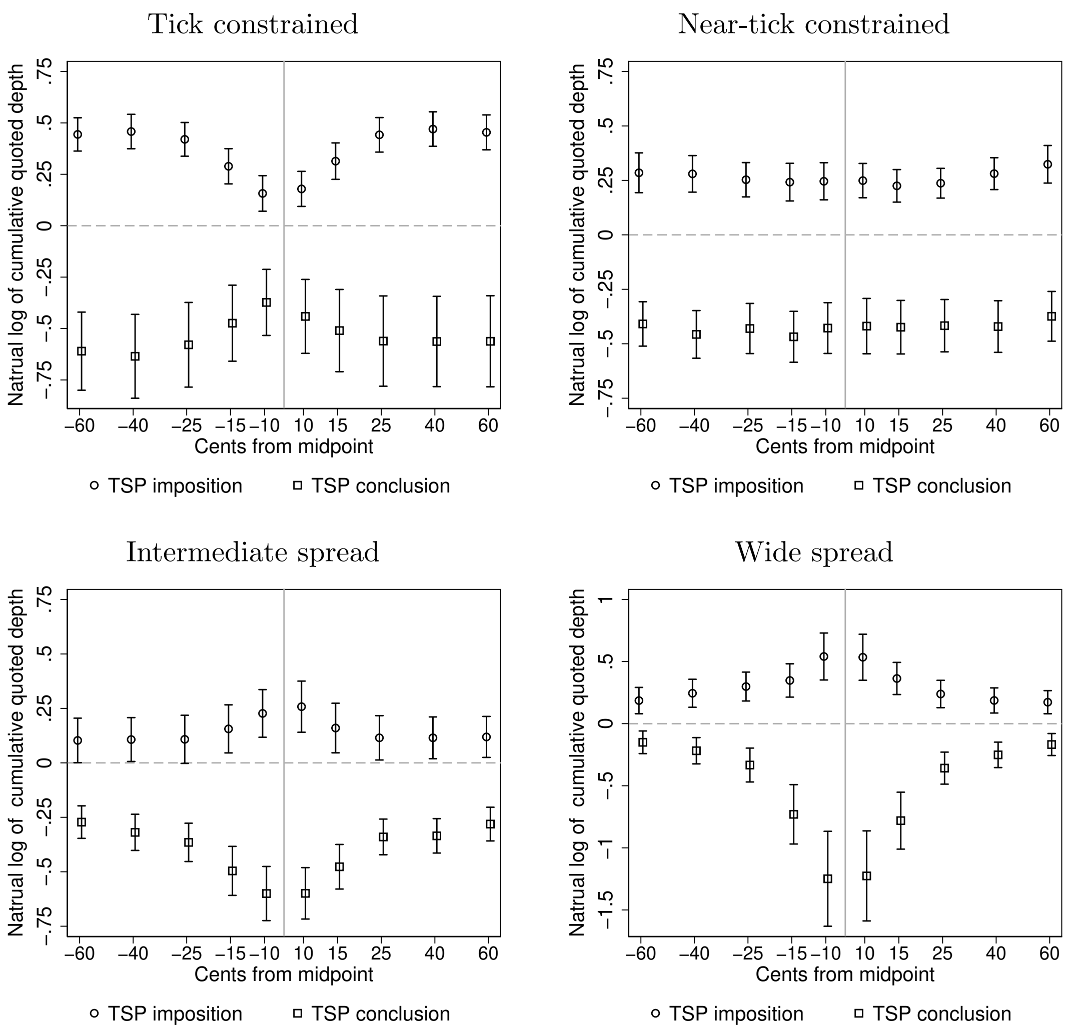

Figure 3. Effective Spreads and Round-Trip Cost of 500 shares: TSP Treatment Effect and Tick Constraints.

The figure presents visual evidence of the causal impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, for differentially tick constrained stocks. Stocks in the TSP imposition period 08/12/2016-12/14/2016, where tick size increased from 1¢ to 5¢ for pilot stocks, are grouped into overlapping 6¢ intervals of average May and June 2016, i.e., pre-shock, quoted spreads: $\{(0, 6¢), (1¢, 7¢), \ldots, (15¢, 21¢), (16¢, 22¢)$. Likewise, stocks in the TSP conclusion period 08/12/2016-12/14/2016, where tick size decreased from 5¢ to 1¢ for pilot stocks, are grouped into overlapping 6¢ intervals of average May and June 2018, i.e., pre-shock, quoted spreads. For each intervals, the effect of a tick size change on dollar effective spreads and the per-share round-trip cost of trading 500 shares are estimated by Equation (1) using quantile (median) regressions that control for date fixed effects and double-cluster standard errors by stock and date. Point estimates of the treatment effects along with the corresponding 95% confidence intervals are plotted against the median pre-shock quoted spread in the respective interval.

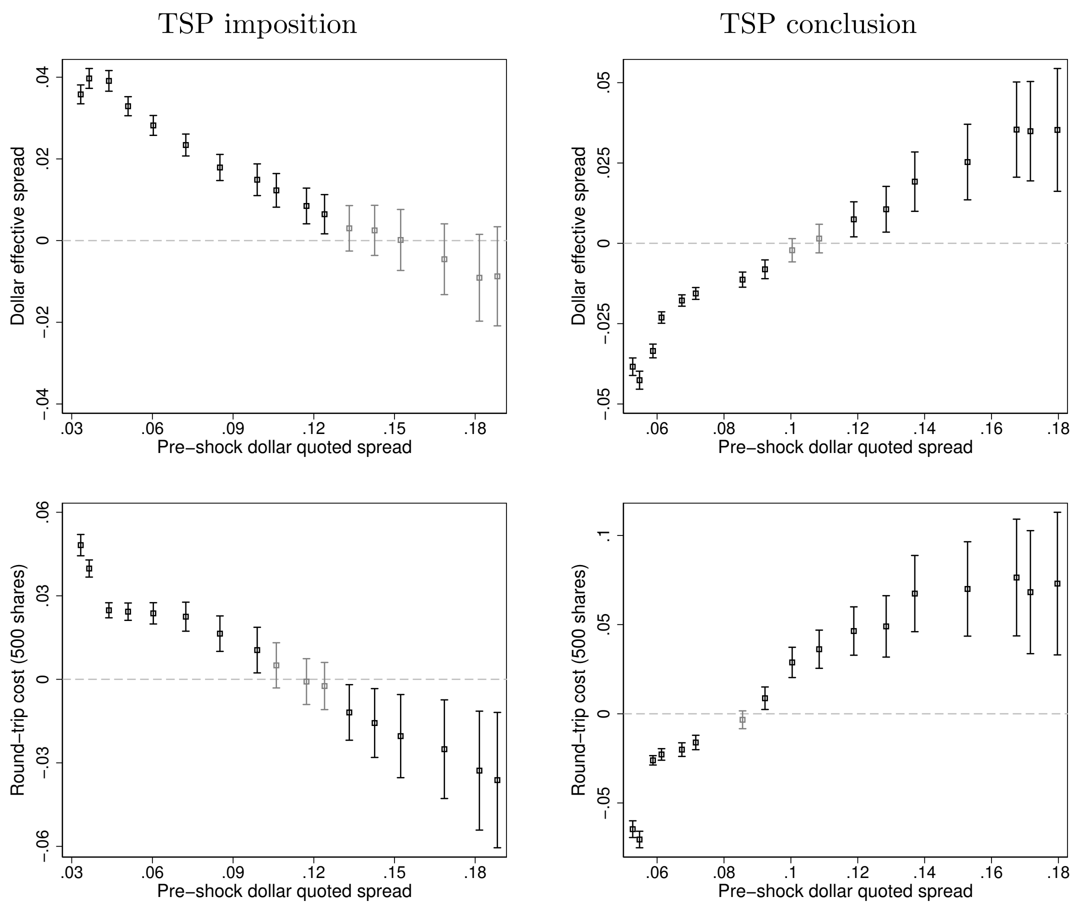

Figure 4. Round-Trip Cost of 100, 250, and 1,000 shares.
The figure presents visual evidence of the causal impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, for differentially tick constrained stocks. Stocks in the TSP imposition period 08/12/2016-12/14/2016, where tick size increased from 1¢ to 5¢ for pilot stocks, are grouped into overlapping 6¢ intervals of average May and June 2016, i.e., pre-shock, quoted spreads: $\{(0, 6¢), (1¢, 7¢), \ldots, (15¢, 21¢), (16¢, 22¢)$. Likewise, stocks in the TSP conclusion period 08/12/2016-12/14/2016, where tick size decreased from 5¢ to 1¢ for pilot stocks, are grouped into overlapping 6¢ intervals of average May and June 2018, i.e., pre-shock, quoted spreads. For each intervals, the effect of a tick size change on per-share round-trip cost of trading 100, 250, and 1,000 shares are estimated by Equation (1) using quantile (median) regressions that control for date fixed effects and double-cluster standard errors by stock and date. Point estimates of the treatment effects along with the corresponding 95% confidence intervals are plotted against the median pre-shock quoted spread in the respective interval.

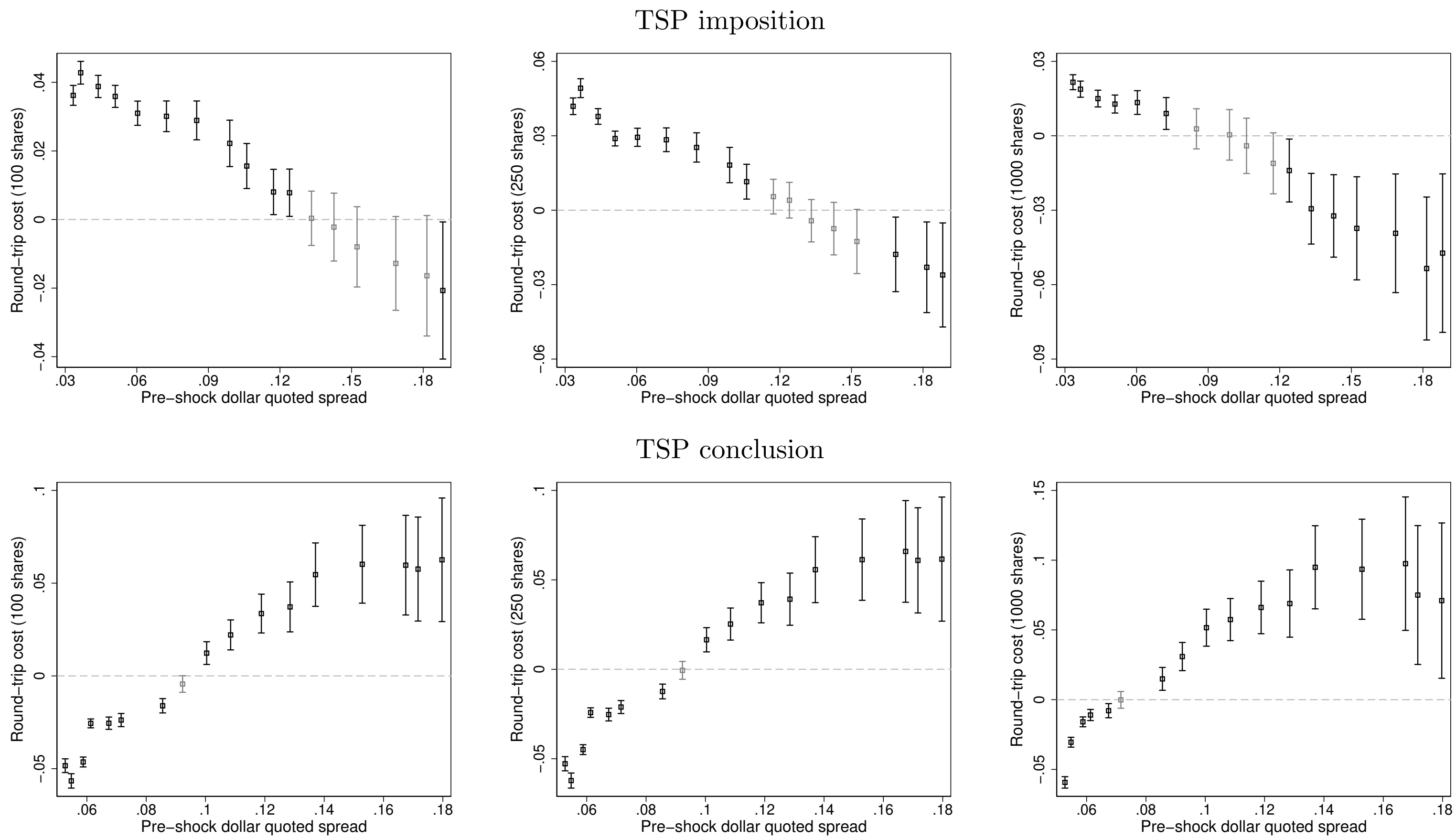

Figure 5. Round-Trip Cost of 2,500, 5,000, and 10,000 shares.
The figure presents visual evidence of the causal impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, for differentially tick constrained stocks. Stocks in the TSP imposition period 08/12/2016-12/14/2016, where tick size increased from 1¢ to 5¢ for pilot stocks, are grouped into overlapping 6¢ intervals of average May and June 2016, i.e., pre-shock, quoted spreads: $\{(0, 6¢), (1¢, 7¢), \ldots, (15¢, 21¢), (16¢, 22¢)\}$. Likewise, stocks in the TSP conclusion period 08/12/2016-12/14/2016, where tick size decreased from 5¢ to 1¢ for pilot stocks, are grouped into overlapping 6¢ intervals of average May and June 2018, i.e., pre-shock, quoted spreads. For each intervals, the effect of a tick size change on per-share round-trip cost of trading 2,500, 5,000, and 10,000 shares are estimated by Equation (1) using quantile (median) regressions that control for date fixed effects and double-cluster standard errors by stock and date. Point estimates of the treatment effects along with the corresponding 95% confidence intervals are plotted against the median pre-shock quoted spread in the respective interval.

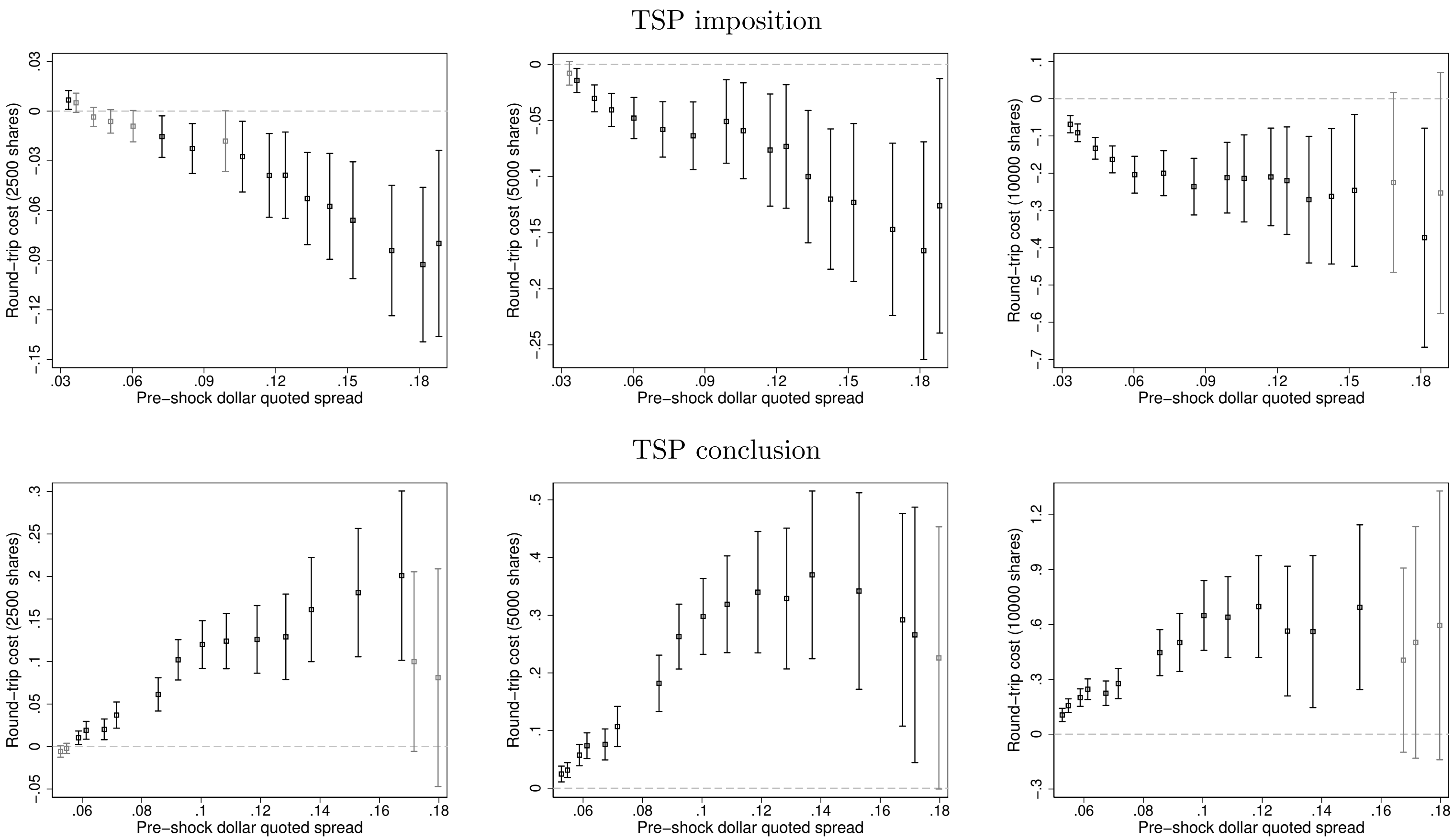

Table 1. Summary Statistics for Key Stock Characteristics.
The table presents stock characteristics of the firms involved in Tick Size Pilot program. Stock characteristics are measured in the month of May prior to an increase (from 1¢ to 5¢ in Oct, 2016) and a reduction (5¢ to 1¢ in Oct, 2018) in the minimum tick sizes of treated (G1 and G2) stocks. Means of dollar quoted spread, market-capitalization (in $million), monthly dollar volume ($million), and daily return volatility are calculated for differentially tick-constrained control and treated firms. Differences in means of control and treated firms in each category are reported along with the difference-in-means t-statistics are presented. Panel A presents results for control and treated stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents results for control and treated stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. The numbers in brackets are *t*-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively. The last row present pairwise cross-stock correlations between the percentile statistics of average quoted spreads vis á vis percentile statistics of averages of closing share price, market-capitalization, dollar trading volume, and return volatility, all calculated from May & June of the respective year for each stock. Correlation coefficients are extracted from correlation matices.

		Panel A: TSP imposition				Panel B: TSP termination			
		May-June 2016 quoted spread bin				May-June 2018 quoted spread bin			
Variable	Group	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Number of Stocks	Control	465	299	136	259	478	188	106	243
	Treatment	290	174	101	171	102	283	126	144
$ Quoted Spread	Control	0.03	0.07	0.12	0.45	0.03	0.07	0.12	0.53
	Treatment	0.03	0.07	0.12	0.37	0.05	0.08	0.12	0.50
	Difference	0.000	0.001	−0.002	−0.081	0.023***	0.004***	−0.002	−0.033
	t-statistic	[0.14]	[−0.56]	[0.92]	[1.20]	[−15.81]	[−2.73]	[1.17]	[0.54]
Market-cap ($M)	Control	701.0	704.0	586.5	449.9	853.5	1346.9	1503.0	844.9
	Treatment	694.6	672.9	644.7	395.7	841.2	1130.1	1332.1	787.5
	Difference	−6.4	−31.2	58.3	−54.2	−12.3	−216.8	−170.9	−57.4
	t-statistic	[0.09]	[0.32]	[−0.49]	[0.66]	[0.10]	[1.71]	[0.89]	[0.44]
Dollar Volume ($M)	Control	133.4	117.8	117.3	75.7	191.3	331.3	327.8	165.9
	Treatment	121.1	124.4	141.0	69.1	198.9	238.5	255.9	145.6
	Difference	−12.3	6.6	23.7	−6.6	7.6	−92.8	−71.9	−20.2
	t-statistic	[0.73]	[−0.28]	[−0.60]	[0.27]	[−0.18]	[1.61]	[1.18]	[0.43]
Return Volatility	Control	0.028	0.026	0.025	0.024	0.026	0.024	0.021	0.020
	Treatment	0.027	0.028	0.028	0.021	0.028	0.023	0.019	0.019
	Difference	−0.002	0.002	0.003	−0.003	0.002	−0.001	−0.002	−0.002
	t-statistic	[1.16]	[−0.97]	[−1.39]	[1.69]	[−0.71]	[0.29]	[1.00]	[1.00]

	Share price	Market -cap	Dollar volume	Volatility	Share price	Market -cap	Dollar volume	Volatility
Correlation with $ quoted spread	0.40	−0.23	−0.34	−0.21	0.54	−0.02	−0.18	−0.21

Table 2. Minimum Tick Size and the Trade Execution Complexity.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on the complexity of trading trading strategies for differentially tick-constrained stocks. Cancel-to-trade ratio divides the daily number of order cancellations by the daily number of trades; hidden ratio divides the daily number of trades involving hidden orders to the daily number of trades; odd-lot ratio divides the total number of trades involving odd-lot orders by the daily number of trades; and ISO volume share divides the share volume of executed ISOs by total trading volume. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

Panel A: TSP imposition

	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Cancel-to-Trade	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × Event	−4.21***	−9.47***	−7.78***	−14.3***	−4.35***	−8.56***	−10.9***	−21.6***
	[−7.95]	[−9.40]	[−4.52]	[−7.46]	[−6.59]	[−6.55]	[−4.33]	[−5.31]
Hidden Ratio (×100)								
Pilot × Event	−1.06***	−7.97***	−10.8***	−12.1***	−1.21***	−7.78***	−11.5***	−13.2***
	[−3.69]	[−17.46]	[−13.47]	[−12.54]	[−4.42]	[−18.41]	[−16.48]	[−15.47]
Odd-lot Ratio (×100)								
Pilot × Event	−3.07***	−3.44***	−1.02	−2.57**	−1.92***	−2.14***	−0.42	−2.00**
	[−6.20]	[−5.30]	[−1.14]	[−2.36]	[−4.77]	[−3.87]	[−0.47]	[−2.04]
ISO Volume share (%)								
Pilot × Event	−4.41***	−2.03***	−1.87***	−0.69	−3.68***	−1.96***	−2.59***	−0.0092
	[−13.19]	[−4.45]	[−3.52]	[−1.16]	[−13.58]	[−5.82]	[−5.45]	[−0.02]

Panel B: TSP conclusion

	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Cancel-to-Trade	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × Event	4.28***	8.55***	7.26***	11.9***	3.58***	6.19***	8.19***	18.1***
	[5.54]	[14.64]	[8.24]	[8.90]	[4.08]	[8.49]	[8.46]	[8.50]
Hidden Ratio (×100)								
Pilot × Event	−7.55***	5.40***	15.1***	14.8***	−7.47***	5.68***	16.5***	16.8***
	[−11.80]	[9.41]	[17.94]	[13.01]	[−11.56]	[9.43]	[18.20]	[17.63]
Odd-lot Ratio (×100)								
Pilot × Event	5.51***	5.89***	2.59***	2.69***	5.25***	5.76***	2.23***	2.35***
	[5.70]	[9.23]	[2.85]	[3.08]	[8.10]	[10.45]	[2.70]	[2.88]
ISO Volume share (%)								
Pilot × Event	5.51***	2.05***	−0.29	0.12	5.92***	2.29***	−0.14	−0.43
	[9.78]	[5.37]	[−0.62]	[0.25]	[11.77]	[6.50]	[−0.36]	[−0.92]

Table 3. Minimum Tick Size and Quoted Spreads.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on time-weighted average dollar quoted spreads for differentially tick-constrained stocks. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

Panel A: TSP imposition

	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Quoted Spread	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × *Event*	0.032***	0.032***	0.0074*	−0.039***	0.033***	0.021***	0.0054	−0.027*
	[22.16]	[13.05]	[1.78]	[−3.43]	[64.76]	[12.64]	[1.24]	[−1.77]
Observations	53278	33051	16552	28711	53278	33051	16552	28711

Panel B: TSP conclusion

	QR				OLS			
Dependent variable:	May & June 2018 quoted spread bin				May & June 2018 quoted spread bin			
Quoted Spread	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × *Event*	−0.052***	−0.022***	0.031***	0.099***	−0.036***	−0.024***	0.035***	0.11***
	[−25.73]	[−10.63]	[5.44]	[4.94]	[−34.73]	[−9.77]	[4.79]	[5.35]
Observations	45769	22221	21536	26270	45769	22221	21536	26270

Table 4. Minimum Tick Size and Quoted Depth at the Best Prices.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on the natural log of time-weighted average quoted depth, in round lots, at the best bid/ask prices for differentially tick-constrained stocks. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are *t*-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

Panel A: TSP imposition

	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Ln(NBBO Depth)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × *Event*	1.08***	0.96***	0.47***	0.20***	1.01***	0.67***	0.40***	0.19***
	[22.36]	[21.48]	[10.49]	[6.29]	[37.71]	[28.77]	[12.01]	[6.86]
Observations	53278	33051	16552	28711	53278	33051	16552	28711

Panel B: TSP conclusion

	QR				OLS			
Dependent variable:	May & June 2018 quoted spread bin				May & June 2018 quoted spread bin			
Ln(NBBO Depth)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × *Event*	−0.81***	−1.13***	−0.54***	−0.069***	−1.34***	−0.75***	−0.31***	−0.067***
	[−8.01]	[−23.85]	[−15.28]	[−3.18]	[−34.56]	[−33.96]	[−13.89]	[−3.11]
Observations	45769	22221	21536	26270	45769	22221	21536	26270

Table 5. Minimum Tick Size and Trading Outcomes.

The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on size-weighted average dollar effective spreads, the natural log of average trade size, and regular-hours trading volume, in 1,000 shares, for differentially tick-constrained stocks. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

Panel A: TSP imposition

	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Dollar Effective Spread	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × *Event*	0.032***	0.025***	0.0078***	−0.018***	0.025***	0.016***	0.016***	−0.012
	[28.34]	[17.29]	[3.08]	[−2.95]	[28.91]	[7.92]	[3.24]	[−1.08]
Ln(Trade Size)								
Pilot × *Event*	0.11***	0.077***	0.037**	0.043***	0.089***	0.063***	0.029**	0.044**
	[9.99]	[6.30]	[2.32]	[2.66]	[9.94]	[5.82]	[2.07]	[2.54]
Trading Volume								
Pilot × *Event*	−1.11	−2.72	−7.12**	−1.87*	−21.7**	−5.67	0.75	−2.41
	[−0.13]	[−0.55]	[−2.23]	[−1.98]	[−2.39]	[−0.85]	[0.15]	[−1.45]

Panel B: TSP conclusion

	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Dollar Effective Spread	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × *Event*	−0.036***	−0.016***	0.0052*	0.032***	−0.018***	−0.012***	0.011**	0.032***
	[−27.00]	[−13.76]	[1.88]	[3.13]	[−6.83]	[−3.30]	[2.35]	[2.76]
Ln(Trade Size)								
Pilot × *Event*	−0.16***	−0.10***	−0.037**	−0.035**	−0.13***	−0.11***	−0.034**	−0.029*
	[−6.34]	[−7.70]	[−2.36]	[−2.31]	[−9.86]	[−10.66]	[−2.24]	[−1.84]
Trading Volume								
Pilot × *Event*	−3.20	−19.2***	−3.64	−0.60	66.8**	16.0*	8.70	−7.67**
	[−0.30]	[−2.84]	[−0.79]	[−1.00]	[2.44]	[1.90]	[1.04]	[−2.57]

Table 6. Minimum Tick Size and Round-trip Trading Costs.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on the round-trip cost of trading for different order sizes of differentially tick-constrained stocks. The round-trip cost captures the costs, in dollars per share, of immediately buying and selling a given position size, accounting for available depth in the entire order book. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP imposition								Panel B: TSP conclusion							
Dependent variable:	QR				OLS				QR				OLS			
Round-trip cost of	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
1 round lot	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × Event	.029***	.030***	.0085**	−.038***	.033***	.022***	0.005	−.028*	−.045***	−.023***	.029***	.095***	−.035***	−.024***	.033***	0.12***
	[22.34]	[13.63]	[2.36]	[−3.60]	[74.09]	[13.95]	[1.26]	[−1.96]	[−24.18]	[−11.32]	[5.70]	[4.97]	[−36.04]	[−10.28]	[4.76]	[5.37]
2.5 round lots																
Pilot × Event	.034***	.028***	0.0054	−.046***	.032***	.019***	0.0017	−.037**	−.049***	−.021***	.034***	.096***	−.035***	−.023***	.034***	0.12***
	[22.30]	[12.11]	[1.42]	[−3.90]	[63.19]	[11.47]	[0.39]	[−2.28]	[−24.50]	[−9.92]	[6.15]	[4.74]	[−33.90]	[−9.27]	[4.78]	[4.92]
5 round lots																
Pilot × Event	.045***	.023***	−.00073	−.052***	.029***	.014***	−.0019	−.044**	−.061***	−.014***	.043***	0.11***	−.034***	−.019***	.041***	0.13***
	[22.49]	[8.91]	[−0.16]	[−4.07]	[46.42]	[7.42]	[−0.37]	[−2.42]	[−25.44]	[−6.04]	[6.53]	[4.85]	[−29.30]	[−7.11]	[5.30]	[4.77]
10 round lots																
Pilot × Event	.025***	.0083**	−.011*	−.069***	.022***	0.0037	−.010	−.061***	−.068***	0.0027	.062***	0.15***	−.031***	−.012***	.059***	0.16***
	[16.24]	[2.59]	[−1.69]	[−4.12]	[24.76]	[1.43]	[−1.42]	[−2.67]	[−27.94]	[0.77]	[6.68]	[4.71]	[−20.36]	[−3.41]	[6.07]	[4.87]
25 round lots																
Pilot × Event	.0089***	−.018***	−.035**	−0.10***	.010***	−.022***	−.033**	−.098**	0.0018	.044***	0.13***	0.18***	−.023***	.014**	0.13***	0.27***
	[3.34]	[−2.80]	[−2.48]	[−2.99]	[5.76]	[−4.48]	[−2.48]	[−2.52]	[0.48]	[4.98]	[6.60]	[2.81]	[−9.04]	[2.03]	[6.95]	[5.55]
50 round lots																
Pilot × Event	−.0031	−.060***	−.061**	−0.16**	−.0085**	−.077***	−.073***	−0.23*	.036***	0.14***	0.32***	0.12	−.0094**	.091***	0.24***	0.30***
	[−0.64]	[−4.75]	[−2.09]	[−2.38]	[−2.46]	[−7.85]	[−2.88]	[−1.98]	[4.00]	[6.39]	[6.35]	[0.99]	[−2.13]	[6.46]	[7.45]	[3.34]
100 round lots																
Pilot × Event	−.053***	−0.21***	−0.17**	−0.43***	−.093***	−0.28***	−0.25***	0.18	0.11***	0.34***	0.68***	0.42	.022**	0.24***	0.48***	−1.72**
	[−5.21]	[−6.37]	[−2.27]	[−2.72]	[−11.62]	[−11.53]	[−4.24]	[0.20]	[4.67]	[6.48]	[4.85]	[1.51]	[2.39]	[6.27]	[5.41]	[−2.20]

Table 7. Minimum Tick Size, Realized Spreads, and Price Impacts.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on size-weighted average dollar realized spreads and price impacts for differentially tick-constrained stocks. Three versions of realized spreads are calculated with respect to the quote midpoints at 15, 60, and 300 seconds after each transaction. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (qantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP imposition							
	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Realized Spread 15s	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × Event	.0048***	.0043***	.0022**	−.0064***	.0062***	.0036***	0.0021	−0.00036
	[21.97]	[11.69]	[2.35]	[−2.92]	[24.37]	[6.58]	[1.56]	[−.08]
Price Impact 15s								
Pilot × Event	.023***	.018***	.0079***	−.0092**	.019***	.013***	.013***	−0.0057
	[29.46]	[14.76]	[3.82]	[−2.29]	[23.74]	[8.64]	[3.16]	[−0.76]
Realized Spread 60s								
Pilot × Event	.0043***	.0042***	.0036***	−.0043**	.0058***	.0036***	.0033***	0.00096
	[21.38]	[12.46]	[4.25]	[−2.25]	[22.49]	[6.26]	[2.77]	[0.23]
Price Impact 60s								
Pilot × Event	.023***	.018***	.0059***	−.0090**	.019***	.012***	.012***	−0.0079
	[28.42]	[14.49]	[2.67]	[−2.14]	[22.97]	[8.23]	[2.85]	[−1.00]
Realized Spread 300s								
Pilot × Event	.0039***	.0041***	.0050***	−.0041**	.0052***	.0043***	.0047***	0.0026
	[20.17]	[11.89]	[5.71]	[−2.18]	[20.53]	[7.19]	[3.83]	[0.61]
Price Impact 300s								
Pilot × Event	.023***	.018***	.0047**	−.0097**	.020***	.012***	.011**	−0.0075
	[28.08]	[13.35]	[2.01]	[−2.24]	[23.88]	[7.44]	[2.47]	[−0.91]

	Panel B: TSP conclusion							
	QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Realized Spread 15s	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Pilot × Event	−.0051***	−.0036***	.0053***	.017***	−.0069***	0.00015	.0078***	.023***
	[−16.35]	[−9.00]	[5.34]	[4.82]	[−11.88]	[0.16]	[4.90]	[4.97]
Price Impact 15s								
Pilot × Event	−.025***	−.015***	−0.0016	.018***	−.012***	−.013***	0.0039	.020**
	[−25.18]	[−14.17]	[−0.80]	[3.03]	[−5.44]	[−4.87]	[1.14]	[2.45]
Realized Spread 60s								
Pilot × Event	−.0046***	−.0035***	.0029***	.015***	−.0060***	−0.00029	.0051***	.019***
	[−15.37]	[−9.76]	[3.05]	[4.80]	[−11.57]	[−0.32]	[3.23]	[4.12]
Price Impact 60s								
Pilot × Event	−.026***	−.015***	0.0012	.019***	−.013***	−.014***	.0066*	.023***
	[−24.04]	[−13.40]	[0.57]	[2.98]	[−6.19]	[−5.41]	[1.89]	[2.73]
Realized Spread 300s								
Pilot × Event	−.0045***	−.0038***	−0.00023	.012***	−.0053***	−0.001	0.0021	.016***
	[−16.45]	[−10.10]	[−0.26]	[4.63]	[−8.81]	[−1.15]	[1.31]	[3.39]
Price Impact 300s								
Pilot × Event	−.027***	−.015***	.0055**	.024***	−.013***	−.014***	.0097**	.032***
	[−23.81]	[−12.34]	[2.43]	[3.52]	[−5.36]	[−5.00]	[2.59]	[3.55]

Table 8. Minimum Tick Size and Price Efficiency.
The table presents impacts of an exogenous change in tick size on the efficiency of market prices for differentially tick-constrained stocks. AR(1) models of 5-minute midpoint returns are estimated by stock-day. The first two measures reflect the R-squared and the slope coefficients of the AR(1) models. Variance ratios reflect return volatility over given horizon divided by the volatility over a shorter horizon, scaled to fit the horizon of the numerator volatility: 15-second/3×5-minute and 5-minute/5×1-minute. Equation (1) is estimated for these outcomes using median (quantile) and OLS regressions. Daily returns of stock j on day t, calculated using midpoint prices at the open, 1pm, and 4pm, are used to estimate $R_{jt} = \rho_0 + \rho_1 R_{j,t-1} + \rho_2 Pilot_j R_{j,t-1} + \rho_3 Event_{jt} R_{j,t-1} + \rho_4 \left(Pilot_j \times Event_{jt}\right) R_{j,t-1} + u_{jt}$, with ρ_1 and ρ_4 reported in the table. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP imposition								Panel B: TSP conclusion							
	QR				OLS				QR				OLS			
Dependent variable:	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Intra-day Return AR(1)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Coefficient																
Sample Median/Mean	-.063	-.081	-.089	-0.105	-.070	-.087	-.099	-0.125	-.042	-.045	-.039	-.062	-.051	-.068	-.054	-.092
Pilot × *Event*	−.017***	−.0067	−.013	0.012	−.022***	−.0027	−.0087	.013*	.020**	.020***	.032***	−.0026	.045***	.030***	.029***	−.0015
	[−3.59]	[−1.17]	[−1.61]	[1.40]	[−5.61]	[−0.57]	[−1.20]	[1.87]	[2.23]	[3.56]	[3.75]	[−0.36]	[6.89]	[3.02]	[3.77]	[−0.23]
Variance Ratios																
15s/3×5s																
Pilot × *Event*	.066***	.065***	.059***	.031***	.064***	.053***	.043***	.033***	−.076***	−.070***	−.058***	−.016***	−.069***	−.059***	−.036***	−.012***
	[16.74]	[14.04]	[7.89]	[7.02]	[18.85]	[15.79]	[8.22]	[8.60]	[−7.52]	[−12.70]	[−8.60]	[−3.90]	[−6.94]	[−12.54]	[−6.95]	[−3.04]
5m/5×1m																
Pilot × *Event*	.065***	.071***	.086***	.021***	.057***	.049***	.052***	.020***	−.090***	−.066***	−.057***	0.008	−.066***	−.042***	−.024***	−.00014
	[11.89]	[6.63]	[6.22]	[2.74]	[13.21]	[7.44]	[7.15]	[4.36]	[−5.96]	[−7.11]	[−4.55]	[1.02]	[−7.28]	[−7.95]	[−5.25]	[−.03]
Daily Return AR(1)																
Lag Return	−.0072	0.0007	−.035***	−.040***	−.0074	0.026	−.072**	−.096***	−.0022	−.011	−.026*	−.025***	0.011	−.083*	−.016	−0.11**
	[−0.92]	[0.11]	[−3.32]	[−5.18]	[−0.46]	[1.61]	[−2.49]	[−4.15]	[−0.38]	[−1.15]	[−1.89]	[−3.68]	[0.61]	[−1.87]	[−0.62]	[−2.44]
Pilot × *Event* × Lag Return	0.0061	−.0073	−.0055	0.005	−.028	−.022	−.026	0.012	.028*	0.0076	0.01	0.026	0.10**	−.052	0.0013	0.041
	[0.54]	[−0.58]	[−0.31]	[0.36]	[−0.96]	[−0.78]	[−0.41]	[0.29]	[1.95]	[0.50]	[0.49]	[1.47]	[2.28]	[−0.92]	[.02]	[0.57]

Table 9. Minimum Tick Size and Microstructure Outcomes: Robustness to Estimation at the 1st the 3rd Quartiles.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on various market microstrucure outcomes for differentially tick-constrained stocks. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is augmented with stock characteristics, including market-capitalization, dollar volume, and average quoted spread, measured in the preceding month of June and estimated quantile regressions at the first and third quartile of the respective outcome variable. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP implementation								*Panel B*: TSP conclusion							
	1st Quartile				3rd Quartile				1st Quartile				3rd Quartile			
	May & June 2016 quoted spread group				May & June 2016 quoted spread group				May & June 2018 quoted spread group				May & June 2018 quoted spread group			
Dependent variable:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Quoted Spread	.012***	.019***	.021***	−.0078	.041***	.033***	−.0097	−.028	−.023***	−.029***	.014***	.055***	−.046***	−.011***	.045***	0.15***
	[10.82]	[8.85]	[4.42]	[−1.07]	[33.36]	[8.77]	[−1.63]	[−1.15]	[−11.70]	[−14.26]	[3.41]	[3.65]	[−24.97]	[−3.57]	[3.39]	[3.51]
Ln(NBBO Depth)	0.62***	0.27***	0.26***	0.16***	1.32***	0.98***	0.52***	0.23***	.060**	−0.11***	−0.15***	−.056***	−2.87***	−1.32***	−0.41***	−0.13***
	[16.03]	[12.61]	[8.05]	[7.72]	[17.27]	[15.42]	[6.96]	[4.18]	[2.51]	[−3.92]	[−5.75]	[−3.03]	[−18.85]	[−16.34]	[−7.80]	[−3.53]
Effective Spread	.0080***	.017***	.014***	−.0044	.035***	.020***	−.00030	−.016	−.013***	−.026***	−.0041**	.024***	−.038***	−.010***	.020***	.043**
	[12.76]	[11.85]	[6.14]	[−1.14]	[35.08]	[8.69]	[−.06]	[−0.94]	[−12.57]	[−17.95]	[−2.18]	[3.42]	[−21.11]	[−4.23]	[3.23]	[2.35]
Round-trip cost of 10 round-lots (bps)	.028***	.011***	.0074	−.045***	.018***	.000050	−.023**	−.053	−.038***	−.014***	.058***	.065***	−.0089***	.0023	.051***	0.17***
	[11.27]	[4.11]	[1.00]	[−3.72]	[8.34]	[.01]	[−2.44]	[−1.37]	[−11.09]	[−5.86]	[7.30]	[2.86]	[−4.11]	[0.38]	[3.01]	[2.66]
Realized Spread (60s)	.0019***	.0021***	.0028***	−.00083	.011***	.0080***	.0025*	−.0025	−.0020***	−.0018***	.0025***	.0075***	−.014***	−.0035***	.0074***	.024***
	[12.82]	[7.48]	[4.24]	[−0.65]	[25.97]	[10.36]	[1.76]	[−0.38]	[−10.16]	[−6.36]	[3.81]	[4.16]	[−24.21]	[−6.02]	[3.41]	[3.18]
Price Impact (60s)	.0075***	.011***	.0088***	−.00065	.035***	.015***	.00059	−.0099	−.013***	−.019***	−.0045***	.012**	−.025***	−.011***	.0099**	.033**
	[14.21]	[11.05]	[4.60]	[−0.22]	[28.85]	[8.34]	[0.17]	[−1.00]	[−14.24]	[−15.10]	[−2.72]	[2.56]	[−14.56]	[−5.81]	[2.39]	[2.55]
Trading Volume	−10.8**	−1.29	−3.39*	0.18	−42.6**	−14.9	7.50	−3.65	−1.75	−1.98	0.93	−0.30	59.1*	25.5*	16.8	−0.17
	[−2.45]	[−0.43]	[−1.99]	[0.40]	[−2.52]	[−1.32]	[0.91]	[−1.09]	[−0.28]	[−0.65]	[0.65]	[−0.73]	[1.97]	[1.80]	[1.00]	[−.06]
Cancel-to-Trade	−3.76***	−7.25***	−6.14***	−11.1***	−4.95***	−1.00***	−11.6***	−26.1***	4.83***	6.18***	6.97***	8.31***	2.90*	8.37***	9.18***	21.3***
	[−9.14]	[−10.63]	[−5.49]	[−7.56]	[−4.90]	[−4.87]	[−3.13]	[−4.94]	[9.28]	[13.89]	[9.42]	[8.87]	[1.97]	[6.83]	[5.61]	[6.78]
Hidden Ratio (×100)	−0.48**	−6.82***	−15.3***	−18.5***	−1.79***	−8.79***	−9.05***	−11.2***	−4.71***	4.24***	25.5***	20.3***	−10.5***	5.63***	12.6***	13.7***
	[−2.14]	[−19.18]	[−16.85]	[−14.08]	[−4.17]	[−12.92]	[−8.33]	[−7.51]	[−9.66]	[9.42]	[27.53]	[14.91]	[−9.36]	[6.70]	[8.87]	[9.08]
Odd-lot Ratio (×100)	−0.94*	−2.24***	−0.58	−2.14	−3.90***	−3.70***	−1.08	−3.24***	5.60***	5.24***	2.30**	3.20***	4.71***	6.67***	3.43***	3.08***
	[−1.79]	[−3.06]	[−0.49]	[−1.61]	[−7.17]	[−5.63]	[−1.02]	[−2.78]	[4.46]	[6.22]	[2.11]	[2.78]	[5.88]	[8.53]	[3.73]	[3.46]
ISO Volume Share	−3.97***	−1.60***	−2.61***	−0.69	−3.75***	−1.96***	−2.77***	0.17	7.20***	2.55***	−0.65	−0.42	4.62***	2.24***	−0.14	−0.21
	[−11.29]	[−3.88]	[−4.99]	[−1.12]	[−9.84]	[−4.17]	[−4.18]	[0.28]	[12.20]	[7.44]	[−1.35]	[−0.98]	[6.70]	[4.63]	[−0.30]	[−0.36]

Table 10. Minimum Tick Size and Microstructure Outcomes: High-Volume Stocks.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on various market microstrucure outcomes for differentially tick-constrained stocks. The sample includes stocks with above median dollar volume in month of May prior to the respective change in tick size. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is augmented with stock characteristics, including market-capitalization, dollar volume, and average quoted spread, measured in the preceding month of June and estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP imposition								Panel B: TSP conclusion							
	QR				OLS				QR				OLS			
	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2018 quoted spread bin				May & June 2018 quoted spread bin			
Dependent variable:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Quoted Spread	.022***	.024***	0.009	−.033**	.034***	.024***	0.005	0.003	−.041***	−.033***	.026***	0.11***	−.072***	−.027***	.023***	0.18***
	[9.58]	[6.22]	[1.44]	[−2.32]	[39.86]	[10.12]	[0.83]	-0.08	[−32.93]	[−10.52]	[3.06]	[4.16]	[−30.49]	[−9.84]	[3.45]	[4.85]
Ln(NBBO Depth)	0.95***	0.33***	0.28***	0.16***	1.01***	0.71***	0.38***	0.18***	−1.32***	−0.82***	−0.34***	−.098***	−.033	−0.55***	−0.32***	−0.10***
	[13.69]	[12.96]	[7.74]	[6.42]	[22.61]	[18.11]	[7.82]	[4.22]	[−32.96]	[−30.91]	[−12.58]	[−4.55]	[−0.69]	[−13.08]	[−11.77]	[−4.02]
Effective Spread	.018***	.025***	.0086**	−.017***	.026***	.017***	.0098*	0.002	−.026***	−.018***	.015*	.042***	−.039***	−.018***	0.0009	.064***
	[13.32]	[8.82]	[2.18]	[−2.81]	[37.45]	[7.99]	[1.81]	[0.12]	[−14.36]	[−7.90]	[1.80]	[5.08]	[−26.05]	[−14.27]	[0.31]	[4.78]
Round-trip cost of 10 round-lots (bps)	.037***	0.0058	0.0051	−.051**	.023***	0.0044	0.0028	−.012	−.039***	−.021***	.048***	0.11***	−.047***	−.0033	.056***	0.23***
	[9.58]	[1.07]	[0.57]	[−2.64]	[14.17]	[1.08]	[0.34]	[−0.27]	[−19.87]	[−4.58]	[4.23]	[3.46]	[−11.40]	[−0.72]	[4.90]	[4.14]
Realized Spread (60s)	.0027***	.0026***	.0029**	−.0030	.0048***	.0037***	0.00078	0.0021	−.0058***	−.0011**	.0061***	.013***	−.0040***	−.0023***	.0029***	.013***
	[11.77]	[6.87]	[2.20]	[−1.24]	[15.39]	[7.50]	[0.72]	[0.88]	[−19.39]	[−2.00]	[3.30]	[4.66]	[−15.57]	[−6.24]	[3.63]	[4.47]
Price Impact (60s)	.016***	.019***	.0080**	−.0076	.021***	.013***	.0095*	−.00030	−.020***	−.018***	0.005	.025***	−.032***	−.019***	−.0032	.041***
	[13.60]	[8.60]	[2.38]	[−1.62]	[30.33]	[7.15]	[1.80]	[−.02]	[−11.21]	[−10.24]	[1.02]	[4.83]	[−26.98]	[−14.17]	[−1.23]	[4.06]
Trading Volume	−5.60	4.70	21.4	1.75	−26.4*	14.5	−15.1	−10.4*	118.5***	37.4***	−9.07	−20.1**	0.71	8.75	7.93	8.32
	[−0.39]	[0.39]	[1.09]	[0.18]	[−1.83]	[1.08]	[−1.08]	[−1.72]	[2.66]	[3.09]	[−0.66]	[−2.38]	-0.03	[0.77]	[0.70]	[0.88]
Cancel-to-Trade	−5.22***	−8.13***	−7.40***	−8.40***	−5.89***	−7.05***	−8.13***	−17.3**	7.02***	6.73***	7.10***	12.3***	7.40***	9.10***	6.49***	11.0***
	[−6.47]	[−6.61]	[−3.80]	[−3.88]	[−6.20]	[−4.24]	[−3.05]	[−2.59]	[5.27]	[8.22]	[6.83]	[5.61]	[6.96]	[14.38]	[7.38]	[11.41]
Hidden Ratio (×100)	−0.79*	−6.99***	−7.40***	−10.1***	−0.75*	−6.29***	−7.61***	−12.0***	−9.16***	3.13***	12.6***	14.7***	−8.59***	4.23***	14.9***	11.6***
	[−1.72]	[−10.74]	[−6.60]	[−8.56]	[−1.78]	[−11.81]	[−9.77]	[−12.90]	[−11.44]	[5.62]	[19.27]	[16.59]	[−13.32]	[6.36]	[16.70]	[10.64]
Odd-lot Ratio (×100)	−5.68***	−5.48***	−3.71***	−2.93*	−4.49***	−4.88***	−3.54***	−3.10**	4.66***	5.45***	3.09***	1.99**	4.82***	5.26***	3.05***	0.75
	[−7.88]	[−5.78]	[−3.53]	[−1.93]	[−8.21]	[−7.22]	[−3.12]	[−2.47]	[5.74]	[10.56]	[3.95]	[2.45]	[4.81]	[7.91]	[3.55]	[0.83]
ISO Volume Share	−4.79***	−2.81***	−1.52	−0.54	−4.27***	−2.22***	−1.37	−0.28	7.94***	2.26***	0.007	0.37	6.82***	1.88***	0.026	0.62
	[−9.85]	[−4.43]	[−1.43]	[−0.73]	[−9.43]	[−4.42]	[−1.57]	[−0.36]	[11.66]	[5.62]	-0.02	[0.68]	[10.50]	[4.29]	-0.05	[0.96]

Table 11. Minimum Tick Size and Microstructure Outcomes: Robustness to Excluding Penny Stocks.
The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on various market microstrucure outcomes for differentially tick-constrained stocks. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) and OLS regressions after excluding stocks whose average closing price in the same year's May and June was below $5. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP imposition								Panel B: TSP conclusion							
	QR				OLS				QR				OLS			
	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2018 quoted spread bin				May & June 2018 quoted spread bin			
Dependent variable:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Quoted Spread	.032***	.032***	0.0069	−.047***	.033***	.021***	0.003	−.031*	−.057***	−.024***	.032***	0.10***	−.039***	−.027***	.037***	0.11***
	[19.54]	[12.47]	[1.62]	[−3.83]	[59.99]	[11.94]	[0.71]	[−1.87]	[−27.77]	[−10.87]	[5.54]	[5.03]	[−32.70]	[−10.54]	[4.80]	[5.49]
Ln(NBBO Depth)	1.00***	0.78***	0.46***	0.21***	1.00***	0.69***	0.41***	0.17***	−0.19***	−1.00***	−0.53***	−.073***	−1.37***	−0.78***	−0.30***	−.067***
	[22.98]	[21.71]	[10.91]	[6.46]	[38.36]	[29.94]	[12.87]	[6.04]	[−3.22]	[−23.53]	[−15.50]	[−3.38]	[−32.47]	[−36.53]	[−13.48]	[−3.22]
Effective Spread	.032***	.025***	.0072***	−.021***	.025***	.018***	.013***	−.014	−.037***	−.016***	.0054*	.034***	−.025***	−.021***	.025***	.031***
	[25.82]	[16.84]	[2.74]	[−3.33]	[26.85]	[6.05]	[2.74]	[−1.13]	[−24.99]	[−14.19]	[1.96]	[3.28]	[−9.94]	[−8.39]	[2.67]	[2.66]
Round-trip cost of 10 round-lots (bps)	.023***	.0076**	−.014**	−.074***	.022***	0.003	−.013*	−.067***	−.044***	0.0028	.062***	0.15***	−.035***	−.014***	.060***	0.17***
	[12.98]	[2.18]	[−2.03]	[−4.05]	[21.17]	[1.07]	[−1.89]	[−2.66]	[−14.62]	[0.76]	[6.52]	[4.78]	[−19.41]	[−3.90]	[5.75]	[4.98]
Realized Spread (60s)	.0040***	.0038***	.0031***	−.0052**	.0054***	.0032***	.0033***	−.00012	−.0047***	−.0033***	.0032***	.016***	−.0062***	−.0017**	.0071***	.019***
	[19.13]	[10.69]	[3.69]	[−2.58]	[21.08]	[3.58]	[2.76]	[−.03]	[−17.27]	[−9.23]	[3.59]	[5.14]	[−11.65]	[−2.10]	[3.57]	[4.14]
Price Impact (60s)	.025***	.019***	.0059**	−.012***	.020***	.012***	.0080**	−.0092	−.029***	−.016***	0.001	.020***	−.020***	−.019***	.014**	.023***
	[26.75]	[14.15]	[2.62]	[−2.71]	[21.59]	[6.35]	[2.09]	[−1.06]	[−21.89]	[−14.04]	[0.47]	[3.07]	[−9.31]	[−9.30]	[2.34]	[2.76]
Trading Volume	4.92	−0.63	−7.05*	−1.56	−12.7	−4.17	−0.43	−1.67	11.8	−14.0*	−0.40	−0.88	82.3**	2.0**	8.60	−7.79**
	[0.52]	[−0.12]	[−1.85]	[−1.62]	[−1.24]	[−0.57]	[−.08]	[−0.90]	[0.96]	[−1.90]	[−.07]	[−1.42]	[2.33]	[2.28]	[0.93]	[−2.61]
Cancel-to-Trade	−4.92***	−9.30***	−7.87***	−14.0***	−4.91***	−8.28***	−10.3***	−21.4***	6.41***	9.02***	7.21***	12.0***	6.53***	6.82***	8.08***	18.2***
	[−8.56]	[−9.70]	[−4.63]	[−7.40]	[−7.10]	[−6.66]	[−4.32]	[−5.19]	[7.42]	[16.43]	[8.59]	[8.96]	[5.66]	[10.16]	[9.11]	[8.65]
Hidden Ratio (×100)	−1.00***	−7.50***	−10.7***	−12.3***	−1.21***	−7.32***	−11.0***	−13.6***	−7.61***	4.92***	15.1***	15.0***	−7.97***	4.38***	16.0***	17.0***
	[−3.25]	[−17.48]	[−13.34]	[−12.70]	[−4.29]	[−18.17]	[−16.68]	[−15.97]	[−12.68]	[8.21]	[18.34]	[13.07]	[−11.95]	[7.94]	[17.93]	[17.69]
Odd-lot Ratio (×100)	−4.25***	−3.82***	−1.19	−3.00***	−3.45***	−3.19***	−0.53	−2.75***	5.32***	5.66***	2.69***	2.97***	5.25***	5.69***	2.48***	2.70***
	[−8.22]	[−5.98]	[−1.27]	[−2.76]	[−8.51]	[−6.02]	[−0.59]	[−2.76]	[5.86]	[8.94]	[2.94]	[3.52]	[6.98]	[10.89]	[3.02]	[3.41]
ISO Volume Share	−4.41***	−2.22***	−1.77***	−0.63	−3.81***	−1.99***	−2.43***	0.08	6.18***	2.07***	−0.21	0.03	6.85***	2.31***	−0.26	−0.56
	[−12.07]	[−4.82]	[−3.19]	[−1.08]	[−12.71]	[−5.61]	[−5.29]	[0.15]	[9.17]	[5.31]	[−0.45]	[.06]	[10.52]	[6.70]	[−0.66]	[−1.20]

Table 12. Minimum Tick Size and Microstructure Outcomes: Robustness to Inclusion of Stock Characteristics. The table presents estimated impacts of an exogenous change in the minimum quoting and trading increment, i.e., tick size, on various market microstrucure outcomes for differentially tick-constrained stocks. Panel A presents the impacts of an increase in tick size from 1¢ to 5¢, using data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Panel B presents the impacts of a reduction in tick size from 5¢ to 1¢, using data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size reduction. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is augmented with stock characteristics, including market-capitalization, dollar volume, average quoted spread, and return volatility measured in the preceding month of June and estimated using median (quantile) and OLS regressions. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A: TSP imposition								Panel B: TSP conclusion							
	QR				OLS				QR				OLS			
	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2018 quoted spread bin				May & June 2018 quoted spread bin			
Dependent variable:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Quoted Spread	.024***	.026***	0.0048	−.037**	.033***	.020***	0.0089	−.026	−.035***	−.023***	.037***	0.13***	−.053***	−.023***	.031***	0.10***
	[13.09]	[7.80]	[0.87]	[−2.08]	[45.38]	[8.76]	[1.39]	[−1.09]	[−30.92]	[−8.30]	[4.70]	[5.47]	[−22.82]	[−9.50]	[5.08]	[4.68]
Ln(NBBO Depth)	0.97***	0.67***	0.37***	0.21***	1.01***	0.70***	0.37***	0.18***	−1.31***	−0.74***	−0.29***	−.059**	−0.63***	−1.12***	−0.54***	−.062***
	[15.10]	[14.97]	[6.54]	[4.18]	[24.91]	[24.56]	[7.66]	[4.56]	[−31.59]	[−29.46]	[−11.96]	[−2.60]	[−6.44]	[−22.69]	[−14.11]	[−2.76]
Effective Spread	.022***	.022***	.0078**	−.018*	.026***	.015***	.016**	−.013	−.023***	−.011***	.024**	.046***	−.034***	−.015***	.0049*	.034***
	[17.17]	[10.50]	[2.05]	[−1.95]	[31.39]	[6.96]	[2.60]	[−0.81]	[−13.90]	[−3.93]	[2.51]	[3.65]	[−23.41]	[−12.46]	[1.70]	[3.03]
Round-trip cost of 10 round-lots (bps)	.029***	0.004	−.0059	−.065**	.024***	−.00092	−.00077	−.079**	−.030***	−.010**	.061***	0.16***	−.065***	0.0043	.064***	0.16***
	[11.21]	[0.86]	[−0.68]	[−2.52]	[17.04]	[−0.25]	[−.08]	[−2.34]	[−17.84]	[−2.57]	[5.81]	[4.54]	[−25.95]	[1.11]	[6.46]	[4.55]
Realized Spread (60s)	.0037***	.0037***	.0040***	−.0054*	.0060***	.0043***	0.0025	−.00015	−.0066***	−.00087	.0078***	.020***	−.0044***	−.0031***	.0037***	.015***
	[14.05]	[8.91]	[3.30]	[−1.83]	[18.93]	[8.12]	[1.66]	[−.03]	[−21.78]	[−1.28]	[3.55]	[4.29]	[−14.29]	[−7.85]	[3.61]	[4.20]
Price Impact (60s)	.018***	.016***	.0067**	−.011*	.020***	.010***	.013**	−.012	−.016***	−.012***	.012**	.025***	−.025***	−.015***	0.00073	.019***
	[17.90]	[8.71]	[2.03]	[−1.81]	[24.93]	[5.87]	[2.45]	[−1.11]	[−10.57]	[−5.60]	[2.05]	[2.87]	[−21.67]	[−12.50]	[0.33]	[2.71]
Trading Volume	5.66	1.43	−9.22**	0.80	−21.5*	0.68	−12.1*	−2.97	84.5**	21.1**	−0.21	−8.49**	−8.99	−24.1***	−1.16	−0.51
	[0.45]	[0.20]	[−2.01]	[0.50]	[−1.69]	[.08]	[−1.83]	[−1.23]	[2.45]	[2.19]	[−.02]	[−2.49]	[−0.65]	[−2.97]	[−0.16]	[−0.55]
Cancel-to-Trade	−3.62***	−9.13***	−8.50***	−14.7***	−3.69***	−10.4***	−14.7***	−29.7***	3.45***	6.16***	8.12***	18.8***	4.20***	8.51***	7.13***	12.0***
	[−5.05]	[−8.09]	[−3.45]	[−5.61]	[−4.42]	[−5.52]	[−4.10]	[−4.92]	[3.82]	[8.50]	[8.36]	[8.85]	[5.28]	[14.44]	[7.95]	[8.85]
Hidden Ratio (×100)	−0.86**	−8.60***	−9.88***	−11.0***	−0.99***	−7.94***	−12.2***	−12.8***	−7.64***	5.75***	16.5***	16.9***	−7.66***	5.44***	15.2***	14.9***
	[−2.03]	[−14.65]	[−10.35]	[−8.38]	[−2.65]	[−14.85]	[−11.39]	[−11.18]	[−11.87]	[9.35]	[17.99]	[17.53]	[−12.04]	[9.35]	[17.95]	[12.89]
Odd-lot Ratio (×100)	−3.36***	−3.37***	−1.19	−3.04**	−2.02***	−2.38***	−1.15	−2.15	5.07***	5.84***	1.97**	2.38***	5.40***	5.93***	2.49***	2.73***
	[−4.82]	[−3.88]	[−1.22]	[−2.13]	[−3.81]	[−3.36]	[−1.01]	[−1.62]	[7.77]	[10.75]	[2.35]	[2.95]	[5.48]	[9.25]	[2.68]	[3.12]
ISO Volume Share	−4.55***	−2.50***	−0.91	0.13	−4.06***	−1.83***	−1.61***	0.95	5.85***	2.33***	−0.35	−0.44	5.35***	2.04***	−0.35	0.05
	[−10.38]	[−4.35]	[−1.41]	[0.19]	[−11.59]	[−4.18]	[−2.72]	[1.43]	[11.68]	[6.17]	[−0.87]	[−0.92]	[9.28]	[4.92]	[−0.73]	[0.10]

A Main Effects of Individual Test Groups

This section provides robustness analysis comparing each TSP Test Group, i.e., G1, G2, G3, against the control stocks. This analysis ensures that our main findings are mainly attributable to the changes in tick sizes, rather than the known differences between trading rules across the three groups of treated stocks.

Tables A.1 and A.2 report our estimates for individual Test Groups for TSP imposition and conclusion, respectively. Our main results qualitatively extend across individual Test Groups, indicating that our more granular decomposition of the stocks, based on the extent to which they are tick constraint, helps identifying the very different effects that can emerge as a result of a uniform change in tick size.

The only exception is the share of ISO volume. For G1 and G2, a larger tick leads to a decreased use of ISOs, especially for tick and near-tick constrained stocks. In sharp contrast, a larger tick leads to a significant *increase* in ISO usage in G3 stocks. This finding is consistent with the reliance of institutional investors on ISOs and ATSs. For G1 and G2 stocks, a larger tick raises the depth at the top of the order book, and more so for tick and near-tick constrained stocks. As such, institutions can remove significantly more liquidity from one exchange, which reduces their need to use ISOs that would reveal their significant liquidity needs to other market participants, including predatory high-frequency traders. Recall that G3 stocks are also subject to the Trade-At requirement that significantly limits inside quote off-exchange executions (Comerton-Forde et al. (2019)), an important source of liquidity for institutional investors. Reflecting the migration of liquidity to exchanges in response to the Trade-At requirement, institutional investors must seek liquidity accordingly. It follows that due to the exclusive availability of ISOs to institutional investors, ISO usage must rise, offsetting the negative effects on ISOs driven by the larger tick. Our findings are consistent with the the effect of the Trade-At rule dominating the effect of a larger tick on ISO usage.

Table A.1. Minimum Tick Size and Microstructure Outcomes by TSP Groups: Imposition.
The table presents estimated impacts of an exogenous increase from 1¢ to 5¢ in the tick size on various market microstrucure outcomes for differentially tick-constrained stocks. The sample includes data from 08/12/2016-12/14/2016, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2016 quoted spreads of: (1) no more than 5¢, (2) 5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) regressions, comparing, separately, stocks in each TSP Test Group to control stocks. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Test Group 1				Test Group 2				Test Group 3			
	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Dependent variable:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Quoted Spread	.026***	.030***	0.0086	−.048***	.024***	.029***	0.0067	−.032**	.027***	.027***	0.0046	−.023
	[15.77]	[9.46]	[1.50]	[−3.76]	[14.11]	[9.73]	[1.32]	[−2.07]	[16.82]	[8.66]	[0.83]	[−1.58]
Ln(NBBO Depth)	1.01***	0.76***	0.47***	0.18***	0.95***	0.81***	0.44***	0.24***	0.99***	0.70***	0.36***	0.25***
	[16.99]	[14.07]	[8.04]	[4.48]	[15.17]	[15.36]	[7.61]	[5.18]	[16.41]	[13.39]	[6.58]	[5.90]
Effective Spread	.024***	.027***	.0085**	−.020***	.022***	.025***	.0074**	−.016*	.024***	.020***	.0071**	−.0043
	[19.12]	[13.51]	[2.54]	[−2.70]	[18.26]	[13.08]	[2.19]	[−1.99]	[20.73]	[1.03]	[2.01]	[−0.57]
Round-trip cost of 10 round-lots (bps)	.032***	.0092*	−.016*	−.078***	.033***	.0070*	−.0100	−.060***	.044***	.0098**	−.0058	−.062***
	[13.56]	[1.97]	[−1.68]	[−3.67]	[12.82]	[1.73]	[−1.22]	[−2.80]	[17.80]	[2.10]	[−0.70]	[−3.11]
Realized Spread (60s)	.0039***	.0039***	.0032***	−.0052**	.0037***	.0041***	.0040***	−.0040	.0033***	.0032***	.0029**	−.0014
	[16.54]	[8.17]	[2.77]	[−2.18]	[15.08]	[10.38]	[4.00]	[−1.59]	[15.38]	[8.64]	[2.62]	[−0.54]
Price Impact (60s)	.020***	.019***	.0067**	−.011**	.018***	.018***	.0058**	−.0077	.020***	.014***	0.0042	0.0015
	[20.67]	[10.95]	[2.22]	[−2.00]	[18.74]	[10.88]	[2.01]	[−1.46]	[20.66]	[8.72]	[1.62]	[0.29]
Trading Volume	−10.8	−3.67	−7.22*	−2.76***	9.43	−2.36	−7.55**	−1.10	−3.39	−12.8**	−10.7**	−4.99***
	[−1.03]	[−0.54]	[−1.87]	[−4.42]	[0.85]	[−0.38]	[−2.28]	[−0.74]	[−0.30]	[−2.15]	[−2.16]	[−3.92]
Cancel-to-Trade	−4.63***	−8.95***	−7.27***	−14.0***	−3.57***	−9.47***	−8.12***	−14.5***	−6.05***	−9.38***	−7.15***	−18.0***
	[−7.26]	[−5.97]	[−3.87]	[−6.22]	[−5.01]	[−8.46]	[−3.32]	[−5.56]	[−9.43]	[−8.48]	[−3.42]	[−7.27]
Hidden Ratio (×100)	−1.30***	−7.49***	−9.59***	−11.6***	−0.83**	−8.51***	−9.96***	−11.0***	−4.27***	−11.2***	−12.7***	−14.1***
	[−3.77]	[−12.33]	[−9.06]	[−9.72]	[−2.01]	[−14.72]	[−10.59]	[−8.58]	[−1.03]	[−18.21]	[−12.21]	[−11.84]
Odd-lot Ratio (×100)	−3.29***	−3.70***	−0.85	−2.08	−3.15***	−3.37***	−1.16	−3.15**	−6.61***	−5.34***	−0.88	−5.65***
	[−5.44]	[−4.66]	[−0.68]	[−1.58]	[−4.58]	[−3.98]	[−1.21]	[−2.24]	[−11.46]	[−5.80]	[−0.80]	[−4.37]
ISO Volume Share	−4.17***	−1.85***	−2.66***	−0.90	−4.47***	−2.47***	−1.18*	−0.50	6.04***	5.62***	6.62***	6.80***
	[−9.25]	[−3.09]	[−3.73]	[−1.23]	[−10.69]	[−4.46]	[−1.96]	[−0.73]	[12.90]	[10.14]	[9.60]	[9.98]

Table A.2. Minimum Tick Size and Microstructure Outcomes by TSP Groups: Conclusion.
The table presents estimated impacts of an exogenous decrease from 5¢ to 1¢ in the tick size on various market microstrucure outcomes for differentially tick-constrained stocks. The sample includes data from 08/08/2018-11/20/2018, for stocks with different tick constraint status prior to tick size increase. Stocks are classified into four tick constraint bins according to the average May and June 2018 quoted spreads of: (1) no more than 5.5¢, (2) 5.5¢ to 10¢, (3) 10¢ to 15¢, and (4) greater than 15¢. Equation (1) is estimated using median (quantile) regressions, comparing, separately, stocks in each TSP Test Group to control stocks. Estimates control for date fixed effects and double-cluster standard errors by stock and date. The numbers in brackets are t-statistics with ***, **, and * identifying statistical significance at the 1%, 5%, and 10% levels, respectively.

	Test Group 1				Test Group 2				Test Group 3			
	May & June 2016 quoted spread bin				May & June 2016 quoted spread bin				May & June 2016 quoted spread bin			
Dependent variable:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Quoted Spread	−.049***	−.025***	.020***	0.15***	−.049***	−.022***	.025***	.064**	−.048***	−.018***	.023***	0.11***
	[−18.12]	[−8.97]	[3.51]	[5.03]	[−19.19]	[−7.05]	[4.32]	[2.60]	[−18.40]	[−6.84]	[3.22]	[3.31]
Ln(NBBO Depth)	−0.94***	−0.77***	−0.61***	−.067**	−0.73***	−0.64***	−0.58***	−.073**	−0.96***	−0.88***	−0.64***	−0.19***
	[−8.30]	[−11.57]	[−12.40]	[−2.59]	[−6.77]	[−11.18]	[−12.63]	[−2.50]	[−7.91]	[−13.33]	[−11.36]	[−5.89]
Effective Spread	−.034***	−.019***	0.00056	.047***	−.034***	−.016***	0.0028	0.02	−.033***	−.012***	0.0033	.044***
	[−19.42]	[−10.45]	[0.19]	[3.31]	[−20.14]	[−9.39]	[1.01]	[1.63]	[−19.35]	[−7.72]	[1.00]	[3.26]
Round-trip cost of 10 round-lots (bps)	−.069***	0.0038	.051***	0.21***	−.070***	0.0085	.056***	0.11***	−.070***	.015***	.052***	0.15***
	[−19.64]	[0.85]	[5.27]	[4.68]	[−22.16]	[1.47]	[5.94]	[2.78]	[−20.75]	[2.85]	[4.48]	[3.16]
Realized Spread (60s)	−.0040***	−.0041***	0.00073	.019***	−.0042***	−.0030***	.0024**	.0096**	−.0032***	−.0010**	.0024**	.022***
	[−13.16]	[−7.84]	[0.72]	[4.68]	[−10.69]	[−6.25]	[2.49]	[2.57]	[−10.32]	[−2.22]	[2.15]	[5.57]
Price Impact (60s)	−.025***	−.017***	−.0016	.027***	−.026***	−.016***	0.0013	.014*	−.023***	−.014***	0.0016	.023**
	[−16.73]	[−9.50]	[−0.74]	[3.04]	[−19.69]	[−9.71]	[0.60]	[1.79]	[−17.09]	[−9.27]	[0.64]	[2.61]
Trading Volume	−0.15	−1.76	−8.88*	−1.44***	1.60	−21.8***	−6.90	−0.17	13.6	−6.10	6.47	−0.34
	[−.01]	[−0.19]	[−1.70]	[−2.84]	[0.11]	[−2.82]	[−1.37]	[−0.19]	[1.22]	[−0.71]	[1.11]	[−0.35]
Cancel-to-Trade	5.85***	9.50***	7.19***	14.4***	4.24***	8.92***	6.95***	9.27***	7.79***	9.52***	9.52***	13.7***
	[7.32]	[10.87]	[7.65]	[8.55]	[4.51]	[9.42]	[8.10]	[5.49]	[8.99]	[11.04]	[9.56]	[7.38]
Hidden Ratio (×100)	−5.72***	4.92***	13.2***	16.3***	−5.64***	4.39***	12.1***	12.4***	0.69	9.46***	12.7***	16.2***
	[−7.38]	[7.05]	[13.73]	[10.43]	[−6.70]	[4.74]	[13.11]	[8.86]	[0.91]	[10.90]	[11.32]	[9.85]
Odd-lot Ratio (×100)	5.86***	5.49***	2.98***	4.16***	6.09***	5.75***	3.71***	1.34	4.71***	5.44***	4.21***	1.14
	[6.48]	[5.94]	[3.06]	[4.34]	[5.32]	[5.73]	[4.03]	[1.24]	[4.55]	[6.85]	[4.68]	[0.97]
ISO Volume Share	5.62***	1.78***	−0.43	−0.50	5.35***	1.69***	−.049	0.63	−4.20***	−5.62***	−6.35***	−6.36***
	[8.77]	[3.78]	[−0.85]	[−0.84]	[7.68]	[3.38]	[−0.10]	[1.10]	[−7.87]	[−11.43]	[−9.83]	[−9.54]